

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**LIFE CYCLE ASSESSMENT OF COMBINED BIOHEAT AND BIOPOWER
PRODUCTION AND COST: SIMULATED CASE STUDIES BASED ON
COMBUSTION UTILIZING TURKISH OAK (*Quercus cerris L.*) COPPICES**

Ph.D. THESIS

Güner EKŞİ

Department of Chemical Engineering

Chemical Engineering Programme

SEPTEMBER 2017

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**LIFE CYCLE ASSESSMENT OF COMBINED BIOHEAT AND BIOPOWER
PRODUCTION AND COST: SIMULATED CASE STUDIES BASED ON
COMBUSTION UTILIZING TURKISH OAK (*Quercus cerris L.*) COPPICES**

Ph.D. THESIS

**Güner EKŞİ
(506102008)**

Department of Chemical Engineering

Chemical Engineering Programme

Thesis Advisor: Prof. Dr. Filiz KARAOSMANOĞLU

SEPTEMBER 2017

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**BİRLİKTE BİYOİSİ VE BİYOGÜÇ ÜRETİMİ YAŞAM DÖNGÜSÜ DEĞERLENDİRMESİ
VE MALİYETİ: TÜRKİYE MEŞE (*Quercus cerris* L.) BALTALIKLARINI KULLANAN YANMA
TEMELLİ BENZETİLMİŞ DURUM ÇALIŞMALARI**

DOKTORA TEZİ

**Güner EKŞİ
(506102008)**

Kimya Mühendisliği Anabilim Dalı

Kimya Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Filiz KARAOSMANOĞLU

EYLÜL 2017

Güner EKŞİ, a Ph.D. student of ITU Graduate School of Science Engineering and Technology student ID 506102008, successfully defended the thesis/dissertation entitled “LIFE CYCLE ASSESSMENT OF COMBINED BIOHEAT AND BIOPOWER PRODUCTION AND COST: SIMULATED CASE STUDIES BASED ON COMBUSTION UTILIZING TURKISH OAK (*Quercus cerris L.*) COPPICES”, which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Filiz KARAOSMANOĞLU**
Istanbul Technical University

Jury Members : **Prof.Dr. Hanzade AÇMA**
Istanbul Technical University

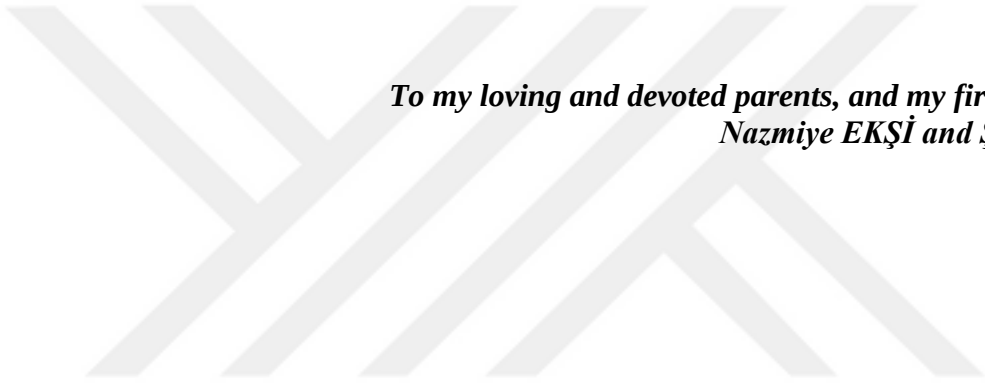
Prof.Dr. İsmail TORÖZ
Istanbul Technical University

Doç.Dr. Sibel BAŞAKÇILARDAN
KABAKÇI
Yalova University

Prof.Dr. Nedim SARAÇOĞLU
Bartın University

Date of Submission : 24 August 2017
Date of Defense : 25 September 2017





*To my loving and devoted parents, and my first teachers,
Nazmiye EKŞİ and Şerif EKŞİ,*



FOREWORD

First and foremost, thanks to my dear professor and supervisor Prof. Filiz KARAOSMANOĞLU, for her continuous guidance, advice, support, encouragement, understanding, facilitation and help, not only during the course of my Ph.D. study, but for the entire duration from my undergraduate years in the 1990s.

Thanks to my steering committee members, Prof. İsmail TORÖZ and Assoc.Prof. Sibel BAŞAKÇILARDAN KABAKÇI, for the valuable suggestions, insights and constructive comments they have made throughout my study.

Thanks to Dr. Mehmet ÖZDEMİR and M.Sc. Abbas ŞAHİN, Marmara Forest Research Institute of General Directorate of Forestry, for their help and effort in getting oak coppice samples.

Thanks to Assoc.Prof. Gülnur MERTOĞLU ELMAS, the Forest Products Chemistry and Technology Laboratory of Forest Industry Engineering at Istanbul University, for her hospitality and polite help in sampling and providing structural analysis of oak coppice samples.

Thanks to the Energy Institute of TÜBİTAK Marmara Research Center for providing laboratory analyses of oak coppice samples.

Thanks to the professors and staff in the Department of Chemical Engineering at Istanbul Technical University who have facilitated my academic work in every way.

Thanks to my sweet friends. They built up empathy with me and made my studies enjoyable.

Thanks to all who think of me with kindness and pray for me throughout all my life.

Last but not least, thanks to my lovely family. They supported me in all possible ways. Special thanks to my housemates, my darling mother Nazmiye EKŞİ, my pretty sisters Emine EKŞİ and Hatice EKŞİ, and to my father beloved in my heart, Şerif EKŞİ.

August 2017

Güner EKŞİ
(Chemical Engineer, M.Sc.)

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	ix
TABLE OF CONTENTS	xi
ABBREVIATIONS	xv
SYMBOLS	xvii
LIST OF TABLES	xix
LIST OF FIGURES	xxiii
SUMMARY	xxvii
ÖZET	xxxix
1. INTRODUCTION	1
2. THEORETICAL STUDY	9
2.1 Biorefineries	9
2.2 Biomass Sources	13
2.2.1 Woody biomass	15
2.2.2 Forest biomass	18
2.2.3 Forests in Turkey	19
2.2.4 Oak coppice forests in Turkey	20
2.2.5 Energy forestry in Turkey	21
2.3 Turkey's Energy Outlook and Biomass Energy	22
2.4 CHP Overview	34
2.5 CBHBP Production	37
2.5.1 Biomass sources and supply chain	38
2.5.2 Design of forest biomass supply chain network	41
2.5.2.1 Chipping at roadside	45
2.5.2.2 Biofuel feedstock preparation yard of a CBHBP plant using wood chips	48
2.5.3 Primary conversion technologies	49
2.5.4 Secondary conversion technologies	51
2.5.5 CBHBP production based on combustion and steam turbine technology	54
2.5.6 Commercial CBHBP plants based on combustion and steam turbine technology	58
2.6 Process Simulation and Aspen Plus Software	66
2.7 LCA and SimaPro Software	70
2.7.1 Assessment methods for environmental impacts and LCA	70
2.7.2 LCA Methodology	74
2.7.2.1 Goal and scope definition	75
2.7.2.2 Inventory analysis	82
2.7.2.3 Impact assessment	83
2.7.2.4 Interpretation	85
2.7.3 Softwares for LCA and SimaPro	85
2.7.3.1 Ecoinvent database	89
2.8 Cost of CBHBP Production	92
2.9 Literature Review	96

2.9.1 Literature review on CBHBP production.....	97
2.9.2 Literature review on LCA of CBHBP and biopower-only production ...	105
2.9.2.1 Review articles	105
2.9.2.2 Research articles.....	115
3. ASPEN PLUS PROCESS SIMULATION OF COMBINED BIOHEAT AND BIOPOWER PRODUCTION UTILIZING TURKISH OAK (<i>Quercus cerris</i> L.) COPPICES.....	123
3.1 The Choice of Solid Biomass Source and Sampling.....	124
3.2 Characterization of TR-Oak Coppices	124
3.3 Stoichiometric Chemical Equations for Combustion of TR-Oak Coppices...	126
3.4 Case Studies for CBHBP Plants	128
3.5 Thesis Methodology	129
3.6 Aspen Plus Process Simulation Model for CBHBP Plants	132
3.6.1 Properties environment	132
3.6.1.1 Components.....	132
3.6.1.2 Methods.....	134
3.6.2 Simulation environment	135
3.6.2.1 Stream class.....	135
3.6.2.2 Unit operation blocks	135
3.6.3 Design specifications.....	139
3.6.4 Validation of Aspen Plus process simulation model.....	139
3.7 Aspen Plus Process Simulation Model Inputs and Outputs for Case Study-1, - 2, and -3.....	143
3.7.1 Case Study-1	144
3.7.2 Case Study-2	147
3.7.3 Case Study-3	147
3.7.4 Environmental impacts from CBHBP Plants	152
3.7.4.1 Stack gas emissions.....	153
3.7.4.2 Solid wastes.....	156
3.7.4.3 Other wastes	157
4. LIFE CYCLE ASSESSMENT OF COMBINED BIOHEAT AND BIOPOWER PRODUCTION UTILIZING TURKISH OAK (<i>Quercus cerris</i> L.) COPPICES.....	159
4.1 Goal and Scope Definition of the LCA study	159
4.1.1 Goal.....	159
4.1.2 Scope	160
4.1.2.1 System boundary	160
4.1.2.2 Functional unit and modeling approach	163
4.1.2.3 Allocation procedure	163
4.1.2.4 Impact assessment methods and impact categories.....	163
4.1.2.5 Required specificity.....	168
4.2 Inventory Analysis of the LCA study.....	169
4.2.1 Data sources and data usage approach	169
4.2.2 LCA inventory general data, and assumptions.....	171
4.2.3 LCA inventory for TR-Oak chip supply chain.....	175
4.2.4 LCA inventory for TR-Oak chip-fueled CBHBP plants and TR-Oak ash utilization.....	180
4.3 Eco-design parameters of the LCA study.....	188

5. COST OF COMBINED BIOHEAT AND BIOPOWER PRODUCTION UTILIZING TURKISH OAK (<i>Quercus cerris</i> L.) COPPICES	191
5.1 The Method Followed in the Cost Study	191
5.2 Cost Inventory Data for Case Study-1, -2, and -3	192
6. RESULTS AND DISCUSSION	195
6.1 LCA Results and Discussion for Case Study-1, -2, and -3	195
6.1.1 Comparative characterization results of midpoint impact categories	196
6.1.2 Comparative normalization results of midpoint impact categories	204
6.1.3 Comparative weighting results of endpoint impact categories	209
6.1.4 Contribution analysis for midpoint impact categories	212
6.1.5 Contribution analysis for endpoint impact categories	224
6.2 Sensitivity Analysis on LCA results	231
6.2.1 Effect of transport distance between roadside and CBHBP plant on LCA results	231
6.2.2 Effect of equipment productivity on LCA results	231
6.2.3 Effect of CBHBP plant lifetime on LCA results	234
6.2.4 Effect of allocation procedure on LCA results	234
6.3 Effect of Eco-design Parameters on LCA Results	236
6.3.1 Effect of feedstock properties on LCA results	236
6.3.2 Effect of Process Conditions on LCA results	238
6.4 Comparison of LCA Results for TR-Oak Chip-fueled CBHBP Production and Turkish Lignite-fueled Power Production	245
6.5 Cost Results and Discussion for Case Study-1, -2, and -3	248
6.5.1 Cost estimates for Case Study-1, -2, and -3	248
6.5.2 Sensitivity analyses on investment cost and TR-Oak chip cost	251
7. CONCLUSIONS AND RECOMMENDATIONS	253
REFERENCES	265
APPENDICES	295
APPENDIX A	296
APPENDIX B	299
APPENDIX C	302
APPENDIX D	304
CURRICULUM VITAE	317



ABBREVIATIONS

ACD	: Acidification
ADE	: Abiotic depletion-elements
ADF	: Abiotic depletion-fossil fuels
BEPA	: Biomass Energy Potential Map of Turkey
BFB	: Bubbling fluidized bed
BIGCC	: Biomass integrated gasification combined cycle
CBHBP	: Combined BioHeat and BioPower
CFB	: Circulating fluidized bed
CHP	: Combined Heat and Power
CS	: Case Study
DALY	: Disability-adjusted life years
DG	: Distributed generation
EPD	: Environmental Product Declaration
eq	: Equivalent
ESP	: Electrostatic precipitator
ETR	: Eutrophication
EU	: European Union
FB	: Fluidized bed
FWET	: Fresh water aquatic ecotoxicity
GDF	: General Directorate of Forestry
GLO	: Global
GHG	: Greenhouse gas
GW	: Global warming
HRSG	: Heat recovery steam generator
HT	: Human toxicity
ICE	: Internal combustion engine
IEA	: International Energy Agency
INDC	: Intended Nationally Determined Contributions
IPCC	: Intergovernmental Panel on Climate Change
IRENA	: International Renewable Energy Agency
ISO	: International Organization for Standardization
LCA	: Life Cycle Assessment
LCI	: Life Cycle Inventory
LCIA	: Life Cycle Impact Assessment
LCM	: Life Cycle Management
LCO	: Life Cycle Optimization
LCOE	: Levelized cost of electricity
LHV	: Low heating value
MENR	: Ministry of Energy and Natural Resources
MET	: Marine aquatic ecotoxicity
MoD	: Ministry of Development
MoEF	: Ministry of Environment and Forestry
MoFWA	: Ministry of Forestry and Water Affairs
MSW	: Municipal solid waste

NREAP	: National Renewable Energy Action Plan
OD	: Ozone layer depletion
ORC	: Organic Rankine cycle
O&M	: Operation and maintenance
PAH	: Polycyclic aromatic hydrocarbons
PDF	: Potentially disappeared fraction of species
PM	: Particulate matter
PCO	: Photochemical oxidation
PCR	: Product Category Rules
RER	: European dataset
ROW	: Rest-of-World
SAM	: System Advisor Model
SETAC	: Society of Environmental Toxicology and Chemistry
SRC	: Short rotation coppice
SRF	: Short rotation forestry
TET	: Terrestrial ecotoxicity
TPES	: Total primary energy supply
TR-Oak	: Turkish oak, Turkey oak
TSE	: Turkish Standards Institution
TÜBİTAK	: The Scientific and Technological Research Council of Turkey
UN	: United Nations
UNEP	: United Nations Environment Programme
UNFCCC	: United Nations Framework Convention on Climate Change
WEC	: World Energy Council
WCED	: World Commission on Environment and Development
VOC	: Volatile organic compounds
YEK	: Turkish renewable energy
YEKDEM	: Turkish renewable energy support mechanism

SYMBOLS

a	: year
cent	: US Dollar cent
CH₄	: methane
CO	: carbon monoxide
CO₂	: carbon dioxide
d	: day
EUR	: Euro
GW_e	: gigawatt electrical
h	: hour(s)
ha	: hectare
H₂O	: water
kW	: kilowatt
kW_e	: kilowatt electrical
kWh	: kilowatt-hour(s)
l	: liter
MJ	: megajoule
mPt	: millipoint
Mt	: million metric tons
Mtoe	: million metric tons of oil equivalent
MW	: megawatt
MW_e	: megawatt electrical
MW_{th}	: megawatt thermal
MWh	: megawatt-hour(s)
NO	: nitrogen monoxide
N₂O	: nitrous oxide
NO_x	: nitrogen oxides
Pt	: point
SO₂	: sulfur dioxide
SO₃	: sulfur trioxide
SO_x	: sulfur oxides
t	: metric ton(s)
USD	: US Dollar
W	: watt
λ	: excess air ratio



LIST OF TABLES

	<u>Page</u>
Table 2.1 : Classification of biomass sources along with their origin	16
Table 2.2 : Economically functional oak forests in the Marmara region including conversion of coppices to high forests	21
Table 2.3 : National targets for installed capacity of renewable-based power generation (MW _e).....	28
Table 2.4 : Renewable-based power generation license situation in Turkey, in 2005 and 2016.....	32
Table 2.5 : Some options of forest biomass supply chains on the basis of the place where the comminution is carried out and the material to be transported	46
Table 2.6 : Combined BioHeat and BioPower (CBHBP) plants currently in operation and based on combustion of solid biofuels with steam turbine technology (Compiled from the sources indicated)	59
Table 2.7 : Global weighted average levelized cost of electricity (LCOE) for renewable power technologies	92
Table 2.8 : Cost figures for biopower and/or bioheat production based on combustion with steam turbine technology (Compiled from the sources indicated).....	94
Table 2.9 : Global warming, acidification and eutrophication ranges of the CBHBP LCAs	107
Table 2.10 : Life cycle emission factors of electricity generation technologies	109
Table 2.11 : Comparison for life cycle emissions of renewable and conventional electricity production systems.....	112
Table 3.1 : Characterization of Turkey oak (<i>Quercus cerris</i> L.) coppice samples	127
Table 3.2 : Case studies for Combined BioHeat and BioPower plants.....	129
Table 3.3 : Aspen Plus V8.4 process simulation and validation data for the steam side of the model	142
Table 3.4 : Case studies for Combined BioHeat and BioPower plants.....	143
Table 3.5 : Aspen Plus V8.4 process simulation and validation data for the fuel side of the model	146
Table 3.6 : CBHBP process parameters, Aspen Plus V8.4 process simulation inputs and outputs, and calculations for Case Study-2	149
Table 3.7 : CBHBP process parameters, Aspen Plus V8.4 process simulation inputs and outputs, and calculations for Case Study-3	151
Table 3.8 : Stack gas (combustion gases) emissions of the CBHBP plants: Aspen Plus V8.4 process simulation, and stoichiometric calculation for comparison	154
Table 3.9 : PM-10 emissions of the CBHBP plants calculated using AP 42 and the Aspen Plus V8.4 process simulation outputs	156
Table 3.10 : Air pollutant concentrations of the CBHBP plants and national limits for Turkey	157

Table 3.11	: Solid waste (TR-Oak ash) amounts of the CBHBP plants.....	157
Table 3.12	: Waste water flow rate of Combined BioHeat and BioPower plants ..	158
Table 4.1	: CML-IA baseline method: An overview of the connections between environmental problems and midpoint impact categories along with characterization factors and units.....	165
Table 4.2	: ReCiPe Endpoint (H) method: An overview of the connections between environmental problems and endpoint impact categories along with units.....	167
Table 4.3	: Turkish electricity mix used in the LCA study	171
Table 4.4	: Moisture content assumptions used in the LCA study	173
Table 4.5	: Dry matter loss assumptions used in the LCA study	173
Table 4.6	: The operational performance factors of TR-Oak chip-fueled CBHBP plants	174
Table 4.7	: Allocation factors calculated and the basic data used in the calculations for each case study	175
Table 4.8	: Basic inventory data and assumptions used in the LCA study for harvesting, forwarding, and chipping operations	179
Table 4.9	: Basic inventory data and assumptions used in the LCA study for the transportation vehicle	180
Table 4.10	: Basic inventory data and assumptions used in the LCA study for feedstock preparation	184
Table 4.11	: Characteristics of the TR-Oak chip feedstock storage silos for daily supply for each case study.....	185
Table 4.12	: Major process parameters, requirements, emissions, and wastes of TR-Oak chip-fueled CBHBP production	187
Table 4.13	: Characteristics of the TR-Oak ash storage silos of 15 days capacity for each case study.....	188
Table 4.14	: TR-Oak ash utilization inventory data	188
Table 4.15	: Eco-design parameters determined for the LCA study	189
Table 5.1	: A summary of technical and cost related data used in the cost estimates of the TR-Oak chip-fueled CBHBP plants.....	193
Table 6.1	: Characterization results of 1 kWh biopower production for CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively)	197
Table 6.2	: Characterization results of 1 kWh bioheat production for CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively)	198
Table 6.3	: Characterization results of 1 kWh energy (biopower and bioheat) production for CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively)	199
Table 6.4	: Normalization factors used in the LCA study (CML-IA baseline V3.3 World 2000)	205
Table 6.5	: Weighting factors used in the LCA study (World ReCiPe H/H)	210
Table 6.6	: Endpoint single scores (World ReCiPe H/H), CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively)	212
Table 6.7	: Top stressors and their contributions for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively), CML-IA baseline V3.03	213
Table 6.8	: Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-1 (2 MW _e), CML-IA baseline V3.03	217
Table 6.9	: Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-2 (5 MW _e), CML-IA baseline V3.03	219

Table 6.10	: Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-3 (10 MW _e), CML-IA baseline V3.03.....	221
Table 6.11	: Contribution analysis for endpoint impacts of 1 kWh biopower and/or bioheat production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively), ReCiPe Endpoint (H) V1.12 World ReCiPe H/H	227
Table 6.12	: Total score distribution of CBHBP plants: CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively), ReCiPe Endpoint (H) V1.12 World ReCiPe H/H.....	229
Table 6.13	: Total score distribution of CBHBP plants: CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively), ReCiPe Endpoint (H) V1.12 World ReCiPe H/A.....	230
Table 6.14	: Effect of transport distance on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03.....	232
Table 6.15	: Productivities of the major pieces of equipment used in the LCA study	233
Table 6.16	: Effect of equipment productivities on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03	233
Table 6.17	: Effect of CBHBP plant lifetime on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03.....	235
Table 6.18	: Effect of TR-Oak chip feedstock moisture content on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03	237
Table 6.19	: Effect of excess air on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03	240
Table 6.20	: Effect of furnace temperature on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03.....	244
Table 6.21	: Air emissions from Turkish lignite power production.....	246
Table 6.22	: Cost estimates of TR-Oak chip-fueled CBHBP plants	249
Table A.1	: Mass and energy balances of Aspen Plus V8.4 process simulation for CS-1	296
Table A.2	: Mass and energy balances of Aspen Plus V8.4 process simulation for CS-2	297
Table A.3	: Mass and energy balances of Aspen Plus V8.4 process simulation for CS-3	298
Table B.1	: PM-10 emission factor information of “AP 42, Compilation of Air Pollutant Emission Factor”	300
Table C.1	: Average temperatures (average values over long years, 1950–2015) for Marmara Region in Turkey.....	303
Table D.1	: Turkish electricity mix inventory.....	304
Table D.2	: LCI for CBHBP production	305
Table D.3	: LCI for TR-Oak chip supply at roadside	306
Table D.4	: LCI for TR-Oak chip feedstock preparation at CBHBP plant	306
Table D.5	: LCI for receiving (front-end loader) operation	307
Table D.6	: LCI for TR-Oak ash spreading in forest	307
Table D.7	: LCI for const & decom of CBHBP plants	308
Table D.8	: LCI for const & decom of TR-Oak chip supply chain.....	309
Table D.9	: LCI information for other processes used in CBHBP production	310
Table D.10	: LCI for CBHBP production, CS-1 (2 MW _e): Eco-design approach for moisture content of (20, 40, 50) %.....	311

Table D.11 : LCI for CBHBP production, CS-1 (2 MW _e): Eco-design approach for excess air ratio of (1.2, 1.8, 2.0).....	312
Table D.12 : LCI for CBHBP production, CS-1 (2 MW _e): Eco-design approach for excess air ratio of (2.2, 2.5).....	313
Table D.13 : LCI for CBHBP production, CS-1 (2 MW _e): Eco-design approach for furnace temperature of (850, 900, 1000) °C.....	314
Table D.14 : LCI for CBHBP production, CS-1 (2 MW _e): Eco-design approach for furnace temperature of (1100, 1200) °C.....	315



LIST OF FIGURES

	<u>Page</u>
Figure 2.1 : Schematic representation of biorefinery technology	10
Figure 2.2 : Schematic representation of a lignocellulosic biorefinery	12
Figure 2.3 : Categories, content, and origins of biomass sources	17
Figure 2.4 : Classification of forest biomass sources used to produce energy	18
Figure 2.5 : Fuel shares of total primary energy supply in Turkey in 2015.....	24
Figure 2.6 : Product shares of total renewable-based energy supply in Turkey in 2015	25
Figure 2.7 : Transport sector energy supply in Turkey in 2015.....	26
Figure 2.8 : Installed capacity by primary energy sources in Turkey as of 31 October 2016	27
Figure 2.9 : Installed capacity development of renewable-based energy sources and their annual share in total installed capacity excluding hydro.....	30
Figure 2.10 : Biopower license situation development in Turkey, 2005-2015.....	33
Figure 2.11 : The major conversion paths for Combined BioHeat and BioPower production	39
Figure 2.12 : A schematic of a Combined BioHeat and BioPower plant power cycle based on combustion with steam turbine technology	55
Figure 2.13 : Electrical and total efficiency (%) of Combined BioHeat and BioPower plants currently in operation and based on combustion of solid biofuels with steam turbine technology (BFB is for bubbling fluidized bed, CFB is for circulating fluidized bed)	62
Figure 2.14 : Aspen Plus version 8.4 user interface	69
Figure 2.15 : The main life cycle stages of a system	73
Figure 2.16 : LCA framework.....	75
Figure 2.17 : Biomass energy life cycles	78
Figure 2.18 : LCIA elements.....	84
Figure 2.19 : A schematic working principle of a Life Cycle Assessment (LCA) software	85
Figure 2.20 : SimaPro 8.1.1 user interface.....	87
Figure 2.21 : An ecoinvent activity dataset with its exchanges	90
Figure 3.1 : Turkey oak (<i>Quercus cerris</i> L.) samples: (a) Stem wood (b) Leaves (c) Stem wood without bark (d) Bark	125
Figure 3.2 : Thesis methodology (Aspen Plus process simulation model development and validation, simulation, and SimaPro LCA for CBHBP case studies).....	130
Figure 3.3 : The Aspen Plus V8.4 process simulation model for TR-Oak chip-fueled CBHBP production.....	133
Figure 3.4 : The components considered in the Aspen Plus V8.4 process simulation model	134

Figure 3.5	: Combustion products of the Aspen Plus V8.4 process simulation model	138
Figure 3.6	: Validation of the Aspen Plus V8.4 process simulation model for TR-Oak chip-fueled CBHBP plant	141
Figure 3.7	: Aspen Plus V8.4 process simulation flowsheet of TR-Oak chip-fueled CBHBP plant for Case Study-1	145
Figure 3.8	: Aspen Plus V8.4 process simulation flowsheet of TR-Oak chip-fueled CBHBP plant for Case Study-2	148
Figure 3.9	: Aspen Plus V8.4 process simulation flowsheet of TR-Oak chip-fueled CBHBP plant for Case Study-3	150
Figure 4.1	: System boundary of the LCA study conducted for TR-Oak chip-fueled CBHBP production	161
Figure 4.2	: Unit processes designed in the SimaPro software for the TR-Oak chip supply chain of the LCA study	177
Figure 4.3	: Unit processes designed in the SimaPro software for the TR-Oak chip-fueled CBHBP plant of the LCA study	183
Figure 4.4	: Schematic of Life Cycle Assessment with an eco-design approach	189
Figure 6.1	: Comparative midpoint characterization results of 1 kWh biopower production for CS-1, -2, -3 (2 MW _e , 5 MW _e , and 10 MW _e , respectively).....	197
Figure 6.2	: Comparative midpoint characterization results of 1 kWh bioheat production for CS-1, -2, -3 (2 MW _e , 5 MW _e , and 10 MW _e , respectively).....	198
Figure 6.3	: Comparative midpoint characterization results of 1 kWh energy (biopower and bioheat) production for CS-1, -2, -3 (2 MW _e , 5 MW _e , and 10 MW _e , respectively)	199
Figure 6.4	: Comparative midpoint characterization results for annual biopower production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively)... ..	202
Figure 6.5	: Comparison of acidification results with the literature, 1 kWh biopower and/or bioheat, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively).....	203
Figure 6.6	: Comparison of eutrophication results with the literature, 1 kWh biopower and/or bioheat, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively).....	203
Figure 6.7	: Comparison of global warming results with the literature, 1 kWh biopower and/or bioheat, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively).....	204
Figure 6.8	: Comparative normalization results (CML-IA baseline World 2000) of 1 kWh biopower production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively).....	206
Figure 6.9	: Comparative normalization results (CML-IA baseline World 2000) of 1 kWh bioheat production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively).....	207
Figure 6.10	: Comparative normalization results (CML-IA baseline World 2000) of 1 kWh energy (biopower and bioheat) production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively)	208
Figure 6.11	: Comparative weighting results of 1 kWh biopower production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively).....	210

Figure 6.12 : Comparative weighting results of 1 kWh bioheat production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively)	211
Figure 6.13 : Comparative weighting results of 1 kWh energy (biopower and bioheat) production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively).....	211
Figure 6.14 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-1 (2 MW _e), CML-IA baseline V3.03	216
Figure 6.15 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-2 (5 MW _e), CML-IA baseline V3.03	218
Figure 6.16 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-3 (10 MW _e), CML-IA baseline V3.03	220
Figure 6.17 : Contribution analysis for endpoint impacts of 1 kWh biopower and/or bioheat production, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively), ReCiPe Endpoint (H) V1.12 World ReCiPe H/H.....	226
Figure 6.18 : Effect of allocation procedure on midpoint impacts to produce 1 kWh biopower, CS-1, -2, -3 (2 MW _e , 5 MW _e , 10 MW _e , respectively), CML-IA baseline V3.03	235
Figure 6.19 : Effect of moisture content on contribution analysis for global warming to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03	239
Figure 6.20 : Effect of excess air ratio on contribution analysis for eutrophication to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03.....	242
Figure 6.21 : Effect of excess air ratio on contribution analysis for acidification to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03.....	242
Figure 6.22 : Effect of furnace temperature on contribution analysis for eutrophication to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03	245
Figure 6.23 : Effect of furnace temperature on contribution analysis for acidification to produce 1 kWh biopower, CS-1 (2 MW _e), CML-IA baseline V3.03	246
Figure 6.24 : Comparison of TR-Oak chip-fueled biopower production and Turkish lignite-fueled power production for midpoint impacts, 1 kWh, CML-IA baseline V3.03	247
Figure 6.25 : Comparison of TR-Oak chip-fueled biopower production and Turkish lignite-fueled power production for endpoint impacts, 1 kWh, ReCiPe Endpoint (H) V1.12 3 World ReCiPe H/H.....	248
Figure 6.26 : Effect of investment cost on biopower unit cost	251
Figure 6.27 : Effect of TR-Oak chip cost on biopower unit cost.....	252



LIFE CYCLE ASSESSMENT OF COMBINED BIOHEAT AND BIOPOWER PRODUCTION AND COST: SIMULATED CASE STUDIES BASED ON COMBUSTION UTILIZING TURKISH OAK (*Quercus cerris* L.) COPPICES

SUMMARY

Combined heat and power (CHP) or cogeneration involves two or more secondary energy carriers such as useful heat and electricity, using a single fuel in one conversion process. Biomass is an alternative fuel for CHP systems. The name Combined BioHeat and BioPower (CBHBP) emphasizes that a biomass source is used as the feedstock for the production of CHP. Turkey is a country with rich biomass potential; however, traditional utilization is predominant. The high technical potential of biomass offers a strategic source for energy supply diversification in Turkey. As an indigenous energy source, biomass could help to minimize fuel import dependency and greenhouse gas (GHG) emissions, and to increase local development. Moreover, biomass is actually an effective means to further develop CHP investments in the country, which would contribute significantly to energy saving measures in Turkey. Although electricity licenses using renewables have been growing based on many investments in Turkey, biopower applications are in the developmental stage and sector growth is slower than anticipated. A challenging further increase in biopower development is needed, not only to reach the national targets, but also to adhere to international commitments. The growth in biopower production has mainly involved biochemical conversion technologies to produce landfill gas and biogas, which are applicable to wet biomass sources. However, biopower production through thermochemical conversion technologies that require solid biomass sources is still at an early stage and therefore limited in the country. In addition, most plants only generate biopower, and CBHBP applications are too few. The majority of the global biopower generated comes from CBHBP plants, and in other countries, CBHBP production through distributed generation (DG) is seen as a viable way of taking advantage of local biomass sources. Moreover, a sustainable supply of feedstock is crucial for biomass energy applications. Modern utilization of solid biomass sources through distributed CBHBP production, including the efficient application of thermochemical conversion technologies, could be put into use for future development of biopower in Turkey.

Oak coppice forests are among the biomass treasures of Turkey and are readily available solid biomass sources for production of biomass energy. Initiating modern energy forestry applications starting with unproductive or poorly productive oak coppice forests in the areas near these biomass treasures that are also near settlements where there is a constant heating/cooling and power demand, distributed CBHBP plants could be implemented rapidly and become widespread in the country. Forest villages, where wood is already often used as a source of energy for heating and cooking, which practice results in a serious threat to forest sustainability, are the best opportunities for distributed CBHBP deployment. This would provide not only environmental, but also technological, social, and economic benefits.

If renewable-based energy technologies are to compete with conventional energy technologies, they must be sustainable. Life Cycle Assessment (LCA) is a preferred key tool to estimate environmental sustainability of biomass energy applications. It is a standardized tool that uses a life cycle approach. An LCA provides a way of looking at any product to determine its resource consumption and the environmental consequences of releases throughout its life cycle, from raw material acquisition to final waste disposal. LCA can also be used as an eco-design (green design) tool. Eco-design aims to minimize environmental life cycle impacts of a product at its design stage. In cases of CBHBP implementation, LCA can be used as the fundamental basis to determine environmental sustainability of the project, including an eco-design approach for CBHBP production.

In this study, the first aim is to conduct an LCA study with an eco-design approach to determine the environmental sustainability of combustion-based in situ CBHBP plants based on simulated case studies. To achieve this aim, the simulated case studies have different scales, all utilize Turkish oak (herein TR-Oak) (*Quercus cerris L.*) coppices, consider CBHBP eco-design parameters, and also take into account current commercial CBHBP plants worldwide. The results of the LCA study include a contribution analysis of midpoint and endpoint impacts for different stages of biomass-to-CBHBP value chain. This helps to figure out the relative importance of the stages in the system boundary. The results also include a sensitivity analysis on LCA results. In order to present an eco-design approach, the LCA study demonstrates the effect of the most fundamental CBHBP design parameters on LCA results. In addition, the LCA study quantifies the most important environmental benefits of CBHBP production compared to Turkish lignite coal-fueled power production. The next aim of the study is to finalize the research with CBHBP production representative cost estimates that could be used to facilitate decision making for investors interested in CBHBP technologies in Turkey. This thesis research is the first attempt, to our knowledge, to conduct an LCA in coordination with process simulation, and to introduce an eco-design approach for sustainable CBHBP production. This study, being the first of its kind in Turkey, should be helpful to all dealing with biomass energy applications in the country.

This thesis starts with a comprehensive review of CBHBP production technology already used. Then, based on the review study, Case Study-1 (CS-1), CS-2, and CS-3 were proposed to characterize distributed CBHBP production. The focus was on a steam turbine system based on direct combustion technology, the conventional Rankine cycle, in line with worldwide biopower developments. CS-1, CS-2, and CS-3 have 2, 5, and 10 megawatt electrical (MW_e) biopower output, respectively. Meanwhile, the biomass feedstock selected for use in CBHBP production was TR-Oak chips from TR-Oak coppice forests in the Marmara region of Turkey. Samples were taken and experiments were carried out to characterize TR-Oak chips. Later, process simulations of CS-1, -2, and -3 utilizing the characterized TR-Oak chips were carried out using Aspen Plus V8.4 process simulation software. The relevant process parameters, requirements, and environmental impacts of the CBHBP plants were quantified based on the simulated case studies considering eco-design parameters. Next, based on CBHBP process simulation outputs and eco-design parameters, the LCA study was conducted using SimaPro V8.1.1.16 LCA software. After defining the goal and scope, and completing the inventory analysis phase of the LCA study, a Life Cycle Inventory (LCI) was prepared using SimaPro software. In the LCA study, the system boundary starts with harvesting of TR-Oak coppices, and ends with biopower

to an electrical grid and bioheat to a district heating network. Three energy output-related functional units were chosen: 1 kilowatt-hour (kWh) biopower, 1 kWh bioheat, and 1 kWh (combined) energy production. The modeling approach used was a unit process-based attributional LCA. Exergy-based allocation was used between biopower and bioheat. While CML-IA baseline V3.03 (with the World 2000 normalization set) was the midpoint impact assessment method chosen, it was ReCiPe Endpoint (H) V1.12, (with World ReCiPe H/A and H/H weighting sets) that was chosen as the endpoint impact assessment method. Then, the LCA results were obtained by following the impact assessment methods provided in the SimaPro software. The LCA results of the study include comparative characterization, normalization, and weighting results. In addition, there is a detailed contribution analysis for midpoint and endpoint impacts. For this, the system boundary (and hence the LCA results) was arranged in the stages of TR-Oak chip supply chain, CBHBP plant operation, TR-Oak ash transport and spreading, and construction and decommissioning. The results also include the effect of feedstock properties and process conditions on LCA results to implement the eco-design approach, a sensitivity analysis of the most uncertain assumptions and choices, and finally, a comparison of TR-Oak chip-fueled biopower production with Turkish lignite-based power production in terms air emissions from combustion. The study ends with CBHBP production cost estimates.

The LCA results showed that when deciding on a scale of CBHBP production, there should always be a trade-off between scale and annual environmental impacts. Moreover, reducing feedstock demand and strain on the biomass supply chain of CBHBP plants is another issue to consider. The chosen characterization results are within the ranges reported in literature. Normalization results revealed the importance of background waste treatment processes on the TR-Oak chip supply chain as well as the construction and decommissioning operations. Weighting results showed that human health has the highest importance followed by resources. The importance of impacts on ecosystems is insignificant relative to those on human health and resources. Contribution analysis showed the relative importance of different stages in the system boundary. Both CBHBP plant operation and TR-Oak chip supply chain are stages that need to be designed with the highest care to minimize environmental loading and to achieve sustainable CBHBP production. To achieve a sense of overall perspective, the TR-Oak chip supply chain contributes ~ 43–52% to the single score, and operation of the CBHBP plant contributes ~ 42–52%. Thus, one is not more or less important than the other is. The TR-Oak chip supply chain is the stage most affected by increases in moisture content due to the consequent higher transportation requirements. Excess air ratio and furnace temperature affected the importance of CBHBP plant operation mostly due to nitrogen oxides (NO_x) emission increases. Sensitivity analysis enabled estimation of the effects of variation in transport distance between roadside and CBHBP plant, equipment productivity, CBHBP plant lifetime, and allocation procedure. In addition, the significance of explaining all the methodological choices and inventory data prepared for an LCA study in as much detail and as transparently as possible, was revealed. Under the current framework conditions in Turkey, the CBHBP cost estimates provided in the thesis are economically feasible. Biopower unit costs were found to be 8.7–9.5 US Dollar cent (cent) per kWh. Comparison of TR-Oak chip-fueled biopower production with Turkish lignite-based power production, when considered in terms of the effects of air emissions from combustion on human health, the single score for 1 kWh of Turkish lignite-fueled power production is 15 times higher than that for 1 kWh of TR-Oak chip-fueled biopower production.



**BİRLİKTE BİYOISI VE BİYOGÜÇ ÜRETİMİ YAŞAM DÖNGÜSÜ
DEĞERLENDİRMESİ VE MALİYETİ: TÜRKİYE MEŞE (*Quercus cerris* L.)
BALTALIKLARINI KULLANAN YANMA TEMELLİ BENZETİLMİŞ
DURUM ÇALIŞMALARI**

ÖZET

Birlikte Isı ve Güç veya kojenerasyon, bir dönüşüm sürecinde tek bir yakıt kullanarak, faydalı ısı ve elektrik gibi iki veya daha fazla ikincil enerji taşıyıcısı üretir. Biyokütle kojenerasyon sistemleri için alternatif bir yakıttır. Birlikte BiyoIsı ve BiyoGüç, Birlikte Isı ve Güç üretiminde hammadde olarak bir biyokütle kaynağının kullanıldığını vurgulamak için isimlendirilmiştir. Türkiye, zengin biyokütle potansiyeline sahip bir ülkedir; bununla birlikte, geleneksel kullanım hakimdir. Yüksek teknik potansiyele sahip biyokütle, Türkiye'de enerji arzının çeşitlendirilmesi için stratejik bir kaynaktır. Yerli bir enerji kaynağı olan biyokütle, yakıt ithalatına bağımlılığı azaltmaya, sera gazı emisyonlarını en aza indirmeye ve yerel kalkınmayı artırmaya yardımcı olur. Üstelik biyokütle, enerji tasarrufu önlemlerine önemli katkı sağlayacak Birlikte Isı ve Güç yatırımlarını ülkemizde daha da geliştirmek için etkili bir araçtır. Türkiye'de yenilenebilir kaynakları kullanan elektrik lisansları birçok yatırımla artmakla birlikte, biyogüç uygulamaları halen gelişim aşamasındadır. Sektörün büyümesi beklenenden yavaştır. Sadece ulusal hedeflere ulaşmak için değil, uluslararası taahhütlere uymak için de biyogüç gelişiminde önemli bir artışın olması gerekmektedir. Türkiye'de biyogüç üretimindeki artış, esas olarak yaş biyokütle kaynaklarına uygulanabilir olan biyokimyasal dönüşüm teknolojileri yoluyla çöp gazı ve biyogaz üretmek şeklinde olmuştur. Bununla birlikte, katı biyokütle kaynakları gerektiren termokimyasal dönüşüm teknolojileri yoluyla biyogüç üretimi ülkemizde halen başlangıç aşamasındadır, ve bu nedenle de sınırlıdır. Buna ek olarak, çoğu santral sadece biyogüç üretmektedir, ve Birlikte BiyoIsı ve BiyoGüç uygulamaları çok azdır. Öte yandan, küresel biyogüç üretiminin çoğunluğunu Birlikte BiyoIsı ve BiyoGüç tesisleri oluşturmakta, ve sürdürülebilir hammadde tedariği biyokütle enerji uygulamaları için çok önemli olduğundan farklı ülkelerde, dağıtık ve diğer adı ile yerinde üretim yoluyla Birlikte BiyoIsı ve BiyoGüç üretimi yerel biyokütle kaynaklarının avantajlı bir şekilde kullanılması için uygulanabilir bir yol olarak görülmektedir. Türkiye'de de termokimyasal dönüşüm teknolojilerinin etkili bir şekilde uygulanması da dahil olmak üzere yerinde Birlikte BiyoIsı ve BiyoGüç üretimi yoluyla katı biyokütle kaynaklarının modern kullanımı gelecekteki biyogüç yatırımları için uygulamaya konulabilir.

Meşe baltalık ormanları, biyokütle enerjisi üretmek için halihazırda mevcut katı biyokütle kaynakları olarak Türkiye'deki biyokütle hazinesidir. Verimsiz veya bozuk meşe baltalık ormanlarından yola çıkarak modern enerji ormancılık uygulamalarını başlatmak suretiyle, hem bu biyokütle hazinesinin hem de sabit ısı/soğuk ve güç talebinin olduğu yerleşimlerin yakınında, yerinde Birlikte BiyoIsı ve BiyoGüç üretim santrallerinin mümkün olan en kısa sürede kurulumu yapılabilir ve böylece ülkemizde

Birlikte Biyolsı ve BiyoGüç üretimi yaygınlaşabilir. Odunun, genellikle ormanların sürdürülebilirliği için ciddi bir tehdit oluşturan ısıtma ve pişirme ihtiyaçları için bir enerji kaynağı olarak kullanıldığı orman köyleri, yalnızca çevresel değil aynı zamanda teknolojik, sosyal ve ekonomik yararlar sağlayan yerinde Birlikte Biyolsı ve BiyoGüç üretiminin yaygınlaşması için en iyi fırsattır.

Yenilenebilir kaynaklı enerji teknolojilerinin geleneksel enerji teknolojileri ile rekabet edebilmeleri için sürdürülebilir olmaları gerekmektedir. Yaşam Döngüsü Değerlendirmesi, biyokütle enerji uygulamalarının çevresel sürdürülebilirliğini tahmin etmek için tercih edilen anahtar bir araçtır. Yaşam Döngüsü Değerlendirmesi, herhangi bir ürüne, ham madde toplama sürecinden son atık bertarafına kadar olan yaşam döngüsü süresince kaynakların kullanımını ve çevresel sonuçlarını belirlemek için bir yaşam döngüsü yaklaşımı ile bakabilme yöntemini kullanan standartlaştırılmış bir araçtır. Yaşam Döngüsü Değerlendirmesi ayrıca eko-tasarım (yeşil tasarım) aracı olarak da kullanılabilir. Eko-tasarım, bir ürünün çevresel yaşam döngüsü etkilerini o ürünün tasarım aşamasından başlayarak en aza indirmeyi hedeflemektedir. Bir Birlikte Biyolsı ve BiyoGüç uygulaması durumunda, Yaşam Döngüsü Değerlendirmesi, Birlikte Biyolsı ve BiyoGüç üretiminin bir eko-tasarım yaklaşımı da dahil olmak üzere çevresel sürdürülebilirliğini belirlemek için temel bir araç olarak kullanılabilir.

Bu çalışmada ilk amaç, benzetilmiş durum çalışmalarına dayanan yanma temelli yerinde Birlikte Biyolsı ve BiyoGüç santrallerinin çevresel sürdürülebilirliğini ortaya koymak için eko-tasarım yaklaşımı ile bir Yaşam Döngüsü Değerlendirmesi çalışması yapmaktır. Bu amaç için, benzetilmiş durum çalışmalarına dayanan santraller farklı kurulu güçlere sahip olup, Türk meşesi (*Quercus cerris* L.) baltalık ormanlarından sağlanan meşe yongalarını (odunsu biyokütle) kullanmakta ve ayrıca dünya genelinde mevcut ticari Birlikte Biyolsı ve BiyoGüç santrallerini dikkate almaktadır. Yaşam Döngüsü Değerlendirmesi çalışması sonuçları, öncelikle, biyokütle-Birlikte Biyolsı ve BiyoGüç değer zincirinin farklı aşamalarının sistem sınırındaki göreceli önemini anlamaya yönelik olarak orta ve son nokta etkilerinin bir katkı analizini, ve bir hassasiyet analizini içermektedir. Eko-tasarım yaklaşımı sunabilmek için ise Yaşam Döngüsü Değerlendirmesi çalışmasında, en temel Birlikte Biyolsı ve BiyoGüç tasarım parametrelerinin Yaşam Döngüsü Değerlendirmesi sonuçları üzerindeki etkisi ortaya konulmaktadır. Ayrıca, Birlikte Biyolsı ve BiyoGüç üretiminin Türkiye'nin linyit yakıtlı güç üretimine kıyasla en önemli çevresel faydaları nicelendirilmektedir. Bu çalışmadaki bir diğer amaç, Türkiye'de Birlikte Biyolsı ve BiyoGüç teknolojileri ile ilgilenen yatırımcılar için karar vermeyi kolaylaştıracak temsili maliyet tahminleri ile araştırmayı sonuçlandırmaktır. Bu tez araştırması, bilgimiz dahilinde kendi spesifik araştırma konusunda, bir süreç benzetimi ile koordineli bir Yaşam Döngüsü Değerlendirmesi yürüten ve sürdürülebilir Birlikte Biyolsı ve BiyoGüç üretimi için bir eko-tasarım yaklaşımı getiren ilk denemedir. Türkiye'de ilk olan bu çalışmanın, ülkemizdeki biyokütle enerji uygulamaları ile ilgilenen herkes için yararlı olacağı düşünülmektedir.

Bu çalışma, Birlikte Biyolsı ve BiyoGüç üretimi için gerçekleştirilen kapsamlı bir teknoloji incelemesi ile başlamaktadır. Daha sonra, bu inceleme çalışmasını temel alarak, dağıtık Birlikte Biyolsı ve BiyoGüç üretiminin karakterize edilebilmesi için Durum Çalışması-1 (CS-1), CS-2 ve CS-3 önerilmiştir. Durum çalışmalarında odak, dünya çapındaki biyogüç gelişmelerine paralel olarak direkt yakma teknolojisine dayanan buhar türbin sistemi, klasik Rankine çevrimi, olmuştur. CS-1, CS-2 ve CS-3 sırasıyla 2, 5 ve 10 megawatt elektrik (MW_e) kurulu gücüne sahiptir. Bu arada, Birlikte Biyolsı ve BiyoGüç üretimi için kullanılan biyokütle hammaddesi, Marmara

Bölgesi'ndeki Türk meşesi baltalık ormanlarından sağlanan meşe yongaları olarak seçilmiştir. Örnekler alınıp, Türk meşe yongalarını karakterize etmek için deneyler gerçekleştirilmiştir. Daha sonra, karakterizasyonu yapılmış Türk meşesi yongalarını kullanan CS-1, -2 ve -3' ün süreç benzetimleri, Aspen Plus V8.4 süreç benzetim yazılımı kullanılarak gerçekleştirilmiştir. Birlikte BiyoIsı ve BiyoGüç santrallerinin ilgili süreç parametreleri, gereklilikleri ve çevresel etkileri, eko-tasarım parametrelerini göz önünde bulunduran benzetilmiş durum çalışmalarına dayanılarak belirlenmiştir. Daha sonra, Birlikte BiyoIsı ve BiyoGüç süreç benzetimi çıktılarına ve eko-tasarım parametrelerine dayanarak, Yaşam Döngüsü Değerlendirmesi çalışması SimaPro V8.1.1.16 Yaşam Döngüsü Değerlendirmesi yazılımı kullanılarak gerçekleştirilmiştir. Yaşam Döngüsü Değerlendirmesi çalışmasının amaç ve kapsamını belirledikten ve envanter analiz aşamasını tamamladıktan sonra, Yaşam Döngüsü Envanteri, SimaPro yazılımı kullanılarak hazırlanmıştır. Yaşam Döngüsü Değerlendirmesi çalışmasında, sistem sınırı Türk meşe baltalıklarının hasatıyla başlamakta ve elektrik şebekesine biyogüç ve bölgesel ısıtma şebekesine biyoısı tedarikiyle sonlanmaktadır. Fonksiyonel birim, enerji çıktısı ile ilgili olarak üç adet seçilmiştir: 1 kilowatt-saat (kWh) biyogüç, 1 kWh biyoısı ve 1 kWh (birlikte) enerji üretimi. Kullanılan modelleme yaklaşımı birim süreç tanımlamasına dayanmaktadır. Biyogüç ve biyoısı arasında ekserji tabanlı tahsisat yapılmıştır. World 2000 normalizasyon seti olan CML-IA baseline V3.03, seçilen orta nokta etki değerlendirme yöntemi, World ReCiPe H/A ve H/H ağırlıklandırma setleri ile ReCiPe Endpoint (H) V1.12 son nokta etki değerlendirme yöntemi olarak seçilmiştir. Ardından, SimaPro yazılımında sağlanan bu etki değerlendirme yöntemlerini kullanarak Yaşam Döngüsü Değerlendirmesi sonuçları elde edilmiştir. Çalışmanın Yaşam Döngüsü Değerlendirmesi sonuçları, karşılaştırmalı karakterizasyon, normalizasyon ve ağırlıklandırma sonuçları ile orta nokta ve son nokta etkileri için ayrıntılı bir katkı analizini içermektedir. Katkı analizi için, sistem sınırı ve dolayısıyla Yaşam Döngüsü Değerlendirmesi sonuçları, Türk meşesi yonga tedarik zinciri, Birlikte BiyoIsı ve BiyoGüç santrali işletmesi, Türk meşe külünün taşınması ve yayılması ile tesisi işletmeye alma ve işletmeden çıkarma aşamalarına ayrılmıştır. Çalışmanın sonuçları ayrıca, eko-tasarım yaklaşımını uygulamak için hammadde özelliklerinin ve süreç şartlarının Yaşam Döngüsü Değerlendirmesi sonuçları üzerinde etkilerini, en belirsiz varsayım ve tercihler için hassasiyet analizini, ve nihayet Türk meşe yongalarını yakıt olarak kullanan biyogüç üretimi ile Türk linyitlerini yakıt olarak kullanan güç üretiminde yanmadan kaynaklanan hava emisyonları için Yaşam Döngüsü Değerlendirmesi sonuçları karşılaştırmasını içermektedir. Çalışma, Birlikte BiyoIsı ve BiyoGüç üretim maliyeti ile sona ermektedir.

Yaşam Döngüsü Değerlendirmesi sonuçları, bir Birlikte BiyoIsı ve BiyoGüç üretimi için bir kurulu güç belirlemek gerektiğinde, her zaman kurulu güç ile yıllık çevresel etkiler arasında bir dengelenme olması gerektiğini göstermiştir. Dahası, Birlikte BiyoIsı ve BiyoGüç santrallerinin biyokütle tedarik zincirindeki hammadde talebini ve yükünü azaltmak da dikkate alınacak bir diğer konudur. Seçilen karakterizasyon sonuçları, literatürde belirtilen aralıklar içinde bulunmuştur. Normalizasyon sonuçları, Türk meşesi yonga tedarik zincirinin arka plan atık işlem süreçlerinin, ve işletmeye alma ve işletmeden çıkarma operasyonlarının önemini ortaya koymuştur. Ağırlıklandırma sonuçları, kaynak kullanımından önce gelen insan sağlığının en yüksek önem derecesinde etkilendiğini göstermiştir. Eko-sistem üzerindeki etkilerin önem derecesi, kaynak kullanımı ve insan sağlığı üzerindeki etkilerin önem derecelerine kıyasla en düşüktür. Katkı analizi, sistem sınırındaki farklı aşamaların göreceli önemini ortaya koymuştur. Bu sonuçlara göre, hem Birlikte BiyoIsı ve

BiyoGüç santral işletimi hem de Türk meşesi yonga tedarik zinciri, çevresel yükü en aza indirmek ve sürdürülebilir bir Birlikte BiyoIsı ve BiyoGüç üretimi sağlamak için en yüksek özenle tasarlanması gereken aşamalardır. Genel olarak farklı ağırlıklandırma perspektifleri için, Türk meşesi yonga tedarik zinciri çevresel etkinin % 43-52'sine katkıda bulunurken, Birlikte BiyoIsı ve BiyoGüç santral operasyonu % 42-52 civarında katkıda bulunmaktadır. Sonuç olarak, biri diğerine göre az ya da çok önemli yada önemsiz değildir. Türk meşesi yonga tedarik zinciri, daha fazla nakliye gereksinimi nedeniyle çoğunlukla nem içeriğindeki artışlardan etkilenen aşamadır. Aşırı hava oranı ve fırın sıcaklığı, çoğunlukla azot oksitlerin emisyon artışlarına bağlı olarak Birlikte BiyoIsı ve BiyoGüç santral işletmesinin önemini göstermektedir. Hassasiyet analizi, orman yol kenarı ve Birlikte BiyoIsı ve BiyoGüç santrali arasındaki nakliye mesafesi, ekipman verimlilikleri, Birlikte BiyoIsı ve BiyoGüç santral ömrü ve tahsisat prosedüründeki değişimlerin Yaşam Döngüsü Değerlendirmesi sonuçları üzerindeki etkilerini analiz etmeyi sağlamıştır. Ayrıca, bir Yaşam Döngüsü Değerlendirmesi çalışmasında hazırlanan tüm metodolojik seçimlerin ve envanter verilerinin mümkün olduğunca açık ve şeffaf olarak açıklanmasının önemi ortaya konmuştur. Türkiye'deki mevcut koşullar altında, çalışmadaki Birlikte BiyoIsı ve BiyoGüç maliyet tahminleri ekonomik açıdan mümkündür. Biyogüç birim maliyetleri 8.7 ila 9.5 ABD Doları cent/kWh arasında bulunmuştur. Türk meşe yongalarını yakıt olarak kullanan biyogüç üretimi ile Türk linyitlerini yakıt olarak kullanan güç üretiminin, yanmadan kaynaklı hava emisyonlarının Yaşam Döngüsü Değerlendirmesi sonuçları karşılaştırılması, insan sağlığı için 1 kWh linyit yakıtlı güç üretimi çevresel etkisinin, 1 kWh Türk meşe yongası yakıtlı biyogüç üretimi çevresel etkisinden 15 kat daha yüksek olduğunu ortaya koymuştur.

1. INTRODUCTION

Energy is essential for all living beings on Earth. Moreover, energy demand continues to grow in parallel with human development in the world: industrialization, urbanization, population growth, increased transportation, quality of life enhancements, etc. Energy statistics show that the global total primary energy supply (TPES) increased by almost 56% between 1990 and 2014 [1,2]. According to projections, global energy demand is expected to rise by 31% from 2015 to 2035, with growth averaging 1.3% per year [3]. On the other hand, to address development and environmental issues in the world, the “United Nations” (UN) report of the “World Commission on Environment and Development” (WCED) defined the concept of sustainable development in 1987 [4]. According to this definition, sustainable development has three essential aspects: economic, environmental, and social. Therefore, production technologies should encompass and accommodate all three of these essential aspects for power generation to become sustainable.

Energy production has many challenges associated with sustainability. Above all, the energy sector is responsible for roughly two-thirds of all anthropogenic GHG emissions globally. The scientific community accepts that GHG emissions, primarily from fossil fuels, are perturbing the Earth’s climate, causing climate change [5,6]. According to current statistics, around 86% of the world TPES in 2014 originated from fossil fuels (including nuclear power) [1,2]. The high usage share and limited reserves of fossil fuels, as well as their GHG emissions and other environmental impacts, forced the energy sector to develop and deploy alternative (renewable-based, hereafter renewable) energy production technologies. If they can be sustained, renewable energy sources offer numerous advantages over conventional energy sources that are nonrenewable (fossil and nuclear energy sources). To maintain a clean environment, renewable energy sources are considered promising alternatives.

Renewable energy can substitute for fossil and nuclear energy mostly in three markets: electricity generation, heating and cooling, and transportation. Global demand for renewable energy has been steadily increasing [7]. Current statistics show that 14% of

the world TPES was produced from renewable energy sources (hydro, biofuels, waste, geothermal, solar, wind, etc.) [2]. Also, the installed capacity of many renewable energy technologies has been growing very rapidly, with the electricity sector having the fastest growth. In 2015, renewable sources represented more than 60% of net additions to global power capacity. By the end of 2015, renewables supplied an estimated 23.7% of global electricity [7]. Today, renewable energy sources are playing a major role in the fuel mix in many countries around the world.

Among renewable energy sources, biomass is a strategic energy source because it is renewable, environmentally friendly, favorable to socio-economic development, and suitable for producing solid, liquid, and gaseous fuels, in addition to power, heat and cold [8]. Biomass, which is a readily available, local energy source, is a general term used to describe all biologically produced carbonaceous materials on Earth [8-11]. Biomass sources either are available from natural processes or can be made available through human activity [11]. Briefly, they are directly or indirectly a result of plant growth [12,13]. Plant biomass (phytomass) [14] is formed through photosynthesis. Animal biomass (zoomass) [14] is formed when plant biomass is used as food by animals and converted into manure. The major anthropogenically modified [10] biomass sources used for energy production include organic residues and wastes from forests, agriculture, industry, and municipalities. Although there are a large number of different biomass sources that could be used to produce energy, the majority come from three areas: forests, agriculture, and wastes/residues.

For energy purposes, biomass has been used since man discovered fire. Today, use of biomass for energy is multi-faceted so that many different biomass sources can be transformed via various conversion technologies for use in the energy sector [7]. Climate change mitigation, energy independence, and local development are major drivers for expanded use of biomass energy sources around the world. Energy from biomass plays a dominant role among renewable energy options. Biomass is the largest renewable energy source and supplies 10.3% of the global energy supply [2]. The third largest source for renewable electricity generation is biomass, and biomass constitutes the largest source for renewable heat generation and largest renewable option for contributing to the transportation sector [2,7,15,16].

A key advantage of biomass energy is its capability to provide base load electricity generation without supplementary energy storage facilities. Moreover, among all the renewable energy sources, biomass is unique since it is the only naturally carbon-rich material source available on Earth besides fossil fuels. Consequently, while electricity and heat can be produced by a variety of renewable sources other than biomass such as wind, solar, and hydro energy; the only alternative to fossil sources for producing fuels, chemicals, and materials is biomass. In this context, the biorefinery concept has arisen for conversion of biomass into energy carriers (biofuels, biopower, bioheat, and biocold) and a range of useful products (biochemicals and biomaterials) including food and feed [17,18]. Many believe that building a bio-based (low carbon) economy using the biorefinery concept will result in environmentally benign global industry [17]. Today, biomass utilization for energy purposes is classified into two broad categories, namely traditional (classic) and modern. While modern biomass utilization includes biomass energy technologies to convert biomass into useful forms of energy, traditional biomass utilization includes direct combustion for heating and cooking purposes, a practice still widely used in many parts of the world, especially in rural areas. To apply the biorefinery concept, considerable research effort has been devoted worldwide to devise biomass conversion technologies, hence enabling modern biomass utilization.

Turkey is an energy importer country. In 2015, the country depended on imports for 76% of its TPES [19]. Therefore, biomass is an indigenous energy source that has strategic importance for Turkey [20]. Moreover, Turkey is a country with rich biomass potential [12,20,21]. Biomass energy accounted for about 20% of the renewable-based energy supply in 2015 [19]; however, traditional utilization predominates. In rural areas like forest villages and agricultural zones, biomass is often the only readily available and affordable energy source [22], and has great potential to provide improved rural energy services in Turkey [23,24]. On the other hand, Turkey is placing great importance on the maximum use of all renewables and to increasing diversification of energy supplies. This includes utilization of all domestic sources, and the use of renewables for power generation has been promoted since 2005 when the first legislation on renewable-based power generation was enacted [25]. Since then, the number of electricity licenses involving renewables has been growing based on

many investments. Even so, biopower applications in Turkey are still in the developmental stage.

There is a large number of different biomass sources that could be used to produce biopower and bioheat/biocold. Solid biomass sources account for the largest share in global biopower production, with 75% by the end of 2014. Biogas, municipal solid waste (MSW), and liquid biofuels have shares of 17%, 7%, and 1%, respectively [26]. Although solid biomass sources are among Turkey's major biomass energy resources, they are not used efficiently enough to meet the national energy demand. Modern utilization of solid biomass sources to produce biopower and bioheat/biocold efficiently is still at an early stage in Turkey.

Of the solid biomass sources, forest (woody) biomass is an important alternative with great potential for biopower and bioheat/biocold production due to its being an indigenous energy resource. Other than wastes/residues, the oak coppice forests readily available in Turkey are a national treasure and the best option for the production of biomass energy. Moreover, unproductive or poorly productive oak coppice forests are reported to be the most interesting areas for introduction of modern energy forestry in Turkey [13,20].

Biomass sources are used most efficiently when generating both bioheat and biopower through cogeneration. CBHBP is defined in this thesis, as the use of a biomass resource as the feedstock for the production of CHP. In the meantime, this definition and abbreviation were added to the scientific literature in March 2017 (in Renewable & Sustainable Energy Reviews) [27,28]. A sustainable supply of the primary feedstock is crucial for biomass energy applications. Therefore, CBHBP production is best suited for DG schemes. In these, energy production occurs close to both energy resources and sites of consumption, as opposed to centralized generation. Thus, DG takes advantage of local biomass sources by reducing transportation requirements and thereby increasing the competitiveness of CBHBP plants with in situ and integrated production models. Other terms used for DG are decentralized, dispersed, embedded, on-site, and in situ generation. In the world, mostly it is distributed CBHBP plants up to medium-scale (20 MW_e) that are applied to take advantage of local biomass sources [29-36]. In Turkey, the government encourages the production and use of the energy derived from biomass sources by establishing biopower generation plants in rural areas. Therefore, in areas like forest villages in the country where solid biomass

sources are locally available, and where there is a constant demand for heat/cold and power, up to medium-scale distributed CBHBP deployment is a way to utilize the existing biomass energy potential efficiently.

Despite the laws, policies, and regulations promoting biomass energy, questions about the sustainability of biomass energy pathways have also been raised. This is because, even using a renewable energy source, sustainability principles can be ignored (and have been in many cases); hence, the presence of a renewable resource does not mean its products are sustainable. In case of a CBHBP implementation, it is very important to design the system so as to minimize its total environmental load.

LCA is a key tool for estimating the environmental impacts of a product. “LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)” [37,38]. LCA is often implemented as a decision support tool for choosing between different systems providing the same product. LCA principles are well known and have been standardized by the “International Organization for Standardization” (ISO) [37-40].

Although LCA principles are well known, in practice, several methodological choices exist. Standards provide guidelines but allow freedom to LCA practitioners for some methodological issues. This enables LCA applications to be open to interpretation and hence to address different specific questions. On the other hand, subjective choices and assumptions lead to a wider range of results, which complicates comparison of LCA of biomass energy studies. Furthermore, biomass energy, either as biofuels or biopower, cannot be sustainable in all geographic locations due to the many variations influencing biomass energy production systems such as biomass availability; climate; environmental, economic and social conditions; policies; etc. To overcome these problems, LCA studies of biomass energy production systems should be conducted based on local conditions. For Turkey, which is on the way to sustainable development, reliable results obtained from reliable methods and interpreted in a specifically Turkish context are needed if they are to be used as a decision support tool to assess biomass energy technologies.

There are numerous LCA studies in the scientific literature about biomass energy LCAs. However, most of these LCAs were focused on biofuels for transportation. Those LCAs focused on biopower production, were mostly interested in either electricity or heat production alone. During a literature search, only a few LCAs concerning both electricity and heat production were encountered. To the best of our knowledge, none of these LCA studies included an eco-design (green design) approach for CBHBP production. Eco-design approach aims to minimize environmental life cycle impacts of CBHBP production at its design stage, and thereby ensures sustainable CBHBP production.

In this thesis research, the first aim is to conduct an LCA study with an eco-design approach to determine the environmental sustainability of combustion-based in situ CBHBP plants based on simulated case studies. To achieve this aim, the simulated case studies have different scales, all use woody biomass (TR-Oak chips) feedstock extracted from TR-Oak coppice forests, consider CBHBP eco-design parameters, and also take into account the results from current commercial CBHBP plants worldwide. To figure out the relative importance of the different stages in the system boundary (mainly the feedstock supply chain and CBHBP operations), the LCA results include a contribution analysis of midpoint and endpoint impacts for the different stages of the biomass-to-CBHBP value chain. The research also includes a sensitivity analysis to analyze the effects of variations in key assumptions and choices on the LCA results. In order to present an eco-design approach, the LCA study is conducted in coordination with a process simulation study, and demonstrates the effect of the most fundamental CBHBP design parameters on the LCA results. In addition, the results of the LCA study are used to quantify the most important environmental benefits of CBHBP production compared to Turkish lignite-fueled power production, in terms of air emissions from combustion. The final aim of the thesis is to provide representative cost estimates of CBHBP production based upon current commercial CBHBP applications worldwide. It is thought that the latter will facilitate decision making for investors interested in CBHBP technologies in Turkey. The aims of the LCA study in this thesis research make it unique from other LCA studies in the scientific literature in that process simulation software and LCA software are used in coordination to develop an eco-design approach for sustainable CBHBP production.

It is thought that this study, being the first in Turkey, should be particularly helpful to investors, policymakers, and academicians dealing with biomass energy applications by presenting major alternatives for implementing CBHBP technologies in Turkey. In addition, this thesis study should present a direction for utilization of forest biomass for biopower production in Turkey, which corresponds to sustainable forest management and hence ensures forest maintenance by reducing wildfire behavior and enhancing forest health in the country.





2. THEORETICAL STUDY

This chapter presents the theoretical study reviews under the headings listed below. Some contents of this chapter are based on the scientific journal paper published in Renewable & Sustainable Energy Reviews [27], and the conference paper published in the 10th International Clean Energy Symposium Proceedings [28] during the course of this thesis study.

- Biorefineries [27]
- Biomass sources [28]
- Turkey's energy outlook and biomass energy [27]
- CHP overview [27]
- CBHBP production [27,28]
- Process simulation and Aspen Plus software
- LCA and SimaPro software
- Cost of CBHBP production
- Literature review

2.1 Biorefineries

The environmental damage the Earth is facing today leads all sectors to the inevitable conclusion that sustainable systems for producing safe and environmentally benign products have to be developed. To achieve this aim, a constant and renewable energy supply with low carbon cost is essential. At present, biomass offers the only globally viable source for such a renewable product. While electricity and heat can be produced by a variety of renewable energy sources other than biomass (e.g., wind, solar, hydro), the only alternative to fossil sources for production of fuels, chemicals, and other carbon-based materials is biomass. On the other hand, while utilizing biomass sources it is essential to maximize their value and minimize waste to meet future sustainability

goals. In this context, the biorefinery concept, “the sustainable processing of biomass into a spectrum of marketable products and energy” [17], has arisen. Sustainability is the main driver of the biorefinery concept; therefore, biorefineries, in a sustainable and synergetic manner, provide ways to convert biomass into energy carriers (biofuels, biopower, bioheat, biocold) and a range of useful bio-based products (biochemicals, biomaterials) including food and feed [18]. In this regard, biorefineries present opportunities not only to the energy sector, but to all sectors.

Figure 2.1 shows a schematic representation of biorefinery technology with biomass as raw material supply, conversion technologies, and products. The products shown in the figure can be either intermediate or final products. As seen in the figure, within the scope of biorefinery technology, a flexible product mixture and energy carriers can be produced via a variety of biomass conversion technologies (biochemical, thermochemical, physico-chemical, or mechanical/physical), which vary depending on biomass source characteristics and desired intermediate and final products [17,41].

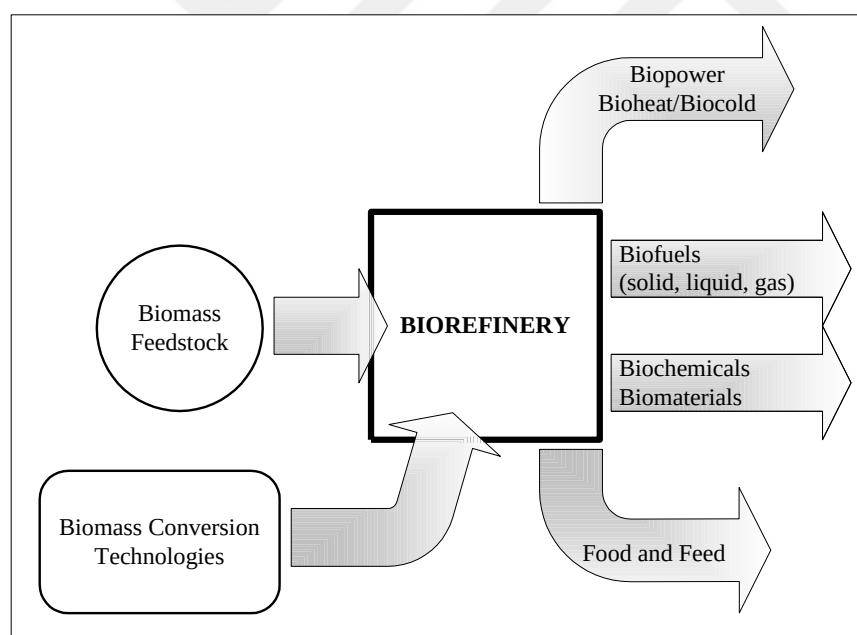


Figure 2.1 : Schematic representation of biorefinery technology.

In terms of functionality, biorefineries are similar to today’s conventional, fossil-based refineries (such as petrochemical (oil) refineries). However, unlike fossil-based refineries, where many energy carriers and products are produced from fossil sources like crude oil, biorefineries utilize biomass as feedstock and produce safe and environmentally benign products including food and feed that cannot be produced by

fossil-based refineries. In addition, a biorefinery designed for energy production must not create competition between energy and food production; hence, food and feed sources cannot ethically be used as raw material for a biorefinery. Biorefineries provide major economic and environmental benefits compared with both fossil-based refineries and other concepts of biomass utilization. Within this context, considerable research effort has been devoted to the concept of biorefinery application for effective biomass utilization around the world.

Indeed, biorefining is not a totally new industrial operation. Many known industries such as those involving sugar, starch, pulp and paper have involved perspectives in line with a biorefinery approach, and now serve as examples of the evolution of biorefining. Also, various economic and environmental drivers (global warming (GW), energy efficiency, energy supply security, national and international policies, etc.) have directed these industries to further improve biorefinery processes [42,43]. Today, energy, most precisely biofuels, is the driver for the development of biorefineries. However, biorefinery technology is developing rapidly and as biorefineries become more advanced with time, more products will be developed [44]. Currently, the major bottleneck for biorefinery operations is the dependence on a single source of biomass feedstock as a result of the composition and complexity of the sources. The challenge is to develop flexible biorefining processes capable of handling different biomass feedstocks and thus to have a higher degree of flexibility in coping with variations in the availability and prices of feedstocks. In the 21st century, the bio-based economy is widening and it is believed that biorefineries, leading to a bio-based economy, will result in environmentally benign industry globally [8,17].

With regard to biorefinery classifications, there are various terms describing biorefineries in the literature [17,18,42,45-47] based primarily on such as their feedstocks, technological status, conversion processes applied, and intermediate or end products obtained. Below is a variety of terms describing biorefineries based on feedstocks.

- “Lignocellulosic feedstock biorefineries” using natural dry lignocellulose containing feedstocks such as forest-based biomass
- “Whole crop biorefineries” using cereals such as wheat, maize
- “Green biorefineries” using natural wet feedstocks such as green grass
- “Marine biorefineries” using algae (micro or macro) as feedstocks

Following is another classification of biorefineries based on technological status.

- Phase I biorefineries
- Phase II biorefineries
- Phase III biorefineries

A Phase I biorefinery is defined as one with a single feedstock, single process, and single product. A Phase II biorefinery is defined as one with a single feedstock, but with multiple processes and multiple products. Phase I and II biorefineries, such as biodiesel and bioethanol plants, are already in operation and have been demonstrated to be economically feasible. A Phase III biorefinery is the most advanced design of biorefinery and is characterized by having multiple feedstocks, processes, and products [42,45,46]. Figure 2.2 shows a simplified schematic diagram of a lignocellulosic feedstock biorefinery, which is one of the most promising Phase III biorefineries [46]. The lignocellulosic feedstock (primarily cellulose, hemicellulose, and lignin) enters the biorefinery and, through an array of platforms and processes, is fractionated and converted into a variety of energy and chemical products.

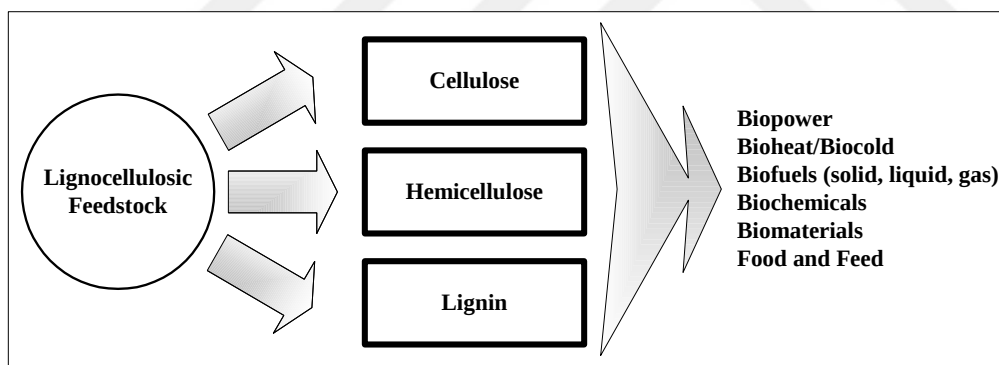


Figure 2.2 : Schematic representation of a lignocellulosic biorefinery.

Below is a classification of the “International Energy Agency (IEA) Bioenergy Work Task 42 Biorefining” [48], roughly divided in two categories.

- i. **Energy-driven Biorefinery:** The main target is to produce one or more secondary energy carriers such as biofuels, biopower, or bioheat from biomass. The biorefinery aspect adds value to co-products. Process residues are valorized to bio-based products thus maximizing the economic feasibility of the full chain from biomass feedstock(s) to product(s).

- ii. **Product-driven Biorefinery:** The main target is to produce one or more bio-based products such as food, feed, biochemicals, or biomaterials from biomass. Process residues are utilized in biopower/bioheat production for internal or external purposes, thus maximizing the economic feasibility of the full chain from biomass feedstock(s) to product(s).

In addition, “IEA Bioenergy Work Task 42 Biorefining” [48] proposed a generic classification system for biorefineries. This classification is defined as a conversion path from feedstock to products, over platforms and processes. The following four main features are used in this classification. Each item in this classification also consists of several subgroups.

- i. **Platforms:** Intermediates connecting different biorefinery systems and their processes (linking feedstocks and final products). Examples are lignin, C5/C6 sugars, syngas, biogas, etc.
- ii. **Products:** Two product groups are energy (such as bioethanol, biodiesel, biopower) and products (such as biochemicals, biomaterials, food, feed).
- iii. **Feedstock:** Biomass source converted into products (such as lignocellulosic crops, oil crops, starch crops, organic residues, etc.).
- iv. **Processes:** Conversion processes used to transform feedstocks into final products (such as thermochemical, biochemical, etc.) [17].

A full overview and framework by which to define various feedstocks, platforms, conversion processes, and final products within any given biorefinery system, along with information about commercial scale biorefinery facilities, can be found in the literature [17,18,47,48].

2.2 Biomass Sources

There is a large number of different biomass sources that can be used to produce biomass energy. The majority of usable biomass originates from three areas: forests, agriculture, and wastes/residues. Added to these three, algaculture is a fourth area currently in development [49]. The biomass sources from these areas are classified differently in the literature because there is no general agreement or international

standard classification of biomass [10]. One classification is provided below, along with a summary in Table 2.1 [8,10,49-51].

- i. Untreated wood: Wood and other woody products (bark, sawdust, etc.) having no chemical treatment. Untreated wood can be provided from various sources including the ones listed below:
 - a. Traditional firewood from coppice forests
 - b. Forest residues from forest operations such as logging residues from final cuttings (nonmerchantable stems, tops, branches), silvicultural residues from first and intermediate thinnings, stumps
 - c. Fallen or dead trees in forests killed by natural disturbances such as insects, fires, and earthquakes or volcanism
 - d. Wood residues from non-forest operations such as managing municipal and private parks and gardens known as arboricultural activities
 - e. Wood processing industry residues such as offcuts, bark, sawdust, shavings, endings and cross-cut ends from sawmills and timber merchants
- ii. Energy crops: High-yield crops cultivated particularly for energy purposes, called energy forestry and energy agriculture
 - a. Energy forestry: Examples are short rotation energy crops such as short rotation coppice (SRC) and short rotation forestry (SRF)
 - b. Energy agriculture: Examples are:
 - fiber plants (linseed, hemp, etc.)
 - grasses (miscanthus, switchgrass, etc.)
 - carbohydrate plants such as starch crops (potatoes, corn, wheat, etc.), sugar crops (sugar beet, sugar cane, sweet sorghum, etc.)
 - oilseed plants (rapeseed, sunflower, soybean, etc.)
 - aquatic plants (water vegetation) such as algae
- iii. Agricultural residues: These are residues obtained from agricultural harvests or processing such as arable crop residues, fruit tree branches, stalks, straw, roots, husks, nutshells, etc.
- iv. Wastes and residues: These are all organic wastes and residues including the ones listed below:

- a. Animal wastes: Animal manures
- b. Municipal wastes: Sewage sludge, organic consumer wastes from hotels, restaurants and individual houses, treated urban wood waste such as woody components of MSW and construction and demolition wood waste, etc.
- c. Industrial wastes and residues: All organic wastes and residues obtained from industrial processes such as food, pulp and paper, textile, forest, agro-, sugar industries. Examples are treated wood from furniture manufacturing, black liquor from the pulp industry, organic waste from the food industry, etc.

2.2.1 Woody biomass

Regardless of origin, biomass sources are also classified into two broad categories. These are woody and non-woody biomass. However, this classification is done for convenience only because there is actually no clear-cut division between them [49,52]. Of the biomass sources explained above, the term woody biomass is mostly used for the items below:

- Biomass obtained as untreated wood (traditional firewood, forest residues from logging and silvicultural activities, fallen or dead trees in forests, wood residues from arboricultural activities and wood processing industries)
- Biomass from energy forestry
- Agricultural residues such as residues from fruit trees
- Wood wastes from municipalities
- Wood wastes from wood processing industries

Woody biomass is also called lignocellulosic biomass because of its primary constituents. The lignocellulosic biomass term is usually reserved for biomass feedstocks utilized in energy production specifically for their lignocellulosic content. Lignocellulose is a term for the combination of cellulose, hemicellulose, and lignin, which are all explained below.

Around 99% of woody biomass is composed of organic compounds. The rest belongs

Table 2.1 : Classification of biomass sources along with their origin.

Biomass Source	Origin	Examples
Untreated wood	Forest operations	Traditional firewood Forest residues
	Natural disturbances in forests	Fallen or dead trees
	Non-forest operations	Untreated wood residues
	Wood processing industry	Industrial residues such as bark, sawdust, shavings
Energy crops	Energy forestry	Short rotation forestry (SRF) Short rotation coppice (SRC)
	Energy agriculture	Fiber plants such as linseed, hemp Grasses such as miscanthus, switchgrass Carbohydrate plants such as starch crops and sugar crops Oilseed plants such as rapeseed, sunflower, soybean Aquatic plants such as algae
Agricultural residues	Harvesting and processing activities	Residues such as arable crop residues, fruit tree branches, stalks, straw, roots, husks, nutshells
Wastes and residues	Animal wastes	Animal manure
	Municipal wastes	Sewage sludge, organic consumer wastes, treated urban wood wastes such as construction and demolition wood wastes
	Industrial wastes and residues	All organic wastes and residues such as treated wood wastes from industrial processes

to inorganic compounds (calcium, potassium, etc.). Three major organic compounds are cellulose, hemicellulose and lignin, which are all polymers. Other organic compounds are extractives, which are low molecular weight organic compounds such as lipids, proteins, simple sugars, starch, water, other hydrocarbons, etc. Of the three major chemical constituents, cellulose is the simpler and better ordered polymer in lignocellulosic biomass. It is a polymer of d-glucose joined in a β -(1:4) arrangement. Unlike cellulose, which is a polymer only of glucose, hemicellulose is constructed from different sugars: hexoses, a mix of six-carbon (C-6) sugars (glucose, mannose, galactose) and pentoses, a mix of five-carbon (C-5) sugars (xylose, arabinose). By contrast to cellulose and hemicellulose, lignin is a non-sugar type aromatic polymer built of hydroxyphenyl propane units. The proportions of these three major compounds differ according to the biomass source, and this is a very important factor in the development of specific processes to produce energy from biomass.

Figure 2.3 presents the broad categories of biomass sources mentioned above, along with information about their content and origin. While forests provide only woody biomass, other biomass sources such as agriculture and waste sources can provide both woody and non-woody biomass. Lignocellulosic biomass can be either woody or non-woody, such as forest residues or agricultural residues. In terms of biomass energy technologies, lignocellulosic feedstocks such as woody biomass are the most investigated types of feedstocks because they do not compete with food production.

	Biomass Sources	
Category	Woody	Non-woody
Content	Lignocellulose	Lignocellulose Sugar Starch Oil
Origin	Forest Agriculture Wastes/Residues	Agriculture Wastes/Residues

Figure 2.3 : Categories, content, and origins of biomass sources.

2.2.2 Forest biomass

Woody biomass that originates from forests is called forest biomass. Figure 2.4 shows the classification of forest biomass sources used to produce energy [53-55].

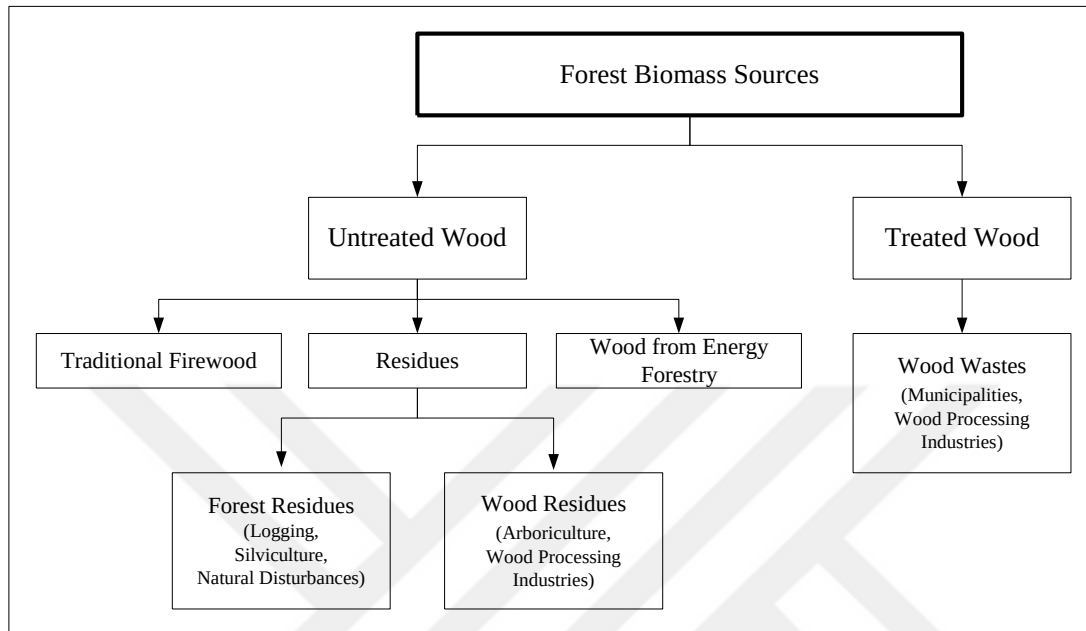


Figure 2.4 : Classification of forest biomass sources used to produce energy [28,53-55].

In Figure 2.4, forest biomass sources are classified into two categories of wood: untreated and treated. Untreated wood originates from forests, the major source of woody biomass, and is either harvested wood logs or forest residue. While harvested wood logs originate from energy forestry or traditional firewood applications, forest residues include all biomass residues left over in forest after industrial forestry or silviculture activities such as logging residues, low quality or rotten woods, other non-commercial woods, debris from forest thinnings such as underbrush, saplings, twigs, and branches. Also included are fallen or dead trees killed by natural disturbances such as insects, fires, and geologic events. Indeed, forest residues typically left in forests after industrial forestry or silvicultural activity could be collected and used to produce biomass energy, especially using the infrastructure already set up and available for harvesting operations [56,57]. Wood residues come from either non-forest operations such as managing municipal and private parks and gardens, known as arboricultural activities, or from wood processing industries such as sawmills and timber merchants. Untreated wood and other products such as offcuts, bark, sawdust, shavings, endings, and cross-cut ends with no chemical treatments or finishes applied are examples of

wood residues from wood processing industries. Treated wood includes wood wastes. Some examples are urban wood waste such as woody components of MSW, wood waste from construction and demolition, and treated wood from wood processing industries such as furniture manufacturing. The focus of this thesis study is untreated wood biomass from forests.

2.2.3 Forests in Turkey

According to 2015 statistics, forests with significant economic, environmental, and cultural functions cover 22,342,935 hectare (ha) in Turkey, which is equal to 28.6% of the entire land area. Of the forest land in the country, 88% is high forests and 12% is coppice forests [58,59]. The total forest area for both high and coppice forests in Turkey is divided into productive forests (57%) and degraded (poorly productive) forests (43%). While coniferous species make up 48% of the mentioned forest area, 33% is of broadleaved species, and 19% is a mix of coniferous and broadleaved species. Among the coniferous species are Turkish red pine, Crimean pine, Scots pine, fir, juniper, cedar, and spruce. Among the major broadleaved species are oak, beech, alder, chestnut, and hornbeam. In terms of the economic, ecological, and socio-cultural functions of these forests, the ratios were 50%, 42%, and 8% respectively [58-61].

In Turkey, 99.9% of the forests are state-owned. Turkish forest organizations are organized under the roof of the “Ministry of Forestry and Water Affairs” (MoFWA), which was known as the “Ministry of Environment and Forestry” (MoEF) between 2003 and 2011. The “General Directorate of Forestry” (GDF) is one of the organizations affiliated with the Ministry, and is responsible for every forest issue in Turkey (management, protection, enhancement, benefitting from forests in a sustainable way, etc.). In Turkey, GDF provided 79–82% of annual wood production in 2015, which includes private sector production and imports. While private sector production was about 12–14% of the annual production, imports amounted to 6–7%. GDF met 65% of annual wood consumption in 2015. In terms of biomass energy, fuelwood is the major forest product in Turkey. Fuelwood production was 17–20% of annual wood production by the GDF in 2015 [62].

In Turkey, 10% of the total population lives in forest villages. Forest villagers are seen as the most important stakeholders of sustainable forest management practices [63]. However, in these forest villages, traditional fuels predominate and wood is used as a

source of energy for basic needs such as heating and cooking. Unfortunately, due to heavy utilization of forests, coupled with uninformed and unsystematic usage, deforestation and erosion are serious problems in Turkey and forest sustainability is under threat. The percentage of land area under erosion pressure is 79.43% [13,20]. In addition, forests in Turkey have suffered from wildfires in the past due to some mismanaged activities [64]. It is emphasized that it is essential to utilize our forests in the most productive way; so degraded forests have to be rehabilitated and protected [13]. With this objective in mind, several protective actions have been taken and projects have been implemented in the country.

2.2.4 Oak coppice forests in Turkey

Oak forests account for 5,610,215 ha (3,451,269 ha productive and 2,158,946 ha degraded) or 25.11% of the total forest cover, the second biggest share after Turkish pine (26.34%) [59]. Oak is the name for trees in the genus *Quercus*. Oak species are divided into three main groups according to the anatomical structures of the wood, fruit ripening periods, and the properties of leaves and bark. Below are the main groups along with their Turkish names.

- i. White oak (Ak meşe)
- ii. Red oak (Kırmızı meşe)
- iii. Evergreen oak (Herdem yeşil meşe)

Currently, there are 18 different species growing in Turkey under the main groups listed above. These species also have many subspecies, varieties, and hybrids [65,66].

Coppice forests are used for economic purposes, and are mainly reproduced from shoots of previous crops or from root suckers (or both) rather than from seeds as in high forests composed of trees that started as seedlings. In terms of coppice operations in Turkey, oak has the largest share (76%). Other species following oak are Crimean pine (9.2%), Turkish red pine (7.4%), Scots pine (4.3%), and fir, juniper, chestnut, and beech (together around 3%). In addition, among oak coppice forests, approximately 64% is degraded and 36% is productive [61]. Considering all coppice forest areas, 29% is productive and 71% is degraded [67].

According to forest management strategies in Turkey, there have been action plans [67,68] and applications [69,70] to convert coppice areas to high forests since the year

2006. This is due to decrease in fuelwood consumption of Turkey, and the high share of degraded coppices as mentioned above. As an application example, Table 2.2 shows the economically functional forest areas (in hectares) for oak in the Marmara region, which includes the conversion of oak coppices to high forests [70]. Almost 70% of oak forests constitute oak coppice planned for conversion to high forest. On the other hand, it has been discussed that some of the oak coppice forests should be utilized for energy purposes instead of transforming them all into high forests [71]. In a survey study to investigate the socio-economic dimensions of converting coppice forests to high forests, it was emphasized that overall conversion of coppice forests to high forests could lead to loss of income to forest villagers, and increase forest crimes such as unauthorized logging and grazing over the long term [72]. In addition, it is important to mention that considering all high forest areas, 58% is productive and 42% is degraded [67].

Table 2.2 : Economically functional oak forests in the Marmara region including conversion of coppices to high forests [70].

Oak	Area (ha)	%
High forest	155,729.9	21.74
High forest (mixed)	62,550.7	8.73
Conversion to high forest	498,182.0	69.53
Total	716,462.6	100.00

2.2.5 Energy forestry in Turkey

Energy forestry is forestry intended to provide biomass feedstock to produce heat/power via specifically cultivated fast-growing trees. The energy forestry forms SRC and SRF indicate crops grown 2–5 and 8–20 years before harvest, respectively.

GDF established 562,513 ha of energy forests between the years of 1978 and 2008 [73]. However, these activities have mostly been in the form of classical energy forestry implementations: thinning, sowing, and planting. However, modern energy forestry requires methods using modern machinery with intensive management (e.g., careful choice of land, soil preparation, weed control, and suitable fertilization) to get the highest wood production per unit area per unit time [12,74]. For example, SRC willow harvests are made every 3–5 years. In the following year, the willow stumps

generate new shoots. Generally, six harvests can be made for each plantation, providing an average rotation of about 25 years [12].

To prevent deforestation and erosion, to supply the raw material required for wood and energy needs, and to provide jobs to many of the people living near forest areas, energy forestry is seen as the best solution [20]. It is thought that heavy utilization of natural forests can be avoided by creating energy forests near the forest villages [75].

The goals of energy forestry, apart from the use of forest biomass for energy purposes (i.e., establishing in situ CBHBP facilities), are to protect biological diversity (particularly near human settlements), increase productivity, reduce soil erosion and environmentally harmful emissions, create new job opportunities for local people, and to have them participate in sustainable forest management [76]. The most suitable areas for the introduction of energy forestry in Turkey, are reported to be the degraded or poorly productive oak coppice areas. The attention is on the enhancement of degraded coppice forests by transforming them into modern, highly productive energy forests; hence meeting the continually increasing demand for woody raw materials in Turkey and preventing the destruction of productive forests [13,20].

In Turkey, the need for production of woody raw materials from forests established for the purpose of wood production rather than from natural forests emerged in the 21st century. In 2005, the “Industrial Tree Agriculture and Trade Co. (ENAT)” [77] was founded with the initiation of the “Turkish Foundation for Combating Soil Erosion, for Reforestation and the Protection of Natural Habitats (TEMA)” [78]”, and MoEF which became known as MoFWA after 2011. ENAT, which has 26 cofounders from fiberboard, pulp and paper, and packaging industries, started making industrial plantations in Turkey from 2005.

2.3 Turkey’s Energy Outlook and Biomass Energy

Geographically, the Republic of Turkey is located on an area of 780043 km² where the continents of Europe and Asia meet. Strategically, Turkey serves as a regional energy hub for major energy consumers and suppliers in the world. As Turkey has the 17th largest economy in the world and the 6th largest in Europe, the demand for energy is constantly growing in the country. Over the past decade, the energy market in Turkey has become one of the fastest growing ones in the world, in parallel to economic

development driven by industrialization and urbanization, and with Turkey's young and dynamic population of almost 80 million people [79,80]

In line with economic development in Turkey, significant increases were observed both in its primary energy supply and electricity consumption. TPES was 129 million metric tons of oil equivalent (Mtoe) in 2015, with an increase of ~105% compared to the figure of 63 Mtoe for 1990 [19]. The average rate of increase in electricity consumption has been 5.5% over the last 14 years [81]. Figure 2.5 shows the fuel shares of TPES in 2015. Renewables (hydro, fuelwood, biofuels, animal and agricultural wastes/residues, geothermal, solar, and wind) constituted almost 12% of the country's TPES, with 15 Mtoe. A closer analysis of the fuel mix in energy supply reveals the importance of natural gas, coal, and oil for Turkey. Unfortunately, Turkey does not have large oil and gas reserves. Almost all oil, gas, and high quality coal are imported. Turkey's total primary energy production was 31 Mtoe in 2015. The primary energy production has provided 24% of the TPES of the country; hence, for 2015 Turkey depended on imports for 76% of its TPES [19]. Turkish dependence on energy imports has been increasing year by year, and it is projected that this increase will continue in the coming years. The high rate of import dependence in terms of primary energy sources is a significant threat to Turkey's energy supply security. Hence, utilization of indigenous energy sources is of vital importance for Turkey. Renewable sources in the country represent the second largest domestic energy source after lignite. Turkey has a wide range of high potential renewable-based energy sources as a result of its geographical location, with its coasts of over 7200 km and an average elevation of 1132 m [12,23,24,74,82-85]. Turkey is a country with rich biomass potential. The total biomass energy potential (forest, agricultural, animal, and municipal wastes/residues) is estimated at approximately 17–20 Mtoe [12,20,21]. Considering the statistics from 2015, annually 20 Mtoe of energy provided from biomass would have been able to meet approximately 16% of Turkey's TPES. However, just a small portion of this potential has been utilized so far. The share of biomass energy (fuelwood, biofuels, and animal and agricultural wastes/residues) in Turkey's TPES was 2.27% in 2015 (Figure 2.5).

Figure 2.6 depicts the product shares of total renewable-based energy supply in 2015. Renewable-based energy supply in Turkey is dominated by mainly hydro and geothermal sources. Among renewables, biomass is a strategic energy source for

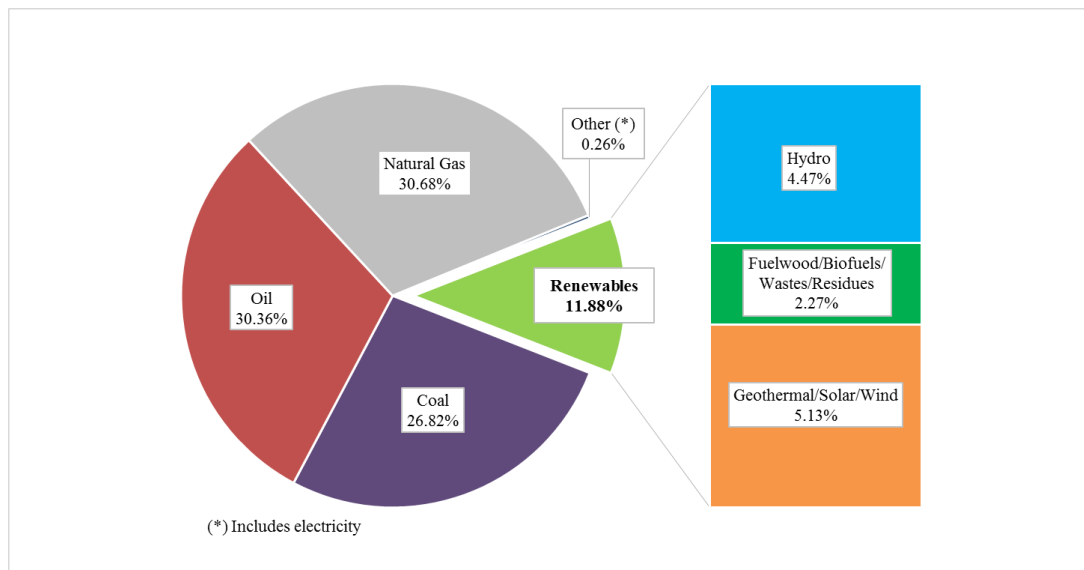


Figure 2.5 : Fuel shares of total primary energy supply in Turkey in 2015 [19,27].

Turkey, so that biomass energy share among renewables is 19.14%, the highest share after hydro and geothermal (Figure 2.6) [19]. However, traditional use of biomass energy prevails in Turkey so that it is mostly consumed by direct combustion for domestic purposes. Of the biomass sources in Turkey, fuelwood is the most significant one since there is good trade in fuelwood in the country. Fuelwood is the primary fuel for rural and poor urban districts. In the residential dwellings of these districts, fuelwood is burned in stoves and fireplaces for cooking and heating purposes. Fuelwood comprises 64% of combustible biomass sources (fuelwood and animal and agricultural wastes/residues) supplied in 2015. The share of fuelwood among renewable-based energy supplies in Turkey is high at 11.80% for 2015 (Figure 2.6). Animal and agricultural wastes/residues come after fuelwood at 6.55%. The lowest share among renewable-based energy supplies belongs to biofuels, which comprise 0.79% [19].

In Turkey, renewable sources are considered as a solution to mitigate not only import dependency but also environmental pollution problems such as GHG emissions. In 2014, Turkey's overall GHG emissions as carbon dioxide (CO₂) equivalent (eq) were 467.6 million metric tons (Mt), which increased by approximately 125% compared with 1990 data. The energy sector had the largest share with 72.5% [86]. On the other hand, Turkey ratified the “United Nations Framework Convention on Climate Change” (UNFCCC) in 2004 and became a member of the Kyoto protocol in 2009. As

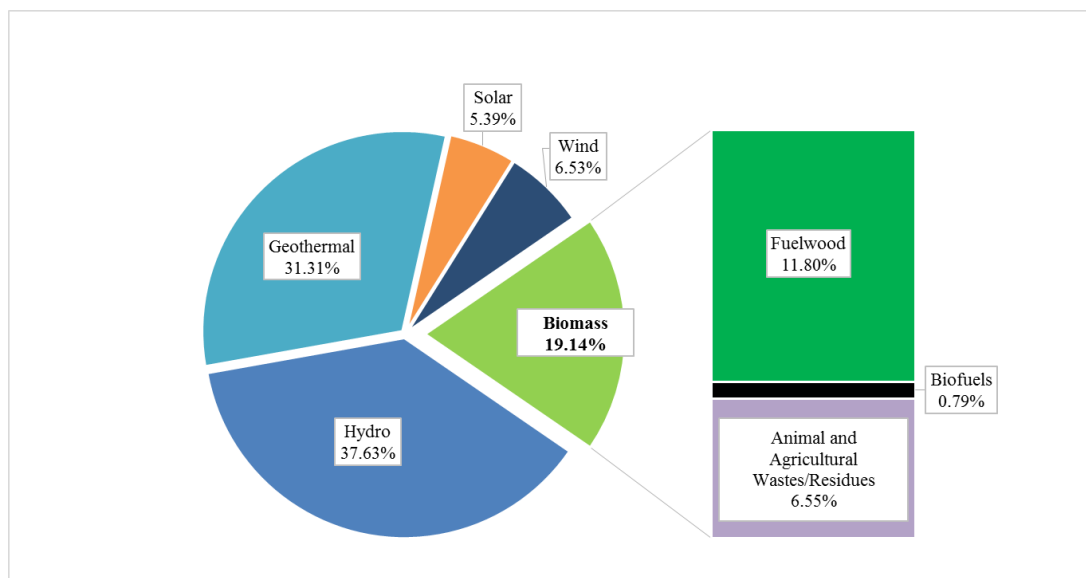


Figure 2.6 : Product shares of total renewable-based energy supply in Turkey in 2015 [19,27].

an annex I party to the convention, Turkey is required to develop annual GHG inventories but is not required to set any quantitative targets to limit CO₂ emissions. Still, Turkey has unilateral commitments to reduce GHG emissions in its strategic aims and action plans [87]. In 2016, Turkey signed the Paris climate agreement at the 21st conference of the parties of the UNFCCC held in Paris. In accordance with the decisions in Paris, Turkey submitted its “Intended Nationally Determined Contributions” (INDC) to the UNFCCC secretariat. By 2030, Turkey aims to reduce GHG emissions by up to 21% below the current business as usual level [88]. In this context, the promotion of energy generation from renewable sources is crucial for Turkey to reduce its GHG emissions that mainly originate from the energy sector.

In order to not only cover the growing energy demand but also to minimize GHG emissions and fuel import dependency, the goal is to increase the use of indigenous energy sources. Turkey, as a European Union (EU) candidate, has prepared long term strategic plans aligned with the EU accession negotiations [89] that started in 2005. In this regard, the Turkish government is giving great importance to the maximum use of all renewables, as well as to increase in energy supply diversification, to the utilization of all domestic sources, and to the integration of nuclear energy into its power production. The “Ministry of Energy and Natural Resources” (MENR) has determined the country's strategic aims, and set targets and certain policy measures considering national priorities. To foster the utilization of renewable-based energy sources in

Turkey, the main target is to provide a 30% share of renewable-based energy sources in power production by the year 2023. Turkey also aims to supply 5% of its power production through nuclear energy by the year 2023. The government has recently reopened its nuclear program, and signed international agreements with the Russian Federation and Japan to build nuclear power plants in Turkey [90,91].

Modern utilization applications of biomass energy in Turkey comprise biofuels (engine biofuels such as biodiesel and bioethanol, and solid biofuels such as pellets), as well as biopower (bioelectricity) and bioheat production. In general, these applications are in a developmental stage in the country. New investments in renewable-based energy technologies have been triggered by relevant policies and incentives in Turkey [8].

Today, the contribution of biofuels to the transport sector energy supply is 0.49% (Figure 2.7).

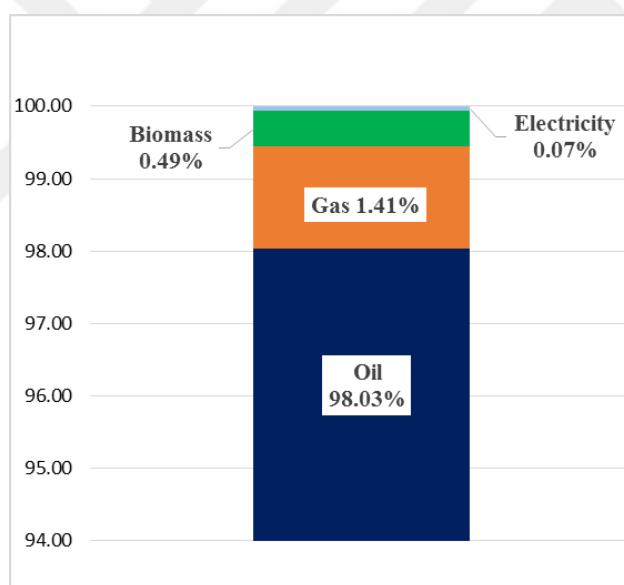


Figure 2.7 : Transport sector energy supply in Turkey in 2015 [19,27].

Oil products dominate the transport sector in Turkey. Still, Turkey aims to meet 10% of the energy needs of its transport sector supply through renewable-based energy by 2023, according to its “National Renewable Energy Action Plan” (NREAP) [92]. The production and consumption of biofuels are expected to increase with the help of blending ratios of biodiesel and bioethanol to the regular diesel and gasoline fuels in the transport sector. While the blending ratio for bioethanol is mandatory, that for biodiesel is optional. The mandatory ratio for bioethanol was first applied in 2013 at

2%, but today it is 3%. For biodiesel, there is an exemption from the special consumption tax in the case of a blending ratio of at least 2% [93].

Figure 2.8 presents the breakdown of Turkey's installed capacity to generate electricity by primary energy sources as of 31 October 2016. The total installed capacity is 78,434 MW_e, which includes both licensed and unlicensed power applications. Of Turkey's total installed power capacity, biopower, which is shown as combustible renewables and waste including waste heat and pyrolytic oil in Figure 2.8, has a share of 0.59% at about 465 MW_e [94]. It is obvious that in Turkey, electricity is produced by thermal power plants consuming mainly coal and natural gas, by hydropower plants, and most recently from wind energy. Turkey aims to have a total installed capacity of 125 gigawatt electrical (GW_e) by 2023 according to its NREAP.

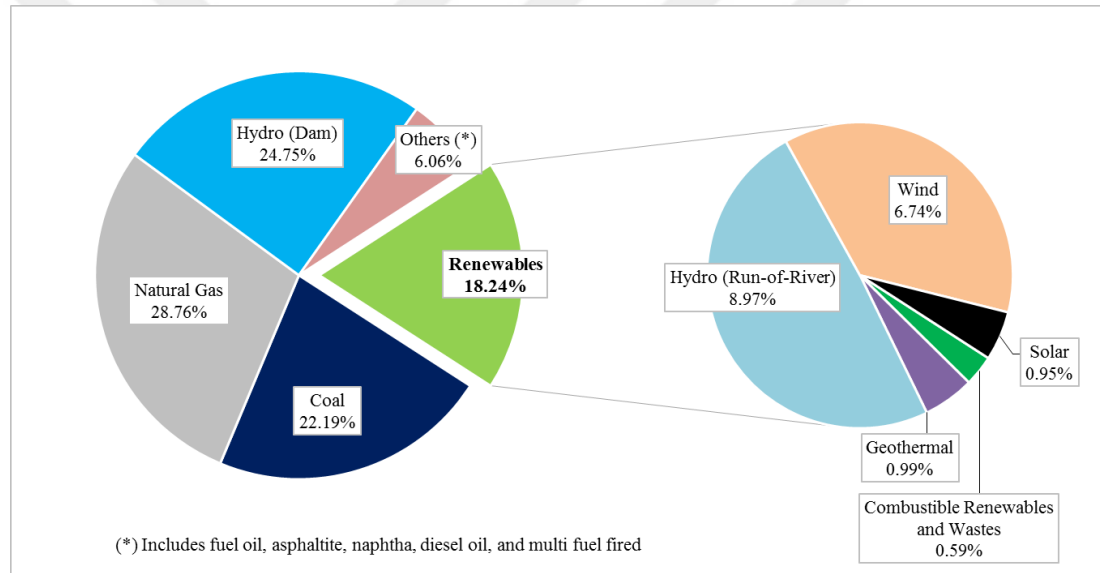


Figure 2.8 : Installed capacity by primary energy sources in Turkey as of 31 October 2016 [27,94].

Table 2.3 presents the most current installed capacities and the national targets set for installed capacities to promote renewable-based power generation in Turkey [91,92,94].

Renewable-based sources are going to supply 61,000 MW_e, of which 27,000 MW_e belongs to the renewables other than hydro. The target for biopower is 700 MW_e by 2019 [91] and 1000 MW_e by 2023 [92]. The target for biopower was set as 540 MW_e by 2017 [91].

Table 2.3 : National targets for installed capacity of renewable-based power generation (MW_e) [27,91,92,94].

Renewable-based Power Generation	Installed Capacity (MW _e) ^a	National Targets for Installed Capacity (MW _e)	
	31.10.2016	By 2019	By 2023
Hydro	26,443	32,000	34,000
Wind	5,286	10,000	20,000
Geothermal	775	700	1,000
Solar	746	3,000	5,000
Biomass ^b	465	700	1,000
Total	33,715	46,400	61,000

^a Includes both licensed and unlicensed power applications.

^b Represents combustible renewables and wastes including waste heat and pyrolytic oil.

In Turkey, significant improvements in power generation from renewable sources have been made since 2005, when the law on utilization of renewable energy sources for the purpose of generating electrical energy (law no. 5346) [25], also known as the “Turkish renewable energy law” (the YEK law), was enacted. In order to foster renewable-based power generation even further, the YEK law amendment with the number 6094 was introduced in 2010. The “Turkish renewable energy support mechanism” (the YEK mechanism or YEKDEM), which is a support mechanism for renewable-based power manufacturers, was enabled in 2011 together with the enactment of amendments to the YEK law. The YEK mechanism has been regulated with the regulation on documentation and support for renewable energy sources first in 2011, and later in 2013. The renewable sources covered in the YEK law are wind, solar, geothermal, biomass, biogas (including landfill gas), wave, stream, tidal, river and arc type hydroelectric generation, and hydroelectric generation facilities with a reservoir area of less than fifteen square kilometers. Based on this law, some incentives include feed-in tariffs, lower license fees, domestic production support, connection priorities, and purchase guarantees. The power plants that will come into operation before 31 December 2020 are eligible to receive the feed-in tariffs. The feed-in tariffs in US Dollar cent per kWh are applicable for the first ten years of operation. The price applicable to biopower production facilities is 13.3 cent/kWh, the highest rate, which also applies to solar power production facilities. While the price applicable to geothermal power facilities is 10.5 cent/kWh, the price for wind and hydropower is 7.3 cent/kWh. As mentioned above, the YEK law also provides a domestic production

incentive for projects using components produced in Turkey with the regulation on domestic manufacturing of components used in renewable energy electricity generation facilities. The maximum possible tariff for a biomass power plant facility can be 18.9 cent/kWh with the addition of 5.6 cent/kWh, the maximum local production premium including the cogeneration system premium, which is 0.4 cent/kWh. There is also an exemption from licensing and setting up a company for small-scale power generation based on renewable sources. With the law no. 6446 and the latest regulation (regulation on the unlicensed electricity generation on the electricity market) that came into force in 2013, power plants based on renewable sources with a maximum installed capacity of 1 MW_e are exempt from licensing and establishing a company. Therefore, individuals are also eligible to generate renewable-based electricity up to 1 MW_e.

Starting with figures from 31 December 2005, Figure 2.9 presents the installed capacity development of the renewable-based energy sources excluding hydro [94,95]. The figure also includes the annual share of renewable-based installed capacity excluding hydro among the total installed capacity. The YEK law and YEKDEM obviously had a clear effect on renewable-based power generation growth. While the share was 0.18% in 2005, it has currently reached 9.27%, excluding hydro. The growth is mainly from wind power. It is important to note that further increases, especially in biopower and solar power development, are needed to reach the national targets listed in Table 2.3.

Both licensed and unlicensed biopower applications are possible in Turkey. Eligible electricity subscribers have the opportunity to produce their own electricity and sell the surplus electricity without being subject to the requirements to obtain a license and establish a new company. For example, the following are exempt from licensing and incorporating a new company:

- renewable-based power generation plants with a maximum installed capacity of 1 MW_e
- micro cogeneration units with a capacity up to 100 kW electrical (kW_e), cogeneration plants with high cycle efficiencies
- renewable-based power generation plants that are at the same production and

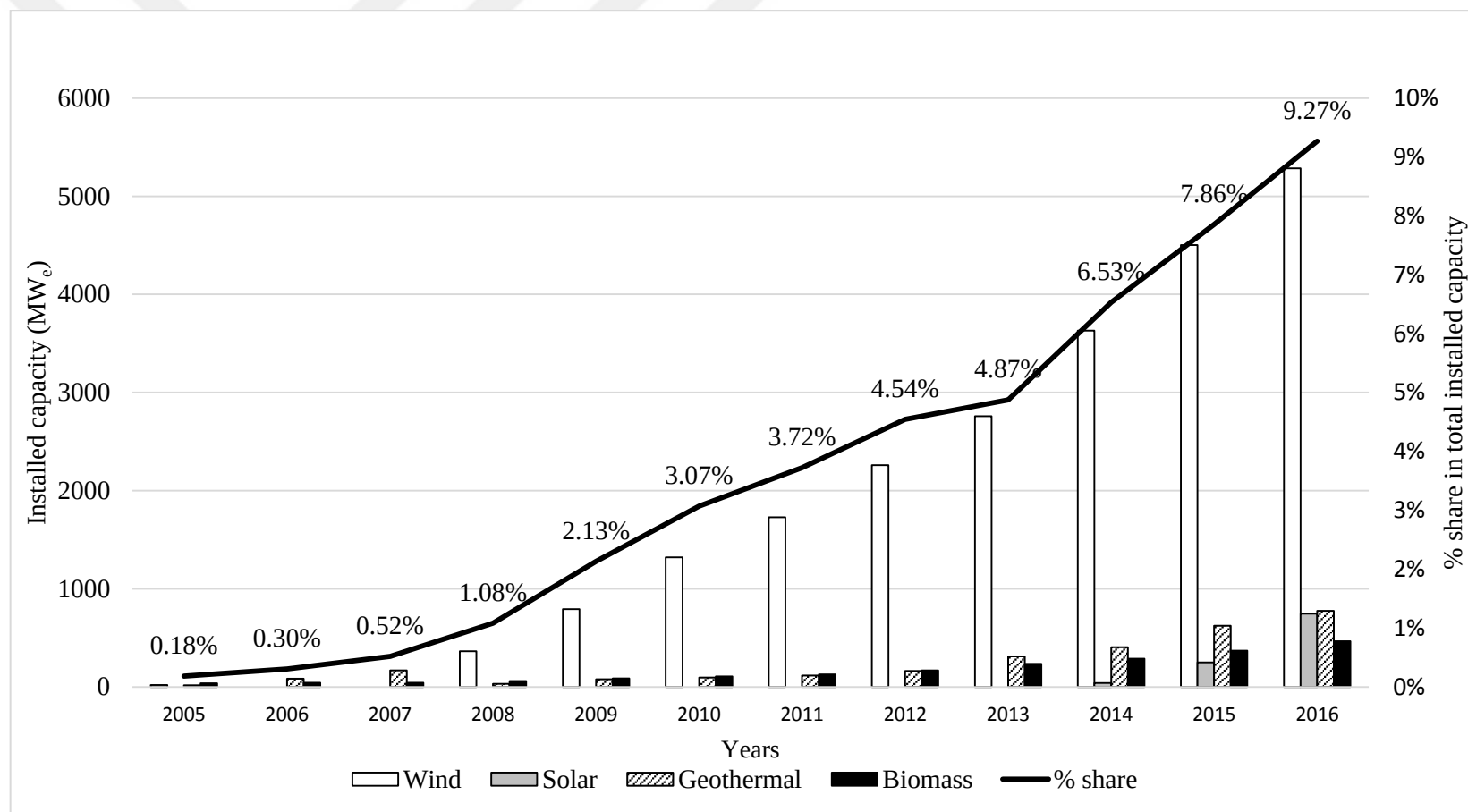


Figure 2.9 : Installed capacity development of renewable-based energy sources and their annual share in total installed capacity excluding hydro [27,94,95].

consumption measurement points and that use the whole amount of the energy produced without providing it to the transmission or distribution networks

- solid waste disposal facilities of municipalities, and power plants established to dispose of treated sludge

As of November 30, 2016, the total installed capacity for biopower applications is about 405.17 MWe, of which 40 MWe is for unlicensed [96] and 365.17 MWe is for licensed production [93]. Unlicensed biopower generation includes both approved and temporary admission projects. The ratio of unlicensed biopower production to total unlicensed production for approved and temporary admission projects is almost 1% [96]. Regarding the licensed biopower applications in Turkey, Table 2.4 provides the current (30 November 2016) renewable-based power generation license situation and its development based on the year 2005 (31 December 2005) [93]. The current total installed capacity for licensed biopower generation is shown as 365.17 MWe. In the table, data from 2005 were chosen as the base to analyze the development in renewable-based power generation in Turkey, since 2005 was the first year when the YEK law was in place in the country. The table includes the number of given licenses and installed capacities for the dates mentioned, and the current installed capacity broken down by type, and whether the plant is in operation or under construction. It is obvious that the YEK law and YEK mechanism had a clear effect on wind, geothermal, hydropower, and biopower development in Turkey. Renewable-based power generation capacities except for solar power have been growing by many investments since 2005.

Figure 2.10 presents biopower license situation development starting from 2005 [93]. Table 2.4 and Figure 2.10 show that for biopower production, while there was only one license with an installed capacity of 0.59 MWe in 2005, today there are 72 licenses with an installed capacity of 365.17 MWe.

However, it is important to mention that a challenging further increase in biopower development is needed to reach the national targets, which were set as 700 MWe by 2019, and 1000 MWe by 2023, as listed in Table 2.3 [91,92].

Existing biopower licenses in Turkey mostly belong to landfill gas and biogas

Table 2.4 : Renewable-based power generation license situation in Turkey, in 2005 and 2016 [27,93].

Renewable-based Power Generation	Licenses	Total Installed Capacity (MW _e)	Current Licenses	Total Installed Capacity (MW _e)	Capacity in Operation (MW _e)	Capacity under Construction (MW _e)
	31.12.2005		30.11.2016			
Hydro	124	12,381.80	850	32,940.10	22,303.36	10,636.73
Wind	13	792.30	244	9745.24	4802.04	4943.20
Geothermal	4	69.70	40	1093.20	761.16	332.04
Solar	-	-	2	12.90	12.90	-
Biomass - Total	1	0.59	72	365.17	259.80	105.37
<i>Biogas</i>	-	-	29	87.35	74.88	12.47
<i>Landfill gas</i>	1	0.59	30	191.86	173.56	18.30
<i>Sewage water</i>	-	-	5	7.60	7.60	-
<i>Biomass - other*</i>	-	-	8	78.35	3.76	74.60
Total	142	13,244.39	1208	44,156.61	28,139.26	16,017.34

* Biomass - other includes thermochemical conversion technologies.

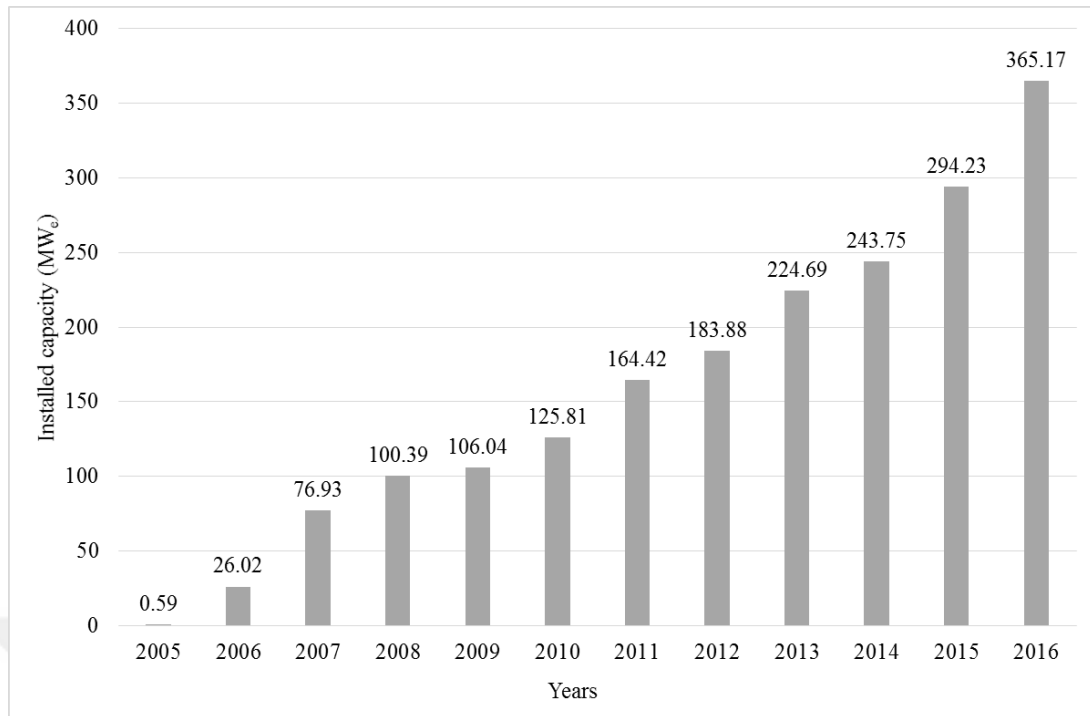


Figure 2.10 : Biopower license situation development in Turkey, 2005-2015 [27,93].

production facilities. Operational plants are landfill gas (67%), biogas (29%), or sewage water (3%) plants. In Table 2.4, 1% of the operational plants, classified as “Biomass – other”, use thermochemical conversion technologies. On the other hand, there are biopower plants under construction, which are biomass - other (71%), landfill gas (17%), or biogas (12%) plants. It is remarkable that among the plants under construction, the plants using thermochemical conversion technologies have the highest share with 71%. However, it is important to mention that the necessary technological experience and infrastructure for all conversion paths related to CBHBP production are available in Turkey.

The growth in biopower production has mainly occurred using wet biomass sources through landfill gas and biogas production facilities, as a result of the significant contribution of local authorities such as municipalities, especially in large cities, which show great interest in waste to biopower production technologies. The first landfill gas production license was issued to Istanbul metropolitan municipality in 2004, with an installed capacity of 0.59 MW_e. As of 19 July 2017, licensed landfill gas production in Istanbul is at approximately 58 MW_e [93]. Since then, landfill gas and biogas production has become popular, and similar applications were carried out by other large municipalities in their municipal waste treatment and purification plants Turkey has become experienced in landfill gas and biogas production technologies. On the

other hand, at present CBHBP applications as well as biopower-only applications using thermochemical conversion technologies are limited in the country. A detailed assessment of biopower applications in Turkey can be found in Eksi and Karaosmanoglu [27].

2.4 CHP Overview

CHP or cogeneration (abbreviated to cogen) is the simultaneous production of two or more secondary energy carriers such as useful heat and electricity using a single fuel in one conversion process.

The thermodynamics of electricity generation require that a large quantity of heat is rejected to a lower temperature sink. CHP is essentially implemented by the addition of a heat exchanger to utilize an important portion of the heat rejected as a by-product in electricity production [97]. While the electricity produced can be used on-site or delivered to grid, the thermal energy recovered is usually used on-site for district heating, cooling networks, hot water, industrial process heat, or for steam generation [98]. In a cogeneration system, it is essential that a significant portion of the recovered heat must be used in a thermal process. Therefore, the main precondition for an effective cogeneration operation is a stable thermal energy demand [99]. CHP is actually an integrated energy system that can be modified according to end user requirements, i.e., to satisfy an existing heat demand at the regional or local level. Hence, the design of CHP systems depends on the relevant site-specific conditions. For example, it is important for CHP technologies that the rejected heat is provided at a sufficiently high temperature in a useful form for space or hot water requirements (CHP for district heating), or alternatively for steam to meet industrial process needs (CHP for industry) [97].

A CHP unit comprises three main components: a prime mover (turbines, engines, and fuel cells) in which fuel energy is transformed into mechanical and/or thermal energy, an electrical generator in which the mechanical energy is transformed into electricity, and a heat recovery system to capture the rejected heat and an absorption cooling unit in the case of trigeneration. For CHP production, two distinct operational modes are possible. While operational mode for small CHP plants is usually heat-controlled, that for large CHP plants is electricity-controlled mode. Fuels used in CHP are diverse:

natural gas, coal, light fuel oil including diesel oil, solid, liquid, and gaseous biomass, and waste fuels, etc.

There are many benefits from using CHP technology. First, the basic technical advantage is increased efficiency. Total system efficiencies of around 60 to 85% to produce electricity and heat can be achieved by CHP systems having waste heat recovery technologies [100]. Alteration of the design of a conventional thermal power plant to cogeneration improves energy utilization, i.e., the efficiency of fuel use. For example, in general, CHP system overall efficiency for district heating can be of the order of 1.5 times greater than the efficiency of separate sources [101]. Second, CHP technology has economic benefits. CHP saves money because it produces two usable energy carriers from a single fuel. In a cogeneration facility, the total fuel needed to generate both heat and power is less than the total fuel needed to generate the same amount of heat and power in separate systems [98,102]. Third, CHP technology offers environmental benefits. Cogeneration is environmental friendly because it uses less fuel overall, hence fewer pollutants will be emitted to the atmosphere. In addition, because it uses less fuel the planet's energy sources will be conserved [29,56,97,103-106]. From the point of view of GHG emission savings, it is estimated that each megawatt (MW) electric of CHP saves about 1000 metric tons (t) of carbon emissions per year [52]. Finally, CHP technologies help to implement the DG model of electrical and/or mechanical power, which means energy generation near to both energy sources and consumption. Other terms used for DG are decentralized, dispersed, embedded, on-site, and in situ generation. The major drivers for DG are defined as environmental and economic [107-110]. CHP systems can be installed in rural or remote areas, for example close to industrial or commercial facilities, providing decentralized source of energy with minimal transmission lines and losses [56,111]. In rural areas, even if the electricity supply is available from a centralized electricity generation system, the service is usually unreliable and expensive [112].

Several actions have been taken to promote the widespread deployment of CHP in the world [113-115]. In the EU, the “European Directive of Cogeneration (2004/8/CE)” promotes cogeneration to increase energy efficiency and reduce GHG emissions [116]. In addition, in the “Climate Action and Renewable Energy” (CARE) package, legislations to ensure the EU meets its climate and energy targets for 2020, 2030, and 2050, cogeneration is seen as an energy efficiency measure that is able to contribute

notably not only to the reduction of GHG emissions but also to reduced dependence on imported fuels [117]. Regulations in Turkey are made in the context of the accession negotiations with the EU. With the most recent legislative changes in Turkey (law no. 6446 that came into force in 2013), there is an exemption from licensing and establishing a company for micro cogeneration units that have a capacity up to 100 kilowatt (kW) and for cogeneration plants that have high cycle efficiencies. Hence, eligible consumers are allowed to build and operate their own CHP facility without a generation license.

In Turkey, the number of cogeneration plants was limited until 1984 when the first legislation (law no. 3096) was enacted to allow the participation of the private sector in the power industry. After that, the first privately owned cogeneration plant was built in 1992 with a 4 MW_e. According to the latest statistics, there are 304 cogeneration plants in operation with a total electrical capacity of 7747 MW_e and a share of approximately 10% of Turkey's total installed capacity. However, there is still a reported growth potential of 10000 MW_e [118].

There are three different types of CHP applications in Turkey. The first is industrial cogeneration. The basic industrial sectors mainly using CHP in Turkey are the textile, iron and steel, chemical, petrochemical, food, ceramic, paper, and wood industries. The second type is use of cogeneration or trigeneration for heating or heating/cooling purposes, respectively, in public places such as university/school campuses, hospitals, shopping malls, housing, hotels, airports, and holiday resorts, etc. The third type is agricultural cogeneration, which is widely implemented in greenhouses and fish farms in Turkey. CHP for district heating is growing slowly in Turkey since investors are hesitant to replace conventional central heating systems with CHP systems. In addition, micro cogeneration is a new concept for Turkey. The high price of micro cogeneration together with the need for more technical knowledge of connection issues are the basic barriers preventing implementation of this technology.

In Turkey, growing energy demand, fuel import dependency, high GHG emissions mainly from energy sector, power quality problems and high energy prices entail developing energy saving policies to the largest possible extent. CHP is a well-understood, mature and cost effective technology. Cogeneration or trigeneration is a possible way of simultaneous electricity and heat/cold production that can contribute significantly to energy saving measures of Turkey.

Although the variety of fuel used in CHP production can be fairly large, the primary fuel used in cogeneration plants in Turkey is natural gas, which is almost entirely imported. Therefore, natural gas costs create a substantial part of the operating costs of the CHP plants in Turkey. Added to this, fluctuations in natural gas prices result in fewer CHP investments in the country. Biomass is an alternative fuel for CHP systems. It is not only renewable but also indigenous energy source favorable to socio-economic development. Sustainable production of CBHBP is a possible way to utilize the biomass energy potential which is not efficiently used in Turkey.

2.5 CBHBP Production

“Combined BioHeat and BioPower (CBHBP)” is a new terminology defined in this thesis research to emphasize that it is the biofuel used as feedstock for the production of “Combined Heat and Power (CHP)”. Other terminologies used in the literature are “biomass CHP”, “biomass-based CHP”, and “biomass cogeneration”.

Biofuels are used most efficiently when generating both bioheat and biopower through cogeneration. This allows an economic use of the bioheat produced in the plant, hence increasing the competitiveness over biopower-only plants. In the USA, higher than 60% of the existing biomass-fueled power generation is in the form of CBHBP [56]. In the EU, the majority of biopower (60.4%) comes from cogeneration plants [119]. Among a total of 3696 plants using wood chips in the EU, 21% are CBHBP plants, 3% are biopower-only plants, and the remainder are bioheat plants [120]. CBHBP is seen in Turkey as an effective way to increase the overall efficiency of biopower-only plants [121]. Also, by using biofuel as feedstock, it is possible to further augment the benefits of conventional CHP applications.

Most of the technical details of CBHBP production are essentially similar to conventional fossil based cogeneration (CHP). The use of biofuel as feedstock and appropriate utilization technologies make CBHBP different from any conventional CHP. Since biomass sources come in different forms, their use for energy is varied so that many biomass sources can be transformed via various conversion technologies for use in the energy sector [7].

Other than a stable thermal energy demand, the critical steps for implementation of a successful CBHBP project are listed below.

- The choice of biomass source
- The design of a biomass supply chain network
- The choice of appropriate conversion technologies

Starting from biomass sources and supply chain, the major conversion paths to produce biopower and bioheat that are currently commercially viable or have high commercialization potential are shown in Figure 2.11. They are differentiated on the basis of the biofuel feedstock used being solid or wet, and the conversion paths applied being thermochemical or biochemical. The conversion paths for biopower production include the primary and secondary conversion technologies. The primary conversion technologies are combustion/co-combustion (co-firing), gasification and anaerobic digestion, and conversion of biomass into steam, vaporized organic fluid, or gaseous products. The secondary conversion technologies (turbines, engines, and fuel cells) transform these products into biopower and additionally bioheat. Two different secondary conversion technologies can be combined, such as gas turbine for electricity production and steam turbine for heat recovery. The end use for all conversion paths includes the use of CBHBP produced [30,56,122,123]. Conversion paths producing liquid biofuels such as bioethanol, biodiesel, and bio-oil are omitted from Figure 2.11 since they are mostly focused on transportation biofuels, biochemicals, and biomaterials, but not on biopower and/or bioheat generation.

The following subsections provide a technology review of the critical steps outlined in Figure 2.11, which are biomass sources and supply chain, and primary and secondary conversion technologies. Then, focusing on the most established path to produce CBHBP, steam turbine technology based on combustion is examined. A flow diagram of a typical steam Rankine cycle and a table listing the basic technical features of commercial CBHBP plants are provided. Some distinctive characteristics of biopower production are also summarized.

2.5.1 Biomass sources and supply chain

The choice of biomass source and hence biofuel feedstock have a significant impact on the sustainability of CBHBP production. Biomass does not require mining, is widely distributed, and relatively easy to collect. However, it is very important to distinguish between biomass produced as waste or residue from deliberately cultivated

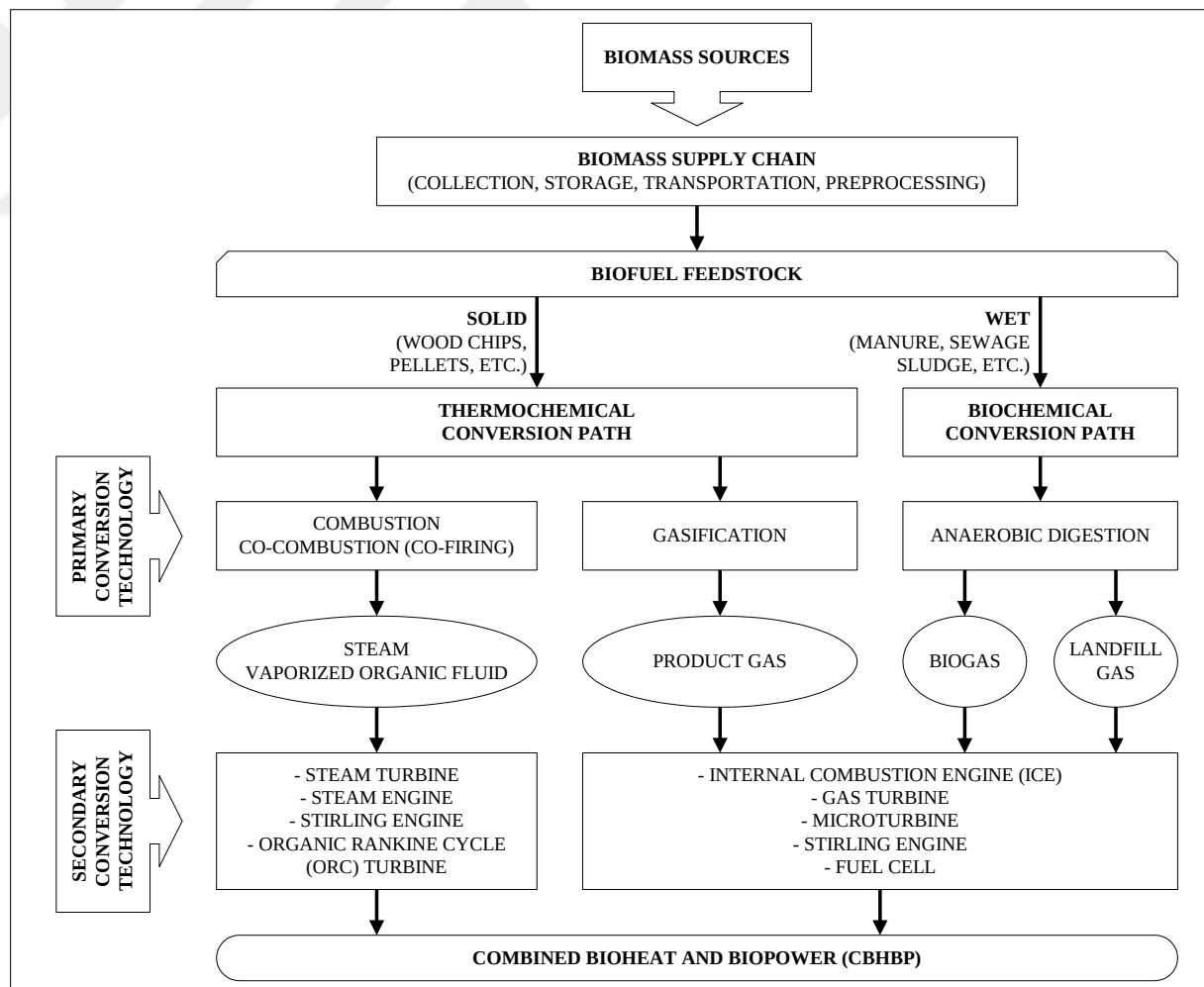


Figure 2.11 : The major conversion paths for Combined BioHeat and BioPower production [27,30,56,122,123].

biomass, and naturally occurring biomass that was removed for energy utilization [10]. Many different biomass sources can be utilized to produce biopower and bioheat. Biomass sources are available both in rural areas (forest residues, agricultural residues, manure, energy forestry, energy agriculture, etc.) and urban areas (urban wood waste, MSW, industrial wastes/residues, sewage sludge, etc.). Their characteristics vary widely, including elemental composition of organic matter, physical properties, calorific value [124], mineral matter content, moisture content, biochemical composition, etc. and therefore typical considerations for their utilization differ depending on the source.

The primary biofuels used in CBHBP plants are solid biofuels [125], and to a lesser extent manure and sewage sludge. Solid biomass sources represent the largest share in global biopower production, comprising 71% at the end of 2015. Biogas, MSW, and liquid biofuels account for 20%, 8%, and 1%, respectively, of global biopower production [7]. For existing CBHBP plants using solid biofuels in European countries, the predominant biomass source is wood chips, either from forestry (38%) or from saw mill residues (24%), while other important sources are bark, waste wood, paper sludge, straw, and peat [126]. For CBHBP applications, the highest reported efficiencies with solid biofuels are for woody biomass sources, followed by non-woody biomass sources [127]. Forest biomass, which is a woody biomass source, is seen as an important choice with high potential for bioheat and biopower generation since it is an indigenous energy source in many countries. Therefore, the focus has recently been placed on the technologies appropriate for local forest wood chips to lower the transportation needs and therefore environmental impacts of the entire biomass supply chain [30]. Moreover, there are many benefits of using biomass wastes/residues for energy production. They can be obtained in a cost effective manner; they do not compete with food and feed under land availability constraints; they reduce waste/residue disposal problems; and as a domestic source, they are not subject to the price fluctuations or supply uncertainties of global fuels.

For sustainable production, the biomass source should be chosen by taking into account not only the conversion path and CBHBP generation technologies but also biomass supply chain activities and operations. Regarding the conversion path and CBHBP generation technologies, various biomass sources need different methods for collection, storage, and transportation, in addition to preprocessing. Preprocessing

refers to any operation performed on biomass to make storage and transportation easy (chipping, baling, and densification, etc.) and to prepare biomass as biofuel feedstock before it can be used for CBHBP generation (cleaning, sizing, grinding, mixing, and sorting, etc.). The biomass supply chain, which includes all activities and operations for removing biomass from its location in the field and feeding it into the conversion unit as biofuel feedstock to be processed [128], is crucial for the sustainable use of biomass sources. Prior to a biomass energy conversion unit, biomass should be engineered to address the related conversion path requirements so that the biofuel feedstock is in a form that will potentially yield the maximum desired conversion products, in this case biopower and bioheat [56,129-131].

In addition, the biomass supply chain of a CBHBP plant is crucial for economic and environmentally responsible use of biomass sources. Since biomass is a low value commodity with low energy density and low bulk density, one of the most important cost drivers is logistics, with transportation costs contributing an important part to the total procurement costs [132]. Transportation is also the step consuming the most energy and releasing the most GHG emissions, illustrating the importance of localized use of biomass sources for energy production [133,134]. Biomass availability within a defined geographical area is essential.

Because the focus of this thesis study is on woody biomass sources, and because forests are the major source of woody biomass, the following section provides a summary of forest biomass supply chain design. The forest biomass considered below is either harvested wood logs or forest residues. While harvested wood logs originate from energy forestry or traditional firewood applications, forest residues include all biomass residues left over in forests after industrial forestry or silviculture activities, as well as fallen or dead trees killed by natural events or conditions.

2.5.2 Design of forest biomass supply chain network

Because forest biomass is a low-value commodity having low energy density and low bulk density, the beneficial economic and environmental aspects of its use for energy purposes are crucial for justifying a conversion plant. The most important cost factors for forest biomass supply chains are logistics, chipping, and storage. Logistical costs contribute an important part of the total supply costs [132]. Logistics is also the most intensive step in terms of energy and GHG emissions, which illustrates the need to

emphasize local production and use of forest biomass [133,134]. For different scenarios in a country context, in Ireland, from seedling production to ending with haulage, transportation accounts for 70–78 % of overall energy requirements and 68–75 % of GHG emissions. These are followed by harvesting operations (19–24 % of energy demand and 21–26 % of GHG emissions) [133]. In Sweden, for seven different forest biomass supply chains studied from an LCA perspective, when transport distance changed from 50 to 300 km, the increase in global warming (GW) potential was from 90% to almost 2-fold [135].

Forest biomass can be transported as comminuted material such as chips, bundles or loose material, and chipping is an efficient way of increasing material handling ability. However, material storability and long-distance transport are negatively affected because chips are more sensitive to fungal attack because of their high moisture content. Fungal attacks result in significant loss of mass, and also create a significant risk of self-ignition due to heat generation from biological activities [132,136]. It is essential to minimize emissions during storage by keeping the storage time of comminuted biomass short enough to prevent decay (up to few weeks) [137]. It is reported that chips should be used within 14 days (d) [136]. Because comminuted materials have higher storage emissions than uncomminuted materials, it is also recommended that comminuted forest residues be used without delay [138]. Contrary to wood chips, bundles can be stored for a longer time without significant mass losses. Moreover, compared with loose residues, bundles have higher bulk density. However, lower throughput, and some organizational problems caused by the independent operation of bundler and log trucks under mountainous conditions are reported disadvantages. Transport of loose forest residue is only suitable when transport distances are short (< 40 km). In Finland, loose residue transport is mostly suitable for large-scale power plants with a stationary chipper, while forest chip transport is more suitable for small-scale power plants [132].

In terms of forest biomass characteristics, it is known that harvested wood has a high moisture content; thus, a low heating value. As an example, average moisture content of roadside logging residues for Canada was 47% (wet basis) [134]. Due to its high moisture content, the weight of the material transported increases, as does its cost. Actually, moisture content is the most substantial manageable factor for determining transport efficiency. Drying, differentiated as natural and technical, improves biomass

transport efficiency. Storage of forest biomass for several months to provide natural drying increases its heating value [132]. By leaving biomass at roadside for a while, fuel quality is retained, material losses are decreased, and natural drying is promoted [134,136].

The place where comminution is carried out is also crucial. A study [134] was done of life cycle energy input and emission analysis of electricity production from forest harvest residues for a regional concept in Canada. Two chipping scenarios were compared considering forest biomass supply chains. For the first scenario, forest residues were chipped at landing; while for the second scenario, they were bundled and sent to the power plant to be chipped. In both scenarios, transportation to the power plant involved the highest energy input and GHG emissions. When the two options were compared, chipping at landings required less energy input and caused less GHG emissions than chipping at power plants. For Sweden, two forest-residue supply systems (bundle and chip systems) were compared to consider costs, CO₂ emissions, dry matter loss, and potential allergic reactions. Forwarding of residues to a roadside, chip production with a mobile chipper, and transporting chips to a conversion plant were the steps included in the chip system. The steps involved in the bundle system were compressing, forwarding to a roadside, transporting to a conversion plant, and then chipping at the plant. According to the results, the chip system had lower primary energy use and CO₂ emissions, but higher dry matter losses than the bundle system. Therefore, if dry matter losses are taken into account, the bundle system, having lower dry matter losses, gives CO₂ emissions per MWh almost as low as the chip system. In terms of cost, the bundle system has lower costs. In terms of potential allergic reactions, both systems do not differ significantly [138]. In another study [139], CO₂ emissions and primary energy use were found to be lowest for a chipping system at the roadside, which includes forwarding forest residues from forest area to a roadside, chipping at the roadside, and transporting the chips to a conversion plant. The cost is lowest for a loose material system, which includes forwarding forest residues from forest area to a roadside, and then transporting these forest residues as loose material to a conversion plant. The costs for bundle systems were found to be lower than for chip systems.

Economical transport modes (road, train, ship) for forest biomass supply are also discussed in the literature [132]. Road transport is usually suitable for relatively short

distances (< 100 km), train transport is suitable for overland distances (> 100 km), and ship transport is economic for long distances (> 800 km). However, there are too many factors influencing the economical transport distance such as transport mode, physical conditions (such as chipped, baled, moisture content, plant scale, etc.); therefore, lowest cost transport distances cannot be fixed generally. Because forest biomass is a bulk material having low energy density and low price, transport is relatively costly compared with its value. Therefore, rather short transport distances are preferred, and most studies of forest biomass transport focus on road transport [132].

It is also essential to ensure sustainable forest harvesting by considering carbon losses due to residue removal. In one study [136], the biomass removal rate from the forest floor was defined as 25% for stem tips and branches. It is important to note that such quantities are site-specific. In another study [140] about assessing agricultural and forestry residues in Spain and their potential for electricity generation, the fraction of residues to be used for energy purposes in potential areas was taken as 25% for cereals and rice residues, and 60% for fruit trees, olive trees, and vine residues. The forest residue-removal rate was not reported separately, but was included in the productivity values reported. Moreover, a technical limit for forest residues is defined so that zones with slopes steeper than 20° are not taken into account for energy purposes because of the difficulties associated with access and environmental considerations. Also, an LCA study [141] about woody biomass utilization for household heating did not consider areas steeper than 35° to avoid expensive tree trimmings.

In terms of environmental considerations about forest biomass supply chains, LCA is reported in the literature as a preferred tool for environmental assessments. The most common environmental impacts found during searches were global warming (GW), human toxicity (HT), eutrophication (ETR), and fossil energy consumption. In terms of social considerations, job and income creation were reported as commonly used and quantified social effects of forest biomass supply chains. However, further research is needed to assess social aspects [142].

In the literature, it is emphasized that further development of decision support tools is needed to quantify and optimize sustainability aspects (economic, environmental, and social) of forest biomass supply chains simultaneously, to aid their design and planning [142]. It is suggested that supply chain costs could be decreased by implementing

internet-based logistic control systems that use mobile data terminals in forests and improve work flows [132].

Table 2.5 shows some options of forest biomass supply chains on the basis of the place (forest, roadside, terminal, conversion plant) where comminution is carried out, and the material to be transported (comminuted material such as chips or loose material) to the conversion plant (Adapted from [132]). Chipping operations can take place in the forest (terrain chipping), at a roadside landing, at a terminal, or at the power plant. Terrain chipping occurs with terrain chippers equipped with a chip container. The load is tipped into a truck trailer, and then is transported to the power plant. Chipping at a roadside landing is a traditional option of forest biomass supply chains and occurs with mobile chippers at the roadside. With mobile chippers, forest biomass is usually chipped directly into a solid fuel transportation vehicle by means of the outlet pipe of the chipper. In case of chipping at the plant, mobile chippers are replaced by stationary crushers appropriate for comminuting all types of biomass. However, loose material has to be transported in this case. Terminal chipping is a compromise between chipping at the roadside and at the plant. A terminal is usually preferred to control the procurement process. To increase the bulk density of the loose material to be transported, bundling can be applied either in forest or at the roadside.

2.5.2.1 Chipping at roadside

The second option among others listed in Table 2.5 is the one that is mostly used in the countries where forest biomass is used for energy purposes [137,138,143-145]. When designing a forest biomass supply chain system for energy purposes in Turkey, the predominant forest biomass supply chain system (chipping at a roadside landing and transporting the chips to the conversion plant) could be taken as a starting point [146].

Below are the steps and details of the second option.

- Collecting and forwarding of forest biomass to the roadside landing
- Storage and natural drying
- Wood chip production
- Wood chip transportation from the roadside landing to the conversion plant
- Wood chip feedstock preparation in the plant

Table 2.5 : Some options of forest biomass supply chains on the basis of the place where the comminution is carried out and the material to be transported [28,132].

Options	Place of comminution				Material to be transported	
	Forest	Roadside	Terminal	Plant	Transport-1	Transport-2
1	Chipping	-	-	-	Chips	-
2	-	Chipping	-	-	Chips	-
3	-	-	-	Chipping	Loose material	-
4	-	-	Chipping	-	Loose material	Chips
5	Bundling	-	Chipping	-	Bundles	Chips
6	-	Bundling	Chipping	-	Bundles	Chips
7	Bundling	-	-	Chipping	Bundles	-
8	-	Bundling	-	Chipping	Bundles	-

Either a wheeled loader and a tractor with trailer, or a conventional forwarder, can be used to collect harvested wood logs and forest residues remaining in forests. The terrain haulage is done to forward the collected biomass to the roadside. While a wheeled loader collects the forest biomass into a tractor's trailer to forward to the roadside landing, a forwarder can do both by means of its mounted grapple for loading and unloading biomass. A forwarder is basically a tractor with a trailer and a grapple.

Storage and natural drying of forest biomass are essential because the energy content and transportation cost of forest biomass is directly related to its moisture content. Reducing the moisture content of forest biomass by natural drying is the simplest and cheapest method to increase its energy content and reduce its transportation cost. Therefore, it is crucial to leave uncomminuted biomass some place (either at roadside or at a terminal) in the biomass supply chain (for an interval of a few months to 1–2 years) to allow for natural drying to take place. The aim is to decrease moisture content, thereby increasing the biofuel quality and transport efficiency. Moreover, forest biomass should be stored and dried prior to wood chip production because wet wood chips decompose rapidly. However, depending on the biomass supply chain strategy, the biomass feedstock could be comminuted before storage as well.

Forest biomass is generally stored in big stockpiles at the roadside under top cover in the most wind-exposed location for at least one summer (i.e., with good air flow to promote rapid drying). The tops of the stockpiles are covered either during the stockpiling or at the latest, before the rainy season. It is reported that, during summertime, the stockpiles can dry effectively from the initial moisture content of 50% to around 30% by weight. The stockpiles of forest residues can be made as high as possible (i.e., up to 5 m), but cannot be too close together or this will slow down the drying process. The forest residues can be hauled to the roadside all year round from the surroundings. On the other hand, the forest biomass in the forests also dries as fast as in the stockpiles. Thus, it is recommended that the forest residues that come out during spring and summer should be left to dry in forests before forwarding them to the stockpiles [57,147,148].

Chippers can either be locally fixed in the CBHBP plant or movable (on a forwarder, trailer, etc.) to operate on site (i.e., mobile chippers). In the production of forest wood chips, the cost determines the approach. Wood chip production occurs at the roadside landing with mobile chippers. Forest biomass is usually chipped directly into a solid

fuel transportation vehicle by means of the outlet pipe of the chipper. This can be turned sideward to direct the chip-stream either to the ground or directly into a long-distance transportation vehicle. The objective of directly chipping to a transportation vehicle is to eliminate the need for chip storage at the site and to prevent any foreign materials such as gravel and rocks from being picked up when the chips are loaded into the delivery vehicle. Chipping of naturally dried woody biomass can be carried out all year round [57].

Depending on the transport distance between biomass acquisition and production sites (i.e., short, medium or long) different means of transport can be used. Tractors with trailers are preferred for short transport distances such as 10 km. Trucks are used for medium- and long-distance transport of all kinds of woody biomass such as logs, chips, unchipped residues, bales, etc. Trains and ships are usually used for long distances [148]. The choice of truck depends on the quantity of the load and also the receiving system in the biofuel preparation yard in the CBHBP plant. To minimize the environmental, economic, and social impacts of biomass transportation, the average distance of the sources from the power plant must be kept as short as possible. The highest transportation cost of wood chips with a moisture content of 50% is reported to be for 50 km [149].

After delivering wood chips to the plant, they have to be prepared before use as wood chip feedstock in the plant. Removal of metals (and other noncombustible materials), sizing, and size reduction are the basic operations. Wood chips are then conveyed into a buffer storage to be used in CBHBP plant [56,150,151]. The following subsection gives information about the biofuel feedstock preparation yard of a CBHBP plant using wood chips.

2.5.2.2 Biofuel feedstock preparation yard of a CBHBP plant using wood chips

Biomass sources have to be prepared before being used as biofuel feedstock in a biomass energy conversion process to produce biopower and/or bioheat. Receiving, processing, storing, and delivering of biomass feedstock to the conversion process comprise the preparation fuel yard (prep-yard) of a biomass energy facility. A prep-yard configuration may include manual or automatic systems depending on the size of the facility. Automatic systems are primarily used for large-scale installations requiring biofuel supply of greater than 100 t/d.

Of the prep-yard steps, the receiving systems for wood chips include equipment such as a ramp, loading dock, storage area, front-end loaders, bulldozers, hydraulic dumpers, self-unloading and live-floor systems, conveyors, radial stackers, etc. A fully automated system, such as used for large-scale installations (> 100 t/d), includes hydraulic dumpers able to lift a whole truck and empty its load into a live-bottom receiving hopper. Wood chips are then conveyed to a storage pile where an automated radial stacker is used to stack them on the pile. For smaller installations either self-unloading trailers with live-floor systems (10–50 t/d) or hydraulic dumpers (50–100 t/d) are used to unload the wood chips and front-end loaders or bulldozers to stack them on a storage pile. Because a significant land area is required for biomass feedstocks, storage is one of the first considerations in the design of a preparation yard. Mostly open or covered storage or a combination of them, and to a lesser extent silos, can be used. Basically, the storage area size should be adequate to supply biomass feedstock, but also considering the amount needed to carry the plant through possible supply shortages. The design of the preparation yard must also be considered. Moisture and foreign materials are the most important problems during woodchip storage. For wood chips, storage pile management (maximum height, residence time, first-in, first-out system, odor control) is critical to minimize biological degradation, heat buildup, prevent spontaneous combustion, and avoid odor problems. Storage areas in the preparation yard are paved to prevent the incidental scraping up of foreign materials with the wood chips. Hence foreign materials do not cause a problem in storage nor in biofuel preparation.

Processing of wood chips include removal of metals or other noncombustible materials, sizing, and size reduction. After magnetic separation, a disc screener rejects oversized materials and sends them to a grinder or hogger to be properly sized. If drying is needed, this occurs after sizing. The processed feedstock, the biofuel, to be used in the boiler is conveyed to buffer storage (24 hour (h) supply). From buffer storage, biofuel is metered and pneumatically transferred into the boiler via a surge bin. Conveyor belts are used wherever necessary in the prep-yard [56,150,151].

2.5.3 Primary conversion technologies

The technologies to convert and utilize biomass energy are today almost as varied and diverse as the types of biomass sources. There are several potential CBHBP conversion

paths and technology options. In Figure 2.11, the primary and secondary conversion technologies are indicated based on the conversion paths, which are thermochemical or biochemical.

Thermochemical conversion paths are appropriate for solid biomass sources since they use heat, in addition to pressure and catalysts, to ensure thermal decomposition of biomass and transformation of plant polymers into transportation biofuels, biochemicals, biopower, and bioheat/biocold. This contrasts with biochemical conversion paths of biomass that use enzymes and microorganisms as biocatalysts in addition to heat and other chemicals for the same purpose, and are mostly appropriate for wet biomass sources.

Among the commercial primary conversion technologies of CBHBP plants, combustion is the complete oxidation of biomass in excess air, where the biomass components are converted into their respective oxidized forms producing hot gases. Co-combustion (co-firing) is the simultaneous combustion of two or more fuels in the same plant so that biomass is introduced as a supplementary energy source primarily with coal and lignite, especially in existing large power plants. Gasification is a process converting solid biomass to a combustible gas mixture via partial oxidation. The terms used for the combustible gas mixture generated through gasification are product gas, producer gas, and synthesis gas or syngas. Biomass gasification conversion technology is still under development and is not widely utilized globally. However, it is likely to become commercially available and to play an important role in future biomass energy portfolios. Anaerobic digestion is a well-developed, commercial conversion technology. Biogas and landfill gas are produced by an anaerobic digestion process that converts mostly wet biomass to a gas, consisting mainly of methane (CH_4) and CO_2 , through biological processes. Landfill gas is a result of the decomposition of organic materials in landfills [123,125,148,152-159].

Biomass has gained great attention as a substitute for fossil fuels because biomass is the only fuel available to achieve renewable and combustion based power generation, and biomass combustion is generally accepted as a carbon-neutral process. At present, combustion is the primary approach to produce bioheat and/or biopower from solid biomass sources [160,161]. In addition, co-combustion of biomass with coal and lignite in large power station boilers is receiving great attention worldwide. The

potential of large-scale biomass power plants is limited because of transportation distances and cost issues. Co-combustion is seen as one of the most cost-effective way of CBHBP production having a high electrical efficiency for large-scale plants [148]. There is another complementary approach currently being developed in Europe involving the conversion of coal fired power plants that are close to the end of their lifetime to biomass-only plants. This can be achieved at lower costs, similar to those achieved through co-combustion [162].

2.5.4 Secondary conversion technologies

Secondary conversion technologies, as indicated in Figure 2.11, include the following systems: steam turbine, steam engine, Stirling engine, organic Rankine cycle (ORC), internal combustion engine (ICE), gas turbine, microturbine, and fuel cell. Today, steam turbine systems are the dominant commercial conversion path, and are seen as secure and reliable due to their established technological record [31,163,164]. For existing CBHBP plants with solid biofuels in European countries, direct combustion coupled with steam turbines has been reported as the most applied technology (57%) followed by steam engine systems (19%), gas turbines (9%), ORC (7%), and Stirling engine (3%) [126]. The most commonly adopted technology in Finland and Sweden for CBHBP plants in the 2–20 MW_e biopower output range is combustion in a fluidized bed (FB) with a steam turbine [32]. FB combustion has been reported as the best technology for burning solid biofuels [165]. At smaller scales below 1000 kW_e biopower output, microturbines, Stirling engines, fuel cells, and ICE are seen as promising technologies. We note that biomass availability and biofuel types (solid, liquid or gaseous) are important factors in the use of a particular technology. At scales less than 1000 kW_e biopower output, for solid biofuels Stirling engines can be used; for liquid biofuels ICE, microturbines, fuel cells as well as Stirling engines can be used; and for gaseous biofuels any of the technologies mentioned above can be used. Below is a summary of the development status of secondary technologies and their possible applications.

Steam turbines are known for their long working time, high reliability, high overall efficiency, and low maintenance costs, but suffer from a slow start-up time. The available steam turbine sizes applicable to biomass power plants are between 0.05 and 250 MW_e [56,166]. On the other hand, steam turbine systems are generally

economically and technically feasible for plants with a scale more than 2 MW_e [35,167]. With a steam turbine system, any type of biofuel can be used. However, the most common biofuels utilized are solid biofuels such as wood chips, pellets, forest residues, bark, and sawdust. Today, of all the technologies suitable for solid biofuels, combustion coupled with steam turbine, the conventional Rankine cycle, is the most widely used commercial technology that results in a well-proven and mature steam turbine technology [30,32,56,122,123,164].

Steam engines use the same operation principles as the conventional Rankine cycle except that an engine is operated rather than a turbine [32]. The steam engine is a well-proven traditional technology and commonly used for industrial applications. However, in recent years, due to their low efficiency and low power-to-heat ratios, steam engines have largely been changed by more effective and economical systems such as steam turbines [33,164]. Available sizes of steam engines applicable to biomass power plants are between 0.01 and 1.5 MW_e [168].

The Stirling engine, an external combustion engine, is named after Robert Stirling, the inventor of the thermodynamic Stirling cycle. Since combustion occurs externally, this technology is suitable for any type of biofuel, solid, liquid, or gaseous. Low noise and low maintenance requirements make the Stirling engine an alternative for residential houses and other micro-scale applications [30,56,164]. Available sizes of Stirling engines applicable to biomass are between 0.01 and 0.15 MW_e [56,168,169]. Today, this technology is still under development. High investment cost is the main drawback of Stirling engine systems [32,56].

The ORC technology is a promising, well-known technology, and has been commercially available since its first successful demonstration in 1999 [35]. The ORC systems use the same working principle as the conventional Rankine cycle systems except that water as a working medium is replaced by an organic fluid such as toluene, propanol, isobutane, or chlorofluorocarbons. These organic fluids evaporate at lower temperatures than water, making ORC operate at lower temperatures and pressures than conventional steam cycle systems. This enables the use of fuels with low heating values such as biofuels without lowering the efficiency. The ORC technology ensures high efficiencies for low temperature heat sources [30,32,148,170]. The possible heat sources other than biomass include geothermal, solar, and industrial heat recovery

applications. The ORC systems for biomass sources are generally available at biopower outputs ranging from 0.2 to 15 MW_e [171]. For distributed CBHBP applications, ORC systems up to 6 MW_e have been reported as suitable and highly developed. Technological developments are still ongoing to reduce investment costs and to increase the electrical efficiency of ORC systems [35].

Reciprocating ICEs (Otto-spark ignition and Diesel compression ignition engines) are well-known and very common technologies widely used for transportation vehicles. They are also used to generate electricity, and heat through heat recovery applications. Liquid or gaseous biofuel is combusted in an internal combustion chamber [30]. While Otto engines are competitive for biomass power plants below 2 MW_e (0.002–2 MW_e), Diesel engines are more appropriate for larger scale plants (0.05–50 MW_e) [32].

Gas turbines have been used for power production for years. A gas turbine is an ICE operating by rotational rather than reciprocating motion, and requires a gaseous fuel. The compressed gaseous fuel is combusted in the combustion chamber and then combustion gases expansion occurs in the turbine. A biomass gas turbine therefore requires either biogas or landfill gas or a biomass gasifier to produce the product gas for the turbine [56]. When a biomass gasifier, a gas cleaning system, and a “Heat Recovery Steam Generator” (HRSG) are used with a gas turbine, the system is named “Biomass Integrated Gasification Combined Cycle” (BIGCC). BIGCC is a highly efficient process, but still under development [122]. The main drawback is that the existing natural gas based turbines need modifications and cannot be easily retrofitted to operate on low heating value gaseous biofuels such as product gas. On the other hand, there are many gas turbines operating on the medium heating value gas generated by landfills. The available gas turbine sizes applicable to biomass power plants are between 0.5 and 40 MW_e [56].

Microturbines are smaller gas turbines that can burn not only gaseous but also liquid biofuels. They are suitable for smaller scale applications, and the size range for microturbines is between 0.025 and 0.5 MW_e [32]. Due to their design simplicity, less maintenance is required compared to reciprocating engines. However, they have lower electrical efficiencies than similar reciprocating engines [56].

Fuel cells require hydrogen for operation. Using hydrogen directly as a fuel source is generally impractical, therefore hydrogen is derived from hydrocarbon fuels or

gaseous biofuels (product gas, biogas, and landfill gas) using a reformer (biomass to fuel cell systems). In fuel cells, there is no combustion, and the fuel is chemically combined with oxygen for electricity production while heat is a byproduct. Fuel cells are appropriate for decentralized power production, and have high electrical efficiency and low emissions. Today, biomass to fuel cell systems are highly scalable, ranging from laptop computers (50–100 watt (W)) to power generation (0.2–2 MW_e). They are still under development and their investment cost is quite high [32,56,172].

The most established path to produce CBHBP is the steam turbine technology based on combustion. The following section provides a flow diagram of a typical steam Rankine cycle CBHBP production along with some technical features of actual CBHBP plants based on combustion and steam turbine technology.

2.5.5 CBHBP production based on combustion and steam turbine technology

A schematic flow diagram is shown in Figure 2.12 for a typical steam Rankine cycle CBHBP plant with a steam turbine of the back-pressure type for maximum steam production.

First, biomass has to be prepared before use as biofuel feedstock in the boiler. The biofuel preparation operations of the CBHBP plant comprise receiving, processing, storing, and delivering of biomass to the conversion unit. The biofuel feedstock is conveyed into buffer storage, and from there, biofuel is metered and transferred into the boiler [56,150,151].

In the figure, the boiler is made up a furnace (combustion chamber) and a heat transfer section. The most commonly used types of boilers are either fixed bed or FB boilers. Fixed bed boilers include either stoker or grate furnaces. A modern stoker, in the furnace part of the boiler, consist of a biofuel feeding system, a grate to support biofuel and provide combustion with a primary air supply system, an overfire secondary air supply system for complete combustion and minimum emissions, and a discharge system for ash. The most commonly used stoker type is spreader stoker, which is an overfeed stoker. Stoker furnaces are best suited for applications up to a nominal boiler capacity of 6 MW thermal (MW_{th}). The technologies for grate furnaces include fixed grates, moving grates, traveling grates, rotating grates, and vibrating grates. Grate furnaces are appropriate for biomass sources having a high moisture content, high ash

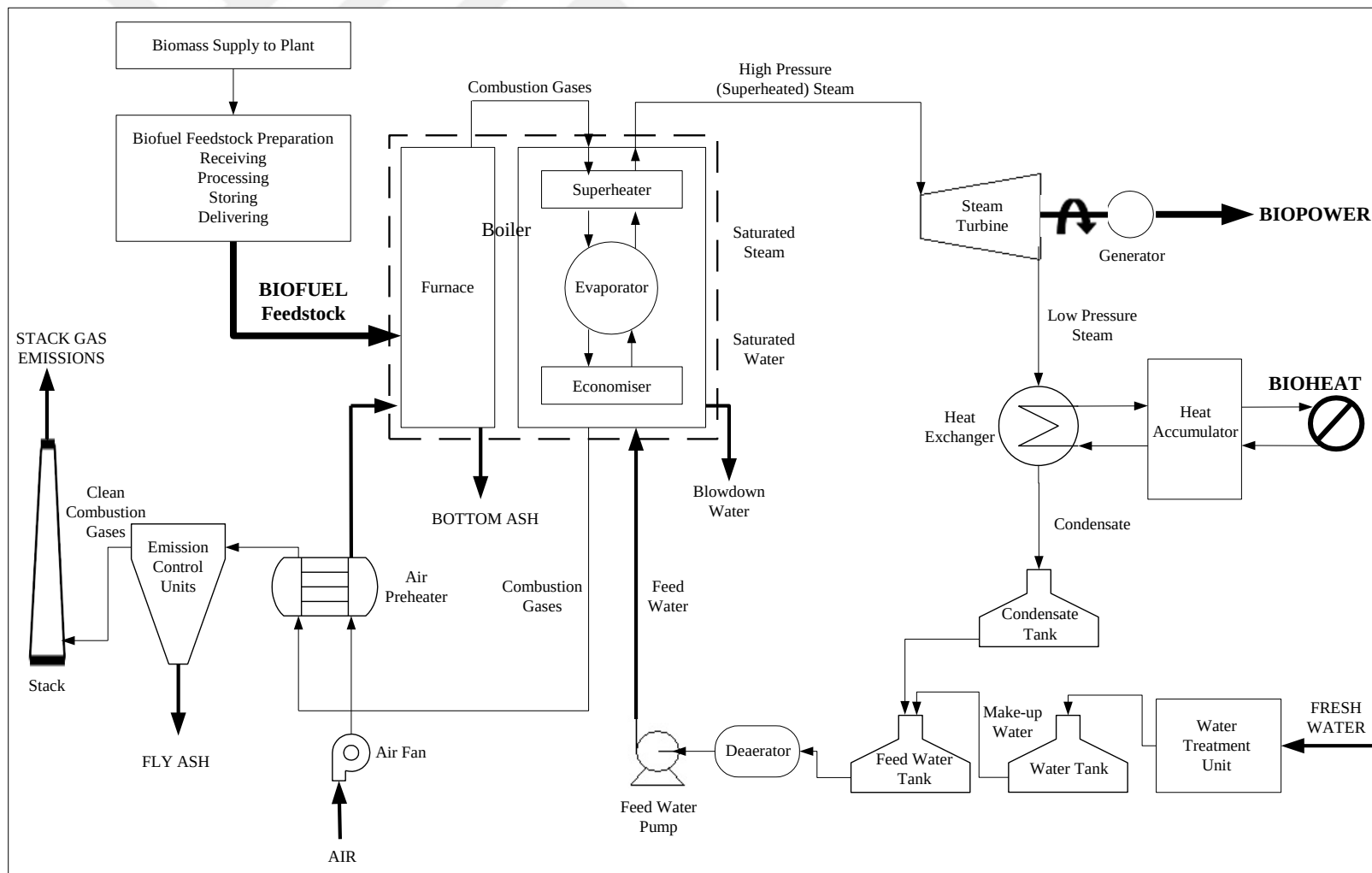


Figure 2.12 : A schematic of a Combined BioHeat and BioPower plant power cycle based on combustion with steam turbine technology [27].

content, and different particle sizes. Primary air crosses through a fixed fuel bed producing combustible gases. Secondary air is provided to burn the combustible gases, generally in a combustion zone detached from the fuel bed. Grate combustion is suitable for applications up to 30 MW_{th} [56,148,150,151,173,174]. FB boilers have an initially stationary bed of inert solid material with good heat conducting ability such as silica sand connected to a nozzle gas distributor. The combustion air is supplied through the distributor and hence the bed material is fluidized. On the basis of fluidization state, two basic types of FB are bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). Compared with stoker boilers, FB boilers enable nearly complete combustion. They are mostly applied for large-scale installations above 20 MW_{th}. For smaller installations, investment and operation costs are usually higher. This is mainly due to the need for more efficient boiler cleaning systems [148,165,173,175]. Correctly installed and maintained modern biomass boilers tend to have an efficiency of approximately 80-90% [176,177].

Combustion takes place after the biofuel is pneumatically transferred into the furnace section of the boiler. During combustion, the optimal value of excess air ratio (λ) depends on the biomass fuel, combustor design, and operational conditions. Typical values of λ for high standard biomass combustion systems are from 1.5 to 2 [178,179]. For wood fuels, typical values for well-designed biomass combustion systems are reported as between 1.6 and 2.5 [180]. In small-scale biomass combustion applications, λ is usually above 1.5 [148], although values of 1.2–1.5 are possible [181]. Typical combustion temperature ranges in biomass systems are reported as 740–1300°C [182], and 850–1400°C [180]. However, to minimize rapid thermal formation of NO_x, to keep the furnace temperature below the ash deformation temperature, and to protect the boiler from internal damage, combustion temperatures are typically maintained at no more than 1200°C [178,179,183]. Biofuel is burned in the furnace to produce hot flue gases (combustion gases), which then produce high pressure and high temperature steam by water absorbing the heat from the hot flue gases in the heat transfer section of the boiler.

The steam, at high temperature and high pressure, is then introduced into a steam turbine generator causing the turbine to rotate and produce biopower. The thermal energy in high pressure and high temperature steam is converted into mechanical energy or shaft power by the steam turbine. The mechanical energy from the steam

turbine is used to drive a generator and produce biopower. The characteristic values for isentropic efficiency of steam turbine generators are reported at between 0.8 and 0.9 [184]. The low pressure and low temperature steam from the steam turbine flows into heat exchangers to produce bioheat. The exhaust pressure of a back pressure steam turbine is typically between 1 and 8 bar [185]. To satisfy an existing heat demand with the recovered thermal energy, the low pressure steam leaving the turbine, which still contains mostly vapor, is sent to a process, facility, or district, etc., where it condenses back into water. Heat accumulators may be used to optimize the load of the boiler for consumption peaks or to run the CBHBP plant with full power when the price of electricity is high [33]. The condensed steam from the heat exchangers is sent to a feed water tank. After that, it is partially or fully returned to the boiler by pressurizing to the appropriate boiler feed pressure with a pump. The representative values for isentropic efficiency of pumps are reported to be between 0.8 and 0.9 [184].

To preheat the combustion air, a heat exchanger is used to recover the heat from the flue gases leaving the boiler. Practically, typical temperatures for air prior to introduction to a combustor are 200–300°C. If biomass drying is needed, waste heat can also be utilized to dry biomass, thus improving the overall efficiency of the CBHBP plant. However, a common practice for biomass combustion systems is not to dry the feedstock before the boiler. Drying takes place in the boiler [103,150,186,187].

For removal of pollutants arising from biomass combustion, it is crucial that the flue gases are sent to cleaning systems. Flue gas cleaning consists of removal of particulates, water soluble gases such as sulfur dioxide (SO₂), NO_x, and toxic materials, if present. Examples of various technologies for removing pollutants are cyclones, electrostatic precipitators (ESPs), bag filters, and scrubbers. Hybrid solutions are also possible [188]. Thereafter, the clean flue gases are sent to the stack. In practice, the temperature of flue gases going to the stack should be kept above 120°C (between 120 and 200°C) to prevent the condensation of water vapor in the flue gases [178,180,189].

Biomass combustion also produces solid waste, namely ash. Bottom ash discharged from the furnace and fly ash collected from emission control units (cyclones, ESPs, etc.) are combined into an ash silo. Biomass ash is mostly beneficial and used as a soil additive because of its large quantities of some ingredients such as phosphorus and

potassium [9,10,190]. Both the bottom and fly ash of the CBHBP plants can be utilized as a fertilizer in forestlands and farmlands or as a material (road base) for land construction. Although the ash can be transported to a nearby landfill for disposal, it is recommended this practice should be a last resort, since ash marketing rather than disposal is more cost effective [56,148,150,151,173].

2.5.6 Commercial CBHBP plants based on combustion and steam turbine technology

Some basic technical data are presented in Table 2.6 for selected commercial CBHBP plants that are in operation and belong to the largest biopower producing countries. The data have been compiled through research articles, reports, or websites of these CBHBP plants. Cross checks have been made for each plant via different references, and in the case of an inconsistency, the plant was not included in Table 2.6. In addition, the focus is on the steam turbine systems based on direct combustion technology, which is the primary approach of most of today's commercial biomass power plants producing biopower and/or bioheat. For the present review, CBHBP plants fueled with solid biofuels are of more interest since steam turbine technology is mostly used with solid biofuels. Of course, each plant is constructed for a specific purpose, and a generic comparison is not possible. Moreover, in order to compare and evaluate the different CBHBP plants, not only technical data but also economic, environmental, and social performance data are needed. However, the aim is to outline different examples, and to get a view of them in one place. The purpose is to summarize the basic technical data of some of the existing commercial CBHBP plants based on combustion and steam turbine technology.

The table lists boiler technology, biofuel feedstock, biofuel input (MW), biopower output (MW_e), bioheat output (MW_{th}), CBHBP electrical efficiency (%), CBHBP total efficiency (%), and location and name of each plant, together with its start-up year. In the table, boiler technologies are either fixed or FB. Fixed bed boilers include the technologies of either grate or biograte, which is a new moving grate technology. FB boiler technologies have either bubbling (BFB) or circulating (CFB) designs. Great care has been taken to include data for all plants on the same basis, so that efficiencies are based on the low (net) heating value (LHV) of the biofuel feedstock, and biopower

Table 2.6 : Combined BioHeat and BioPower (CBHBP) plants currently in operation and based on combustion of solid biofuels with steam turbine technology (Compiled from the sources indicated) [27].

Boiler Technology	Biofuel Feedstock	Biofuel Input (MW)	Biopower Output (MW _e)	Bioheat Output (MW _{th})	CBHBP Electrical Efficiency (%)	CBHBP Total Efficiency (%)	Location	Plant Name	Start-Up Year	Reference
Grate	Wood chips, biowaste	3.8	0.6	2.7	16	86	Denmark	Hjordkær	1997	[191,192]
Grate	Wood chips (35% from forest residues, 65% from saw industry)	9.8	1.3	6.3	13	78	Austria	Reuthe	1995	[193-195]
Grate	Sawdust	10	2	7	20	90	Sweden	Myresjöhus	1994	[33]
Grate	Straw	10.5	2.3	7	22	89	Denmark	Rudkøbing	1990	[33,192,196,197]
Grate	Wood chips, sawdust	17.3	4.7	10.3	27	87	Denmark	Assens	1999	[191,192,198,199]
CFB	Wood residues	20.1	4.8	12.9	24	88	Finland	Kuhmo	1992	[36,200]
BFB	Peat, wood	26	6	17	23	89	Finland	Kankaanpää	1992	[36]
Grate	Wood chips (forest residues, saw industry)	26.7	7	13.7	25	76	Germany	Pfaffenhofen	2000	[201,202]
Grate	Wood chips, municipal waste	35	7	23	20	85-90	Sweden	Bäckelund	2009	[32]
BFB	Bark, wood residues, wood chips	35	8	22 + 8 ^a	23	109 ^b	Sweden	Falun	1993	[36,203]
Biograte	Wood from forestry products, sawmill residues, clean recycled wood	37	8	25	22 ^c	89 ^c	France	Cofely-SODC Orleans	2015	[204]
Biograte	Wood from forestry, uncontaminated residues from wood processing	55	9	36	16 ^c	82 ^c	France	Cofely-Bio Cogelyo Normandie (BCN)	2011	[205]
Biograte	Clean wood	35	9	22	26 ^c	85-87	Austria	Linz Mitte	2005	[206,207]
BFB	Wood	86	10	64	12	86	Finland	Ristiina	2002	[208]
BFB	Wood	36	10	22	28	89	Sweden	Sala	2000	[36]
BFB	Forest residues, bark, sawdust, peat	42	11.7	26 + 7 ^a	28	106 ^b	Sweden	Härnösand	2002	[36]
Grate	wood chips (saw industry, forest residues)	60	13	38	22	85	Germany	Neumarkt	1997	[201,206]
Grate	50% wood, 50% peat	60	13	36	22	82	Sweden	Hudiksvall	1992	[36,203]
CFB	Wood	50	14	28	32	84	Sweden	Lycksele	2001	[36]
BFB	Peat, wood, refuse-derived fuel	48	14.7	30	31	93	Finland	Iisalmi	2002	[36]
CFB	Wood chips	65.7	15.1	37	23 ^c	80	Austria	Vienna Simmering	2006	[209]
BFB	Bark, wood, peat	81.1	17	56	21	90	Finland	Kotka	2003	[208]
BFB	Bark, wood, peat	81	17	53	21	86	Finland	Savonlinna	2003	[33,208]
Biograte	Wood	50	17	25	34 ^c	84 ^c	France	Cofely-BES VSG	2015	[210]
BFB	Wood, refuse-derived fuel	71.7	17.2	48	24	91	Finland	Forssa	1996	[36,211]
BFB	Peat, wood	80	20	50	25	89	Finland	Kokkolan	2002	[36,200]
BFB	Non-industrial round wood, logging residues, wood chips, stumps, peat	73	21	48	29 ^c	95 ^c	Finland	Kerava	2009	[212]
Grate	65% wood residues, 20% bark, 15% wood shavings	92	24	55	26	86	Sweden	Enköping	1994	[203,213]

^a The bioheat produced by flue gas condensation. ^b Since the plant is equipped with a flue gas condensation system; total efficiency is above 100%. ^c Calculated value.

and bioheat outputs are gross figures, i.e., the plants' own consumption of biopower and bioheat are not deducted. CBHBP electrical efficiency (or electrical generating efficiency) is a measure of the amount of biofuel energy converted into biopower. It is a function of the biopower output and the total biofuel input. On the other hand, CBHBP total efficiency (or cycle efficiency) is a function of the biopower output, the bioheat output, and the total biofuel input.

The solid biofuels used in the plants reviewed are wood chips from various woody biomass sources such as residues from forests, logging, the sawmill and forestry products industries, non-industrial round wood, bark, stumps, and clean recycled wood. Table 2.6 includes CBHBP plants with biopower output capacities ranging from 600 kW_e to 24 MW_e. These plants are either district heating or industrial CBHBP plants.

In terms of scales of the CBHBP plants in the world, up to medium-scale distributed plants (up to 20 MW_e) are used more due to scarce availability of local feedstock and high biomass transportation costs [29-36]. As well as economic and technical factors, the scale of a CBHBP plant is dictated by logistics and must be compatible with the availability of local biomass sources [123]. Regarding the bioheat output of a CBHBP plant, it depends on the site-specific conditions, and is mainly determined by the possible existing heat demand. As a consequence, the amount of the existing heat demand is another limitation for the scale of a CBHBP plant in addition to logistics [214]. For existing CBHBP plants with solid biomass in European countries, 44% have a biopower output between 1 and 20 MW_e, 35% less than 1 MW_e, and only 15% higher than 20 MW_e, while the output of 6% is unknown [126]. CBHBP systems with a biopower output less than 100 kW_e (micro scale) are particularly suitable for applications in commercial buildings, such as hospitals, schools, industrial premises, office building blocks, and domestic buildings of residential dwellings [122].

Since CBHBP schemes are most efficient when there is a local and stable heat demand, industries that would like to produce their own electricity using their own biomass residues are another very important and appropriate area for distributed CBHBP applications [215]. This alternative allows industrial users to reduce their energy costs and, in some cases, to sell their excess energy. The forest products industry, which is characterized by significant amounts of wood residue generation, has been

increasingly investing in cogeneration processes [216]. Other major sectors using CBHBP are the food-processing, chemical, and paper industries. These industries can improve their energy efficiency by more than 35% by utilizing the generated heat and steam in their processes [56]. CBHBP is seen as a way for industries to improve their carbon credentials without changing their fuel and heat demand [215]. This alternative has been increasingly adopted by many industries worldwide.

Figure 2.13 shows the electrical and total efficiency (%) of the CBHBP plants listed in Table 2.6. The efficiencies are provided in relation to biopower output (MW_e), together with the boiler technology type (grate or BFB and CFB). For the selected plants ranging from 600 kW_e to 24 MW_e , CBHBP electrical efficiencies range from 13% to 34%, with most between 20% and 30%, and an average of 24%. CBHBP total efficiencies are between 76% and 109%, with most between 80% and 90%, and an average of 88%. Two of the plants in Table 2.6 have a total efficiency over 100%. These plants are equipped with flue gas condensation systems that increase their heat production and cause their total efficiencies to rise to over 100%. In relation to boiler technologies, although it is not possible to make an absolute comparison, the data in Table 2.6 and Figure 2.13 show higher efficiencies for FB combustion technology, with averages of 25% for electrical and 91% for total efficiency, while those for grate technology are 22% and 85%, respectively.

In terms of efficiencies of CBHBP plants, electrical, thermal, and total (thermal + electrical) efficiencies depend very much on the scale, technology, and configuration used in the plants. For example, in Europe for CBHBP plants with biopower output less than 1 MW_e , high electrical efficiencies above 20% and relatively low electrical efficiencies below 10% are possible [126]. For scales between 0.5 and 100 MW_e biopower output and for conventional Rankine cycles, electrical efficiencies between 20% and 30% and total efficiencies between 85% and 93% were reported [36]. In Sweden, CBHBP plants ranging in scale from 8 to 20 MW_e biopower output relying on conventional Rankine cycles have electrical efficiencies from 20% to 32%, while total efficiencies are over 85%. In Finland, CBHBP plants ranging from 5 to 20 MW_e biopower output relying on conventional Rankine cycles have electrical efficiencies from 22% to 25%, and total efficiencies reaching as high as 93% [32]. At a scale between 10 and 50 MW_e , electrical efficiency for biopower generation, not in cogeneration mode, using steam turbines was reported as ranging from 18% to 33%.

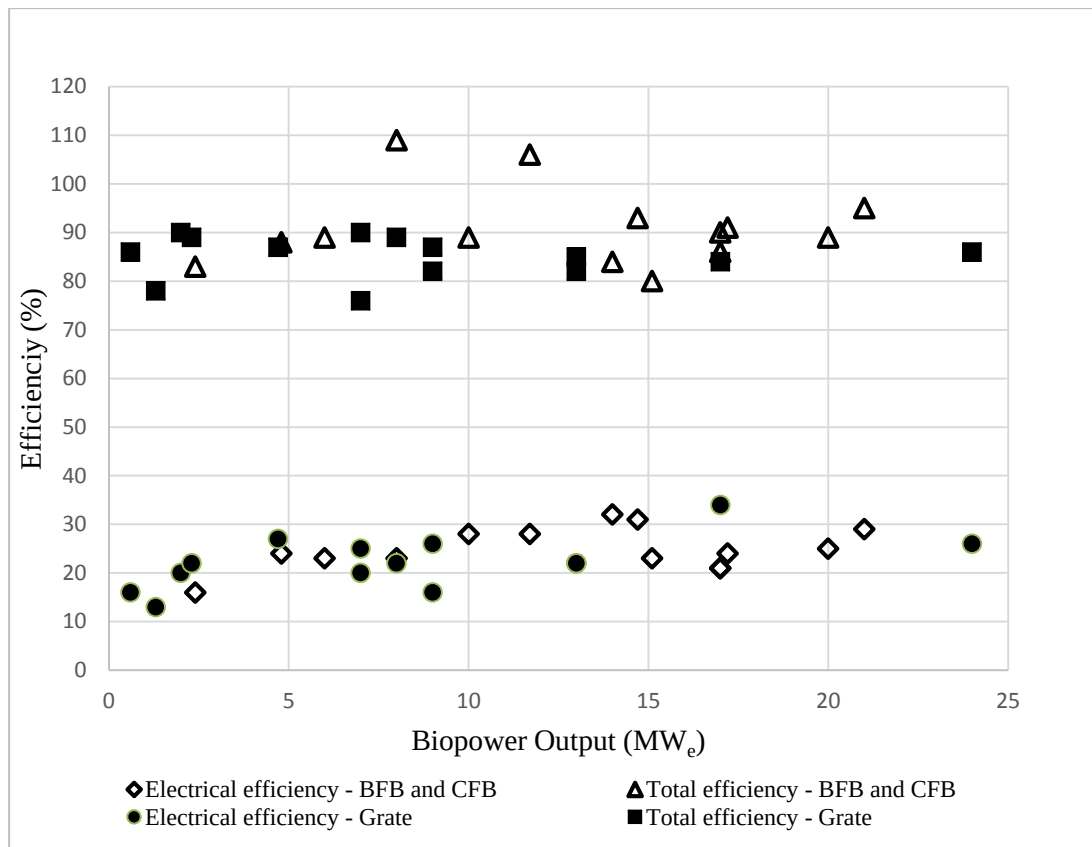


Figure 2.13 : Electrical and total efficiency (%) of Combined BioHeat and BioPower plants currently in operation and based on combustion of solid biofuels with steam turbine technology (BFB is for bubbling fluidized bed, CFB is for circulating fluidized bed) [27,32,33,36,191-213].

For cogeneration mode, overall efficiencies were reported in the range of 80–90% [123,161]. In general, electrical efficiency increases with biopower output [30,126]. In modern CBHBP plants, using high quality wood chips with maximum steam temperature for conventional Rankine cycles, electrical efficiency can reach 33–34% [29,123]. At scales less than 50 kW_e biopower output, 25–26% is reported as the current limit for electrical efficiency [30]. In general, at smaller scales, electrical efficiency is relatively low since small CBHBP applications are usually designed to satisfy an existing heat demand, and hence biopower production is a positive side effect. On the other hand, larger scale plants are usually oriented to produce biopower, and therefore bioheat production is a positive side effect [126].

2.5.7 Distinctive characteristics of biopower production

Among other renewable-based power production options, biopower has some distinctive characteristics that should be taken into account for sustainable

implementation. This section provides a summary of the basic characteristics of biopower production.

Biopower plants, like fossil fuel based power plants, can operate at high capacity factors and are able to provide base load power without any supplementary energy storage facilities. Biomass feedstocks can be stored and continuously used for biopower production, unlike some intermittent renewable-based energy sources such as solar and wind that show variability on an hourly, daily, and/or annual basis [122,217,218].

Biopower can be produced in a biorefinery concept. Among all the renewable-based energy sources, biomass is unique since it is the only carbon rich material source available on Earth besides fossil sources. Consequently, while power and heat can be produced by a variety of renewable-based energy sources other than biomass such as wind, solar, and hydro, the only alternative to fossil sources to produce fuels, chemicals, and materials is biomass. In this context, the biorefinery concept has arisen: “the sustainable processing of biomass into a spectrum of marketable products and energy” [17]. Biorefineries convert biomass into energy carriers (biofuels, biopower, bioheat, and biocold) and a range of useful products (biochemicals and biomaterials), including food and feed [18]. The importance of biorefineries lies behind the sustainable utilization of biomass feedstock, i.e., maximizing its value while minimizing waste. The goal of biopower production should be sustainable utilization of biomass sources based on consideration of the biorefinery concept.

Biopower production can be impacted by logistics. A logistics infrastructure is needed to gather and process biomass sources. Sustainable biopower generation requires gathering of biomass sources within a defined geographic area [217]. The biomass supply chain is crucial for economic and environmental use of biomass sources. Biomass feedstocks with low bulk density and low energy density makes untreated biomass difficult and costly to transport, thus limiting the economic scale of the plant. Logistics is one of the most important cost drivers and is the intensive step of the biomass supply chain in terms of energy consumption and GHG emissions, illustrating the importance of localized use of biomass sources for biopower production [132-134]. Although biomass can be used for centralized as well as distributed biopower generation, it is best suited for DG, providing biopower where needed with fewer transportation and transmission requirements [30,32-34,122,198]. At present, for

biopower production, DG schemes are of paramount importance since they consist of energy production close to both energy sources and consumption, as opposed to centralized generation. The major drivers for DG are defined as environmental and economic [107-110], factors that also apply to biopower plants.

The environmental benefits of biomass energy technologies are among their greatest assets [34,156]. To ensure sustainable production of biopower contributing to a green economy, use of biomass sources and environmental consequences of releases throughout an energy plant's life cycle must be carefully evaluated [219]. To this end, LCA studies are vitally important to evaluate the environmental impacts of biopower production [8,161,220-224]. LCA principles are well known and standardized [37-40]. Standards provide guidelines but allow freedom to LCA practitioners for some methodological choices, which enables LCA applications to address different specific questions. However, the differences in the methodological choices may lead to a wide range of final results, even for the same technological choices, goals and scopes, revealing the importance of local conditions. LCA studies must be conducted using location specific data.

The commercial primary conversion technology for electricity production from biomass is combustion. Biomass combustion is generally accepted as a carbon-neutral process. Carbon neutrality is an assumption that the combustion of biomass does not contribute to an increased atmospheric content of CO₂, as the amount of CO₂ released during biomass combustion is balanced by the CO₂ removed from the atmosphere by photosynthesis when biomass is grown [225]. Although carbon neutrality is seen as a positive aspect of biomass combustion that releases air pollutants, all emissions from biomass combustion should be examined carefully [226]. Today, global biopower plants are designed together with various particle and emission abatement systems (cyclones, filters, ESPs, and scrubbers, etc.) [188]. The major air emissions from biopower plants are carbon monoxide (CO), CO₂, water (steam), and depending on mineral content and combustion temperatures, sulfur oxides (SO_x), particulate matter (PM) (char particles, etc.), nitrous oxide (N₂O), and NO_x [148,156,227,228]. Although the actual amounts and types of air emissions depend on several factors such as biomass source, furnace design, and operating conditions, it is crucial to note that combustion of biomass produces much lower quantities of air pollutants than an average coal-fired boiler. The comparisons of CO₂ emissions from coal combustion

and biomass combustion with different conversion technologies show that the use of biomass energy is a positive strategy to mitigate GHG emissions [122,229,230]. Biopower SO₂ emissions are typically low because of the usually low amount of sulfur found in biomass. As a result, acid rain, which is caused by the SO₂ produced during combustion of fossil fuels, especially coal and oil, is not a major problem for biomass combustion systems. Biomass combustion produces less ash than coal combustion, and the mostly beneficial biomass ash can be used as a soil additive [9,10].

Biomass characterization is of vital importance for a sustainable biopower production. For example, difficulties in biomass combustion are due to its inorganic constituents, consisting of oxides of metals, typically sodium, potassium, calcium, and others [227,231]. Combustion systems (feed systems, furnaces, particle and emission abatement systems, and ash management, etc.), therefore, have to be specifically designed to match biomass feedstock properties to ensure an efficient and clean combustion, and to avoid fouling and corrosion problems. Harmonization of biomass sources may also be needed. In addition, untreated biomass contains high levels of moisture, which affects handling and storage properties prior to conversion systems. Various biomass pre-treatment processes have to be applied taking into account biomass properties and biofuel feedstock necessities. Prior to conversion systems, storing, handling, and feeding units for biomass feedstock have to be bigger than those for fossil fuels. For a given heat input, the biofuel feed rate is about twice that of coal on a weight basis, and more than four times that of coal on a volume basis. Biomass generates less ash than coal, but biomass ash may be more difficult to handle during and after combustion due to its physical, chemical, and electrical properties [52,123,150,190,232,233].

Lessons learned from existing biopower plants shows the importance of the biofuel preparation yard, biofuel feed system, and design for biofuel flexibility, among other factors [150]. Since a significant land area is required for biomass feedstocks, storage is one of the first considerations in the design of the biofuel preparation yard of a CBHBP plant. Biomass storage is needed to provide energy all year round since biomass sources are mostly generated seasonally. The storage area should be sized for an adequate daily supply of biomass feedstock considering the amount needed to carry the plant through possible supply shortages [56,150,151]. Since biofuel quality varies more than coal quality, selection of a proven biofuel feed system is important. When

firing biofuels, proper tuning of automatic combustion controls is essential. In addition, it is crucial to design a CBHBP plant for maximum fuel flexibility, since many plants change fuels over the years due to different opportunities or problems arising from unpredictable availability of biomass sources and biomass supply chains. The best reported strategy is to have a plant design (biofuel processing, feeding, and combustion systems) and emission control systems that allow as much biofuel flexibility as possible [150].

2.6 Process Simulation and Aspen Plus Software

Process simulation lets engineers model and predict process performance and behavior with basic engineering relationships such as mass and energy balances, phase and chemical equilibrium equations, etc. In general, process simulation is very helpful throughout the entire life cycle of a process: from research and development through process design and production stages (e.g. to shorten laboratory experiments and pilot plant runs in research and development, to enable much simpler comparisons of various alternatives in process design, to conduct various what-if scenarios in production, without any risk) [234,235].

Process simulation involves the prediction of process outputs such as flowrates, compositions, temperatures, pressures, properties, etc. using analysis techniques. One of these analysis techniques is to use a computer-aided process simulator tool such as Aspen Plus software. To perform a process simulation using a process simulator, a process flowsheet, which is a blue print (model) of a plant or part of it, is converted to a simulation flowsheet by replacing the process units with appropriate simulation units. Therefore, in process simulation, when process inputs and the flowsheet are given, process outputs are predicted [234,236].

Over the years, different types of process flowsheet simulator tools have been developed in the world to use in actual applications from interpreting laboratory scale data to monitoring a full-scale plant. Some well-known ones are aspenONE Engineering suite [237], Thermoflex [238], ProSim [239], ChemCad [240], PRO/II [241]. Process simulator tools that are used particularly for power generation are Thermoflex, ProSim, and aspenONE Engineering suite [242].

Aspen Plus is a product of the aspenONE Engineering suite. It is a well-known process simulation software used as a computer-aided process flowsheet simulator tool. Aspen, which stands for “Advanced System for Process Engineering”, was developed by MIT’s Energy Laboratory as a model for process simulation in 1970s. A company called AspenTech commercialized the software in the 1980s [234].

Like other simulation tools, Aspen Plus has user-friendly interfaces and various databanks containing chemical, physical, and thermodynamic data for a wide range of chemical components. Aspen Plus, which is suitable for steady state modelling applications, has many built-in model “blocks” such as turbines, reactors, pumps, condensers, etc., which can be directly used in power plant simulations. A complete process flowsheet can be constructed by connecting the blocks with streams (material, work, heat). Briefly, simulation is conducted by first specifying the data (flow rates, compositions, etc.) for inlet streams; second, by specifying the data for unit operation blocks (operating conditions such as temperature, pressure, pressure drops, etc.); and third, by defining material, heat, work inputs into the process. Then, based on these inputs, Aspen calculates flow rates, compositions, and state conditions of all outputs (material, heat, and work streams). Moreover, Aspen Plus conducts not only technical but also economic evaluation of processes. “Aspen Process Economic Analyzer” can be used to evaluate the capital and operating costs of a process simulation [237].

According to the AspenTech guides [235], the following steps should be performed to convert a process flowsheet into an “Aspen Plus process simulation model”:

1. Define the process flowsheet and operating conditions to be simulated.
2. Aspen Plus “Properties” environment:
 - a. Specify which chemical components are used in the process.
 - b. Specify which thermodynamic models represent physical properties of the components and mixtures used in the process (the property methods used to determine properties such as enthalpy, density, K-values, etc.).
3. Aspen Plus “Simulation” environment:
 - a. Define the process simulation flowsheet (place unit operation models on the workspace; connect process streams flowing to and from the unit operation models).

- b. Add the necessary process data to the process simulation flowsheet:
 - i. For feed streams, specify component flow rates and thermodynamic conditions
 - ii. For unit operation models, specify operating conditions
- c. Finally, run the simulation model and examine the results.

Figure 2.14 shows a standard user interface of Aspen Plus version 8.4 [235]. The top “Ribbon” includes tabs to access a set of related commands. The “Quick Access Toolbar” is used to add frequently used commands, which are visible no matter which tab of the ribbon is active. The “Next” command on the quick access toolbar is an expert system of Aspen Plus. It guides users through all the steps to enter specifications for a simulation model. “Navigation pane” applies to all open forms. “Workspace” includes tabbed windows on which it is working during a process simulation: forms, flowsheet, control panel, plots, other windows, etc. appear with separate tabs in the workspace. “Status bar” shows the main status messages along with the “Check Status” button, which provides quick access to the run status and any error or warning messages. “Environment buttons” include three working environments in Aspen: properties, simulation, and energy analysis. Aspen starts a new simulation from the “Properties” environment, which is used to specify the chemical components existing in the simulation. After the “Required Properties Input Complete” message appears in the status bar, the “Simulation” environment can be used to build the process flowsheet, input process data, and execute the calculation. The “Energy Analysis” environment is used for optimizing energy usage in a completed simulation model.

The list of folders and forms on the navigation pane, and also the available ribbon tabs and the open windows differ among the different environments.

One of the advantages of a simulation is the ability to study process performance sensitivity to changes in process variables. With Aspen Plus, process inputs data can be changed, and the effect of the changes on a set of results can be observed easily (this is called sensitivity analysis). Aspen Plus can also be used to ensure a specific process design specification by changing the related process simulation input.

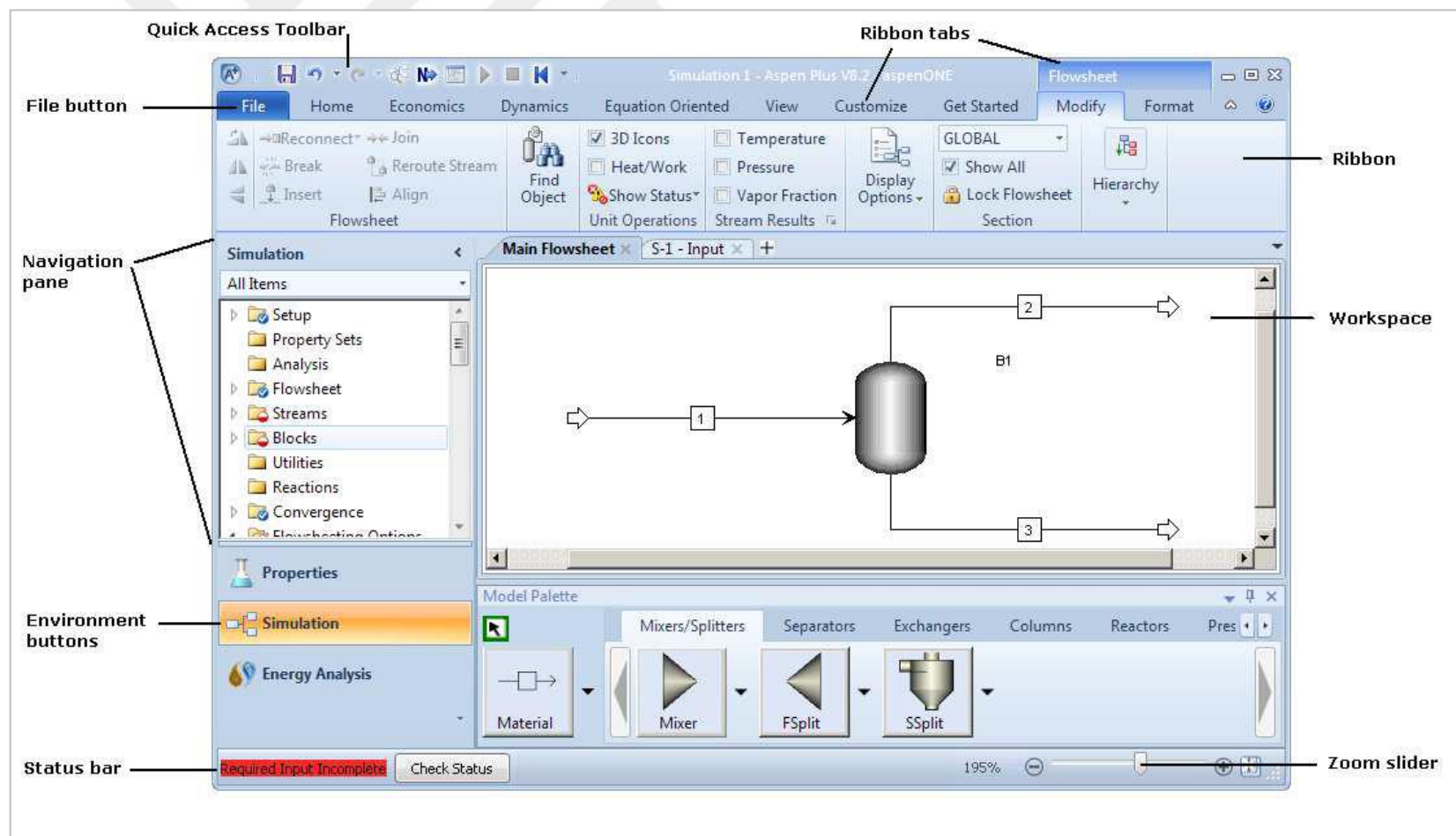


Figure 2.14 : Aspen Plus version 8.4 user interface [235].

The “Aspen Plus component databank” is used to specify physical properties of the chemical components present in the process. However, there might be situations in which a component is not in the databank. In this case, to estimate the missing properties of the unknown component, “Property Estimation Simulation” is run in Aspen Plus after providing Aspen Plus with a starting point such as the molecular structure of the new (unknown to the software) component.

2.7 LCA and SimaPro Software

The following sections provide, first, a summary on environmental impact assessment methods. Then, the life cycle assessment LCA theory and methods: its history, applications, and methodology are explained in detail. After indicating the importance of LCA software generally, SimaPro software and ecoinvent database are introduced.

2.7.1 Assessment methods for environmental impacts and LCA

On the road to sustainable development [4,243], it is essential to understand the economic, environmental, and social impacts of human activities. The “UN WCED Rio Declaration on Environment and Development” [243] points out the need for all countries to work toward sustainable development, during which environmental protection was accepted as the most critical. Today, countries, especially developing countries like Turkey, are struggling with environmental protection challenges while experiencing their economic growth.

Environmental impacts can be assessed by a variety of assessment methods that have been developed as tools for sustainability decision support processes. These assessment methods actually overlap and complement each other. However, they differ in terms of their focus.

Some methods are listed below.

- i. Technology Assessment
- ii. Environmental Impact Assessment
- iii. Risk Assessment
- iv. LCA

“Technology Assessment” studies the consequences of new scientific and technological innovations with a future orientation and no site-specific focus. “Environmental Impact Assessment” evaluates the impact of tangible projects and possible alternatives. “Risk Assessment” assesses the effects of chemicals on human and ecosystems. LCA evaluates the environmental performance of a system over its life cycle for a large range of impacts. The system can be a product, process, technology, service, activity, etc. [244,245].

The life cycle philosophy states that to be sure our environment is protected as a whole, an approach that considers the whole life cycle of the system considered should be adopted. This is called a life cycle approach, and is also known as life cycle thinking or the cradle-to-grave approach. LCA is a standardized environmental management tool that uses a life cycle approach. This approach is a way of looking at any system to determine its resource consumptions (inputs) and the environmental consequences of releases (outputs) throughout its life cycle from raw material acquisition (cradle) to final waste disposal (grave) [37-40,246-250]. Therefore, after compiling and evaluating the inputs and outputs, environmental impacts of the system through its entire life cycle are identified and quantified. An LCA study may include stages and processes that are not considered in other environmental assessment methods such as raw material acquisition, transportation, use, reuse, recycle, and construction and deconstruction.

Figure 2.15 illustrates the main life cycle stages normally considered in an LCA study along with their interactions, system boundaries, typical inputs from the environment to the system, and typical outputs from the system to the environment. As shown in the figure, the life cycle of the system considered, starts with removal of the raw materials from the earth, which are required to manufacture the product. During the production stage, raw materials are transformed into the product. Some systems may produce co-products as well. Co-products are outputs that are not treated as wastes (they still have value). Distribution includes product delivery to retail outlets or directly to consumers. When the product is distributed to consumers, all activities related to the product during its useful life are included in use, reuse, maintenance, and recycle stages. The life cycle of the system ends with the waste disposal stage. In addition, in all stages of the life cycle, environmental impacts caused by the mode of transportation, such as trucking, shipping, etc. are taken into account. Construction and

deconstruction of production units can also be taken into account. As illustrated in the figure, in some situations it may not be possible to follow the life cycle of a target after its production stage. Such LCA studies are named cradle-to-gate (i.e., from raw material acquisition to factory gate). There is another term used in LCA studies, cradle-to-cradle, implying the reuse of wastes from one system as raw materials in the same or a different production system [37-40,246,247,249].

The LCA concept first appeared in the 1960s and has been developing since the 1970s. The level of attention LCA received began increasing in the 2000s. An international life cycle partnership, known as the “Life Cycle Initiative” [251], was launched as a joint organization by the “United Nations Environment Programme (UNEP)” and the “Society of Environmental Toxicology and Chemistry (SETAC)” in 2002. The “Life Cycle Initiative” has three programs, which are “Life Cycle Management (LCM)”, “Life Cycle Inventory (LCI)”, and “Life Cycle Impact Assessment (LCIA)” programs, to put life cycle thinking methodologies into practice and to improve the supporting tools via better data. In 2005, the “European Platform on LCA” in the “European Commission Joint Research Centre” [252], was established to provide an EU-level knowledge base for LCA that responds to business and policy needs. Today, many countries have initiated their own national LCA programs and promote the use of LCA, as an example the “U.S. Environmental Protection Agency” in the USA [253].

In addition, various national LCA networks have been established in the world, for example, the “American Center for LCA (ACLCA)” [254], the “Australian LCA Society (ALCAS)” [255]. LCA has also become a field of academic study. All over the world, there are various research groups on LCA at universities. Some scientific journals entirely or partly devoted to LCA are the “International Journal of Life Cycle Assessment”, the “Journal of Cleaner Production”, and the “Journal of Industrial Ecology”. On the other hand, parallel to the developments in LCA studies, there are various software and database providers offering products to enhance the use of LCA [246,256].

In recent years, the life cycle approach has gained great importance in industry, research, and environmental policy making. LCA is now a well-established tool that is being used by an increasing number of applications to measure environmental

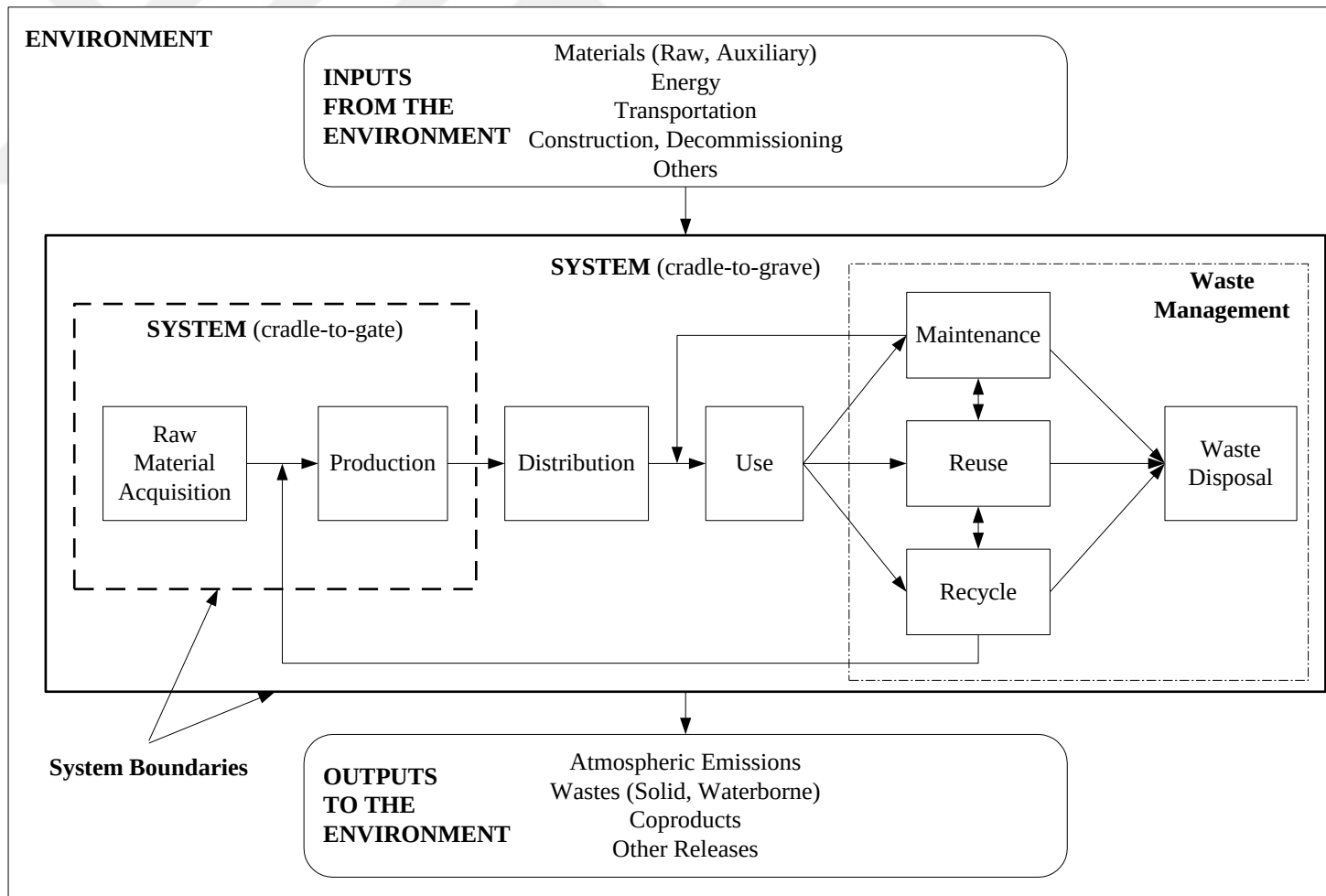


Figure 2.15 : The main life cycle stages of a system (adapted from [37-40,246,247,249]).

sustainability. Some applications of LCA include identification of more sustainable environmental options, life cycle hot spots and options for improvements, process optimization, product design and labelling, as well as single issue LCA approaches such as carbon and water footprinting [247,249,257]. To demonstrate the claims of green products, ISO 14025 [258] has introduced the concepts of “Product Category Rules” (PCR) and “Environmental Product Declaration” (EPD) which are based on LCA basic principles. PCRs are specific guidelines to calculate the environmental impact of products within the same product category. A product category is defined as a group of products with similar characteristics. Hence, a company can develop an EPD for its product by following the requirements in its related PCR based on LCA basic principles [259].

New requirements for effective GHG mitigation measures have been growing in response to climate change worldwide. As a result, interest in LCA for energy applications has been increasing because of the specific evaluation needs for GHG emissions [31]. LCA is used as a fundamental basis from which to determine relative advantages or disadvantages of biomass energy applications. These days, LCA is seen as a key to effective environmental sustainability using biomass energy.

2.7.2 LCA Methodology

The SETAC [260] was the first (1989) to prepare an LCA framework, a consistent terminology and methodology at world level. Before this time, LCA was known under many names such as “Resource and Environmental Profile Analysis (REPA)” or “Ecobalance” [246,256].

After SETAC, ISO got involved in LCA, and the LCA basic principles were documented within the ISO 14040 series. ISO released a systematic framework to conduct LCAs during the period 1996–2000. At the end of this period, the ISO standards numbered 14040, 14041, 14042, and 14043 were prepared. These standards were updated in 2006, and the previous four standards were consolidated into two standards (ISO 14040 and 14044) [37,38]. The “Turkish Standards Institution” (TSE) issued matching standards in 2007 in Turkish [39,40].

The general methodological framework of LCA is organized into four phases, which are listed below.

- i. Goal and scope definition
- ii. Inventory analysis (Life Cycle Inventory analysis, LCI)
- iii. Impact assessment (Life Cycle Impact Assessment, LCIA)
- iv. Interpretation

These phases are all interrelated. Figure 2.16 illustrates the relationship between these phases [37-40], and is now a logo of LCA studies.

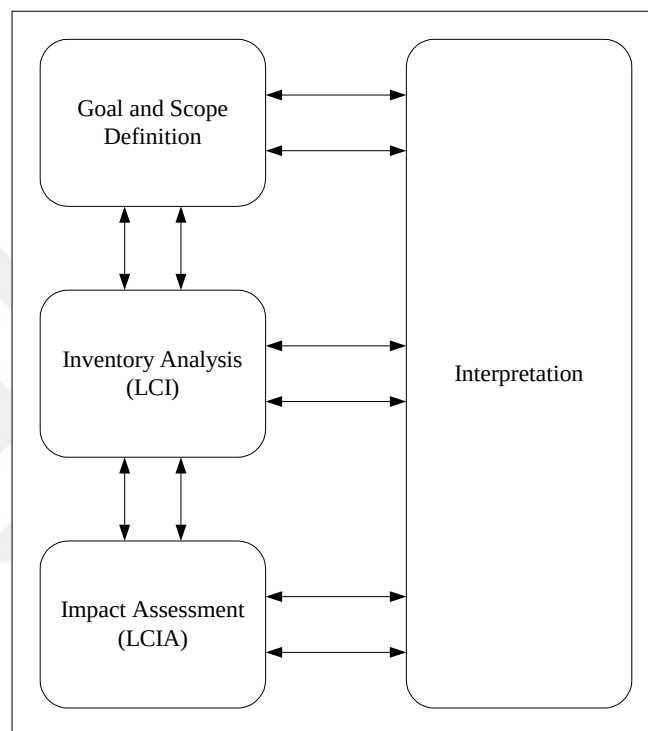


Figure 2.16 : LCA framework [37-40].

Briefly, an LCA study starts with “goal and scope definition”, then continues to “inventory analysis”, after that proceeds to “impact assessment”, and finally ends with “interpretation”. Actually, LCA is an iterative study (e.g. after the preliminary inventory work, it may be necessary to look again at the “goal and scope definition”, or to go back to “inventory analysis” from “impact assessment”, etc. [37,39,250]. The following sections give a brief overview of the phases of an LCA framework and some methodological choices that were applied to CBHBP LCA studies.

2.7.2.1 Goal and scope definition

“Goal and scope definition” is the planning part of an LCA study. Goal definition states the aim of the study and its prospective application, reasons to perform the study,

the target group, and whether the LCA results will be open to the public. Scope definition specifies a number of methodological choices and requirements that are needed to perform the study. These include system description, system boundary and functional unit definitions, modeling approach and allocation procedure to be applied, impact categories to be selected and impact assessment methodology to be used, data necessities and quality descriptions, required specificity, and the assumptions and limitations of the study [37-40]. It is important to note that the scope definition establishes preliminary choices and needs which may be updated after more information is available. Also, the collection of data and calculation of results are not associated with “goal and scope definition” [37-40,246,247,249,250,259,261].

Of the choices and requirements mentioned above, including the most critical ones, the terminology is listed below and explained in lines following, along with some methodological choices from the literature about CBHBP LCAs.

- System boundary
- Functional unit
- Modeling approach
- Allocation procedure
- Impact categories
- Impact assessment methods
- Required specificity

System boundary

The system boundary shows what is involved in a particular LCA study. The system boundary separates the system under study from its environment. For example, the system boundary is set to cradle-to-grave in full LCA studies, which means LCA study includes all stages from raw material acquisition to waste disposal (Figure 2.15). A boundary must also be set between the studied system and other systems. An LCA system boundary includes the four stages below for its life cycle:

- Raw material acquisition
- Production
- Distribution

- Use
- Maintenance/reuse/recycle
- Waste disposal

To determine which stages should be within the system boundary of an LCA, its goal, the accuracy required in its results, and all resources and time available must be assessed [246].

Figure 2.17 shows biomass energy life cycles according to Muench and Guenther [222]. There are three significant paths (three biomass energy life cycles) in the system boundary definition of biomass energy systems. The first path, called the “biomass feedstock life cycle”, includes biomass acquisition, biomass transportation, and conversion, as well as end-of-life treatment. The second path, called the “biomass conversion system life cycle” includes commissioning and decommissioning (infrastructure) of all equipment in the conversion system. The third path, called the “biomass energy service life cycle” includes the distribution of energy. In this work, the reviewer stated that these definitions are used quite heterogeneously and sometimes contradictorily in biomass energy LCAs. They concluded that in terms of the biomass life cycle, biomass production and transportation are generally included in biomass energy life cycles. They also added that although end-of-life treatment of biomass is included in the majority of biomass energy LCA studies, a higher degree of heterogeneity is observed. In terms of the conversion system, capital equipment was found to be handled very differently among biomass energy LCAs. With regard to energy service life cycle, it was found that the impacts of energy transmission are included in few LCA studies and, therefore, they are usually not within the focus of biomass energy LCAs.

Functional unit

How data and results should be organized and displayed is defined in terms of a functional unit: a quantitative description of the output(s) that the system produces. The focus is generally on the function of a physical product of the system under study. This allows comparison of different systems based on their functional units. The functional units in biomass energy LCAs may be input-related or output-related. Examples for input-related units are energy input (e.g., megajoule (MJ) calorific value of biofuel), mass input (e.g., biofuel feedstock in t), and volume input (e.g., sludge in m³). This

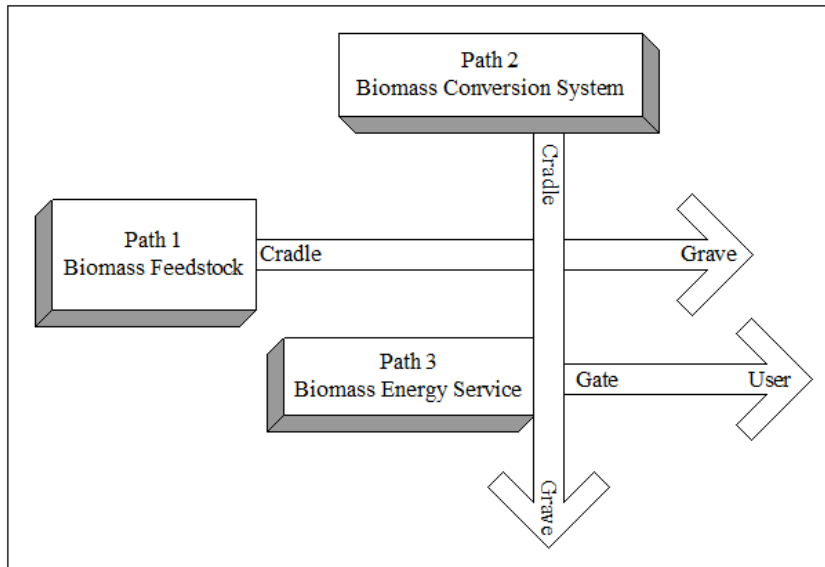


Figure 2.17 : Biomass energy life cycles (adapted from [222]).

type of functional unit is often preferred for studies aiming to understand the optimum use options for a given biomass feedstock. Energy output is an example of output-related functional units. Energy output-related units represent primary function of a biomass energy system such as biopower production, bioheat production, or both (CBHBP). This type of functional unit is often preferred for studies aiming to compare the provisions of specific product(s) from different biomass feedstocks. Being independent from the biofuel feedstock is the advantage of energy output-related functional units. There are also case-specific functional units such as annual biopower and bioheat demand of a district. Biomass energy LCA reviews show that biomass energy LCAs mostly used at least one functional unit related to energy output [220,222]. Below are some examples of functional units used in CBHBP LCA studies:

- 1 MJ electricity to end user and 1 MJ thermal to end user [223,262]
- 1 kWh electricity and 1 kWh heat [263-265]
- 1 kWh electricity and heat in total (0.33 and 0.67 kWh, respectively) [265]
- Annual electricity, heat and hot water supply to a village of 150 houses [266]
- Total electricity and heat produced in one year in the plant [267]
- 1 t of wood pellets and 1 t of wood waste [141,268]
- Area (ha) of crop production [269,270]
- Sugarcane harvested from 1 ha of land per year [271]

- Amount of agricultural residues treated per year [272,273]
- 1000 kg straw entering the biorefinery [274]

Modeling approach

In an LCA, goal and scope definition determines the modeling approach of the study. There are two types of modeling approaches in LCA studies. These are “consequential modeling” and “attributional modeling”. “Consequential modeling” investigates the effects of a change based on a reference state. “Attributional modeling” is applied to understand the environmental impacts of a system and hot spots in its processes, or to compare environmental burdens of two different systems having the same functional units. On the other hand, in SimaPro software, processes are defined as unit processes or system processes. Unit processes describe a single process with high transparency. System processes represent a combination of more than one unit process. In general, system processes are used in screening LCAs while unit processes are used in full LCAs [259].

Allocation

Allocation assigns to each product in a system only the environmental impact that it is responsible for. If a system has more than one product, such as a co-product or reuse and recycling systems; then environmental impacts of the system must be allocated to each product. To apply an appropriate allocation procedure is crucial because it influences the LCA results [37-40,246,247,249,250,259,261]. Many processes produce more than one product. These processes are called multifunctional processes. In such cases, environmental impacts of inputs and outputs are divided among these products and co-products. This concept is very important for CBHBP plants because they are characterized by multiple products (biopower and bioheat).

ISO presents a stepwise procedure for allocation. According to ISO 14044 [38,40], allocation as a first solution should be avoided. To this end, co-products should be included in the system boundary. Dividing processes into sub-processes (subdivision) or expanding the system boundary (system expansion and substitution) avoids allocation. Allocation is unavoidable when the life cycles are interconnected, which means one production is dependent on the other production, and hence the products cannot be separated. In this case, a physical allocation should be determined. The physical allocation is a relationship between products. It determines how quantitative changes in delivered products change the amount of inputs and outputs. A physical

causality for allocation is a physical property: energy, exergy, mass, volume, etc. Allocation based on other kinds of relationships, such as economic values, should be used only if no physical causality for allocation is present [38,40,220,222,259].

Exergy-based allocation (physical relationship) is mostly used in CBHBP LCA studies. The concept of exergy uses the Carnot factor, which takes into account the different thermodynamic significance of electricity and heat. The Carnot factor of electricity is '1', but is lower for heat, the usefulness of which depends on the surrounding temperature and the produced steam temperature [194,220,222,223,262].

Impact categories

Impact category is a “class representing environmental issues of concern to which LCI analysis results may be assigned” [37]. Examples of impact categories include such as GW, ETR, acidification (ACD), toxicities on human health and ecosystems, resource depletions (elements, fossil fuels), etc.

CBHBP LCA studies cover different types of impact categories. These are GW, ETR, ACD, photochemical oxidation (PCO), ozone layer depletion (OD), toxicity (human, terrestrial, aquatic), land and water use, and resource depletions. Commonly used impact categories for biopower and bioheat LCAs are reported as GW, ACD, and ETR [222]. Some studies include energy balance calculations (e.g., fossil energy requirement, cumulated energy demand, energy input-output ratio) [263,266,269,272,273,275] and a few also include carbon cycle calculations (e.g., soil carbon change, carbon closure) [194,262,271-273].

Impact assessment methods

Impact categories are included in impact assessment methods. When choosing the impact assessment method(s) to use in an LCA study, it is important to know if the method includes the impact assessment categories needed, and if the characterization has a scientific basis or not. Characterization is part of the impact assessment phase.

Various impact assessment methods (LCIA methods) have been developed and used to calculate impact assessment results. In general, these methods are divided into two groups based on their assessment approaches. These are problem-oriented (midpoint) and damage-oriented (endpoint) methods. Midpoint methods classify flows into the environmental problems to which they contribute. Some examples for midpoint categories are climate change, ACD, ETR, impacts of land use, HT, eco toxicity,

stratospheric ozone depletion, and depletion of biotic resources. The damage-oriented methods also categorize environmental flows into various environmental problems (intermediate endpoint impact categories), but model the endpoint damage to protection areas (which include human and ecosystem health and resources) as endpoint impact (damage) categories. Endpoint categories represent the damage caused by midpoint categories and answer questions; for example, why to be worried about climate change, ACD, etc. While midpoint categories are situated between environmental cause and effect, endpoint categories are at the end of the effect (i.e., the real damage) [276]. Both approaches in impact assessment offer certain advantages and disadvantages. Midpoint approaches ensure a comprehensive and science-based decision. Endpoint approaches are simpler than midpoint approaches in that they are easier to interpret and easier to report to decision makers. There are also hybrid approaches combining midpoint and endpoint categories [222]. CML is the most-widely used problem-oriented method, while Eco-indicator 99 and its successor, ReCiPe, are the most-widely used damage-oriented methods [222,247,249,277,278].

There are various methods that are applied to biopower and bioheat LCAs. Of these, midpoint approaches are widely used in these studies. CML is the mostly applied midpoint impact assessment method. Eco-indicator, EPS, Ecotax, LIME, and ReCiPe are among endpoint impact assessment methods most used in these studies. Hybrid approaches have been used in a few studies. There are also some studies including more than one impact assessment method for comparison purposes [264,267,271,279,280].

Required specificity

It is also essential to determine the level of specificity required for the LCA study. To determine the required specificity, it is necessary to define a data collection approach for the LCA study to understand whether the data that will be collected for the inventory should be specific to a manufacturing facility (product specific, foreground, or primary data), or more general to represent common industrial practices (industry average, generic, background, or secondary data). A practical way recommended to define a data collection approach, is to begin with a screening LCA (rough or fast LCA) then continue with a contribution analysis and/or a sensitivity analysis (changing important assumptions) to detect relative significance of data gaps in the database. After these, a data collection approach can be set up, and with the needed degree of

specificity known, identification of the data that should be collected from different resources (literature, suppliers, etc.) in the product chain, can be determined. This approach is also useful to construct an LCI, which helps to figure out what kind of data is needed to carry out the LCA study [246,259].

2.7.2.2 Inventory analysis

“Inventory analysis” or “LCI phase” of an LCA starts with data collection, and involves quantification of the related inputs and outputs at the system boundary using calculation procedures [37-40]. Quantification is an important aspect of LCI. An LCI is set up based on the unit processes designed. ISO specifies a unit process as “the smallest element considered in the life cycle inventory analysis for which input and output data are quantified” [37,38]. Unit processes may represent either one unit operation (a furnace, a reactor, etc.), or a group of unit operations (a furnace and a pump together, etc.), which depends on the data available. Each of these unit processes should be defined quantitatively as inputs and outputs. Input and output data for each unit process may be energy, feedstocks, products, co-products, emissions into air/water/ soil, wastes, etc. LCI includes the steps of preparing a flow diagram including unit processes being assessed, data collection and validation, and allocation and calculation of the final inventory results. Typically, inventory results are presented as a table including the quantified inputs from the environment and outputs to the environment, described based on the functional units. LCI is an iterative study because as more is learned about the system in the inventory analysis phase, new data needs or limitations may be determined, and even the scope may need to be modified to meet the goal definitions [246,247,249,250,261].

The data collection phase needed to construct an LCI is accepted as the most difficult task of an LCA study. The inventory data needed for an LCA study can be based on the following sources.

- Experiments
- Literature
- Databases, information systems, reports at national/international level
- Pilot studies/real facilities/process simulations
- LCA databases available within LCA software (e.g., the ecoinvent database)

2.7.2.3 Impact assessment

“Impact assessment” or the “LCIA phase” of an LCA involves assessment of the importance of potential environmental impacts using the inventory results from the inventory analysis phase [37-40]. During the LCIA phase, LCI results are translated into their related potential environmental impacts (i.e., impact category indicator results: LCIA results). Figure 2.18 summarizes the elements of the LCIA phase. As depicted in the figure, mandatory elements for an LCIA include the steps: selection of impact categories, impact category indicators and LCIA models (characterization models); classification; and characterization. There are also optional elements of an LCIA (normalization, grouping, and weighting).

While classification assigns LCI results to the impact categories they contribute to, characterization calculates impact category indicator results by multiplying each LCI result by its related characterization factor, and then summing them all up. Each characterization factor is determined by LCIA models. Therefore, characterization first converts LCI results to common units and then aggregates the converted results to the same impact categories.

As an example to explain how to calculate an impact category indicator result when GHG emissions are considered, aggregation aims to calculate other GHG (N₂O, CH₄, fluorinated gases) emissions in terms of kg CO₂ eq, which is the unit of the impact category and impact category indicator result. In this example, LCI results are the amount of GHG per functional unit, impact category is climate change, the characterization model is the “Baseline Model of 100 years of the Intergovernmental Panel on Climate Change (IPCC)”, and the characterization factor is the GW potential which is ‘1’ for CO₂ and > 1 for other GHGs. Therefore, the impact category indicator result is calculated as kg CO₂ eq per functional unit by first multiplying each of the LCI results contributing to climate change by its relevant characterization factor and then summing them up [37-40,247,249,250,259].

Normalization, grouping, and weighting are applied to facilitate interpretation of the characterization results. Each impact category of the characterization results has its own unit and thus cannot be compared with others. With a normalization step, each impact category indicator result is compared to a reference (normal) value (i.e., it is divided by this reference or normalized). The reference can be chosen freely. However,

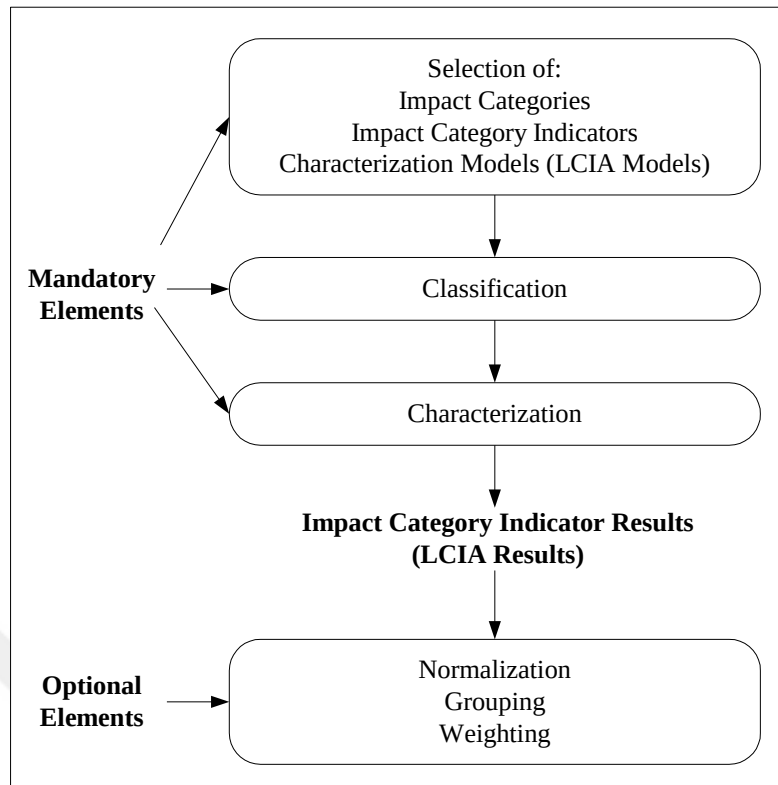


Figure 2.18 : LCIA elements (adapted from [37-40]).

a commonly preferred reference is the average environmental burden in a given area (country, continent, etc.) over a certain time (year, etc.). After normalization, the units of the impact category indicator results become all the same. Looking at normalization results, although it can be concluded that an impact category indicator result is relatively low or high compared to the results for other impact categories, it cannot be concluded whether it is more important or not. This is the subject of grouping and weighting studies. Impacts can be grouped in terms of, for instance, high, moderate, and low importance with grouping that involves sorting and possibly ranking of impact categories based on value-choices. Weighting, also named valuation, assigns importance to impacts via weights. Weights are numerical factors (weighting factors) based on value-choices. Weighting can be made on normalized or non-normalized (impact category indicator) results. Different impact category indicator (non-normalized) or normalized results are first multiplied by weights. Then these converted results are combined across impact categories to create a total or single score. According to ISO, “weighting shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public” [38]. Weighting is to be applied for internal decision-making purposes [37-40,247,249,259,277].

2.7.2.4 Interpretation

“Interpretation”, which is the final LCA phase, is the connection between inventory analysis, impact assessment, and the real world. Life cycle interpretation, in line with goal and scope, should provide understandable results. During this phase, all outcomes from LCI and LCIA are evaluated, major impacts and hot spots in the life cycle are identified, conclusions are reached, and recommendations are provided. Before final conclusions and recommendations, it is also crucial to perform a sensitivity analysis for significant inputs, outputs, and methodological choices used in the study because the inventory data used, determine the results of an LCA study. Effects of variations on the final results are identified by the sensitivity analysis [37-40,247,249].

2.7.3 Softwares for LCA and SimaPro

An LCA software tool is an essential part of an efficient LCA application because an LCA study heavily relies on data processing. Even a standard LCA study needs information about hundreds or thousands of processes, with input and output streams that need to be connected. Therefore, when conducting an LCA study, processes such as ease of display, error checking methods, rapid calculations, data import and export abilities, etc., are essential. Because LCA software encompasses data collection, compilation, modeling, and calculation of results, they have become an essential part of an efficient LCA study. Consequently, a market has been established for professional LCA software for more than twenty years [281]. Figure 2.19 shows a schematic working principle of LCA software that transforms data into a model generated within the LCA software to provide results that are, in the end, used for various applications in decision support [282].

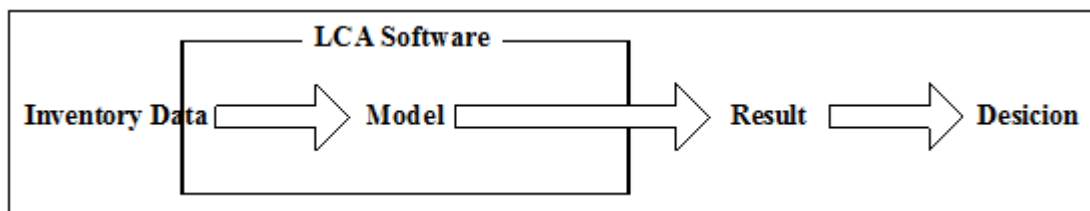


Figure 2.19 : A schematic working principle of a Life Cycle Assessment (LCA) software (adapted from [282]).

Today, the LCA software market is quite dynamic, with many commercial products and much freeware. For example, CMLCA [283] and GEMIS [284] are freely

available; however, these tools do not usually provide some of the useful features of the commercial LCA tools. Examples of LCA software with full features are SimaPro [285], GaBi [286], Umberto [287], and openLCA [288]. OpenLCA is open source software freely available. Of these software packages GaBi from Thinkstep (formerly known as PE International), and SimaPro from PRe Consultants, are the two commercial LCA software packages dominating the global market. Although they both have specific methods in their modeling, they also have a goodly number of features in common [281,289]. SimaPro V8.1.1.16 [285] is the LCA software used in this thesis study. Following are the basic properties of SimaPro software.

Figure 2.20 shows a standard user interface of SimaPro version 8.1.1 [285]. “LCA Explorer” is the bar on the left side, which enables access to all SimaPro functions. The “SimaPro LCA Explorer” is designed as a checklist for an LCA study so that it includes “Goal and scope”, “Inventory”, “Impact assessment”, and “Interpretation” sections in line with the ISO guidelines. Other screen needed to conduct an LCA (e.g., such as literature references; substance names, units and quantities; unit conversions, etc.) are included in the “General data” section. SimaPro also has a “Wizard” section. The LCA wizard is an easy way for new SimaPro users to get started and can be used to set up an LCA model.

The “Goal and scope” section has text fields, “description” as well as a “libraries” part. The text fields are used to describe various aspects needed for a goal and scope definition. Libraries are resources of regional and global data to be used. Libraries can be selected in line with the necessities of an LCA study. The “Inventory” section is used to enter and edit LCA project data. This section involves “processes” and “product stages”, two major data groups in SimaPro. The “System descriptions” function is used for documentation. “Waste types” are labels used to handle materials in waste scenarios. The “Impact assessment” section involves impact assessment methods. In SimaPro, there are a lot of methods that have either problem-oriented (midpoint) or damage-oriented (endpoint) categories. One of these methods can be selected and also edited, if needed. In the “calculation setups” part, which processes, assemblies and life cycles that need to be repeatedly evaluated can be defined. The “Interpretation” section has text fields and document links. Text fields are structured as a checklist to cover the issues present in ISO standards.

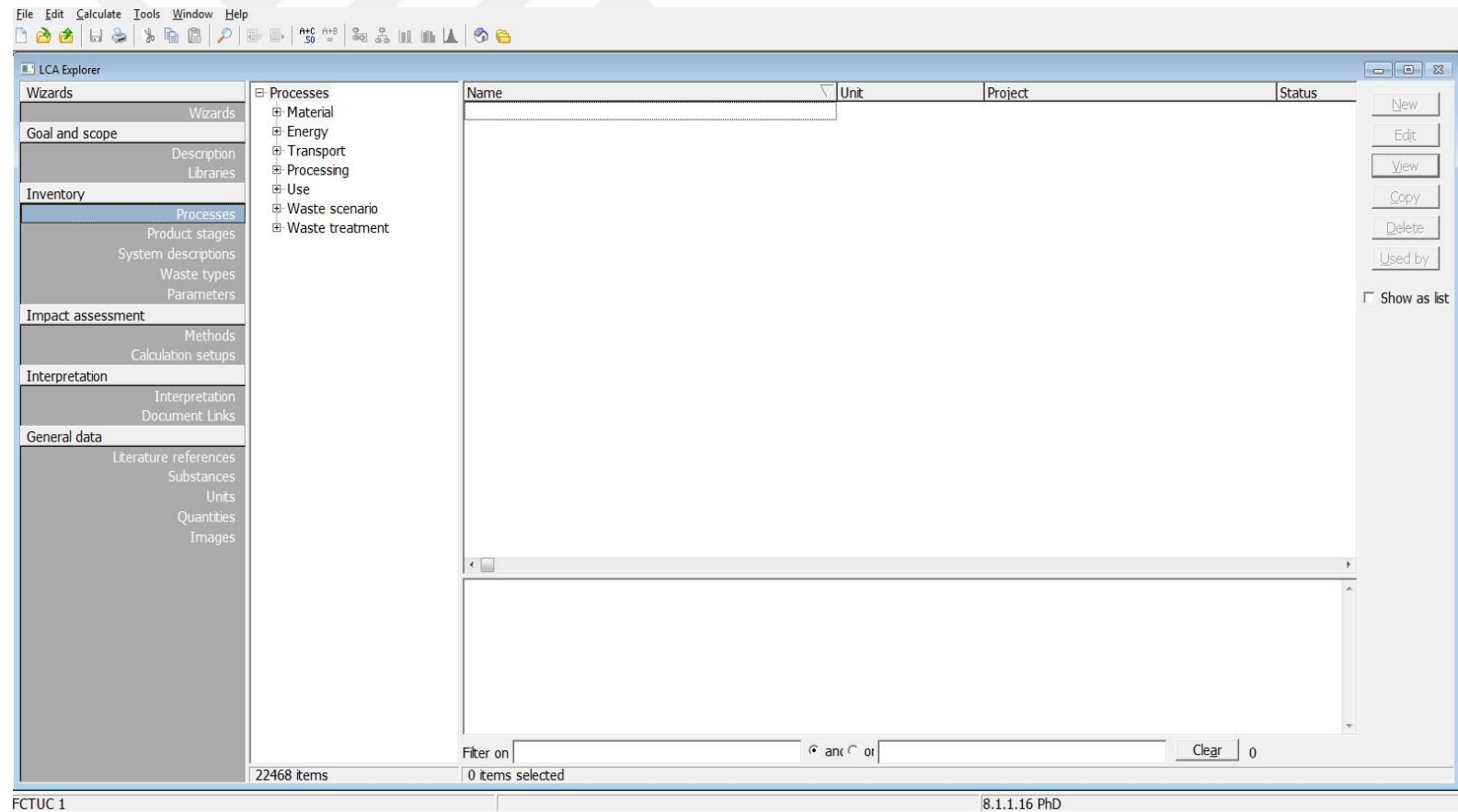


Figure 2.20 : SimaPro 8.1.1 user interface [285].

The SimaPro explorer contains project- or library-specific data, and general data in a set of files referred to as databases. A project is an area containing all specific data that is put in to perform an LCA, such as inventory data and impact assessment data. In other words, the data stored in projects relate to a specific LCA that is being developed in SimaPro. The data stored in libraries is structured in an identical way as in projects. The purpose of libraries is not to perform specific LCA studies, but to develop and maintain data sets that can be used in projects. An example of a library is the “ecoinvent 3—allocation, default-unit” library. It contains all the inventory data that will be used in many projects.

The core of an LCA study is setting up a process tree/network describing all the processes in a life cycle. Processes are described based on their output. They are linked to each other to create networks. It is important to note that process trees in SimaPro are defined as bottom-up. Moreover, links are constructed in process records, not on a graphical user interface [259]. If processes needed for a project are already available in a library, a link can be made between them (i.e., between the process record in the project and process record in the library). To make a link, it is not necessary to copy the process record from library to project. However, libraries cannot be linked to each other, nor can projects, because it is preferable to keep them independent.

Product composition, use phases, disposal scenarios, and life cycles are described under “product stages”. Each product stage involves processes. Product stages can also be linked to each other. There are five different product stages: “assembly”, “life cycle”, “disposal scenario”, “disassembly”, and “reuse”. An assembly is the definition of a product. An assembly can also have subassemblies. The life cycle of a product can only include one assembly as well as other life cycle issues, such as some use processes, disposal/waste scenarios, additional life cycles, etc.

Below is a summary of the steps used to model a complete life cycle of a product.

1. Define a new assembly for the product considered,
2. Describe materials used to produce this product (material production processes should be linked to the assembly),
3. Describe relevant processes required for this assembly (production, transport),
4. Describe a new life cycle for the product considered,

5. Link the assembly to this life cycle,
6. Under life cycle, specify use processes for the product such as transportation for product distribution or product use (in this case link transportation or product use processes to life cycle),
7. Define life cycle waste/disposal scenarios, and
8. In case there are additional life cycles to be included in the LCA such as some auxiliary products or packaging, first specify life cycles for these auxiliary products, and then link them to the life cycle under consideration [259].

After modeling the life cycle of a product, the environmental impacts of the product can be analyzed by choosing appropriate impact assessment methods in the “Impact assessment” section. These methods can also be edited, if needed.

SimaPro software comes with the ecoinvent database, which covers > 10,000 processes and is an important source of information. Within the context of this thesis research, the general structure of the ecoinvent database, its overview and methodology, and its specific data quality guidelines were studied using ecoinvent reports [290]. It is accepted that ecoinvent is a rich source and in most cases meets all the LCA needs for background data. In addition, recent versions of the ecoinvent database have a more international scope. The ecoinvent database [291], offered in SimaPro software [285] is the database used in this LCA study for background inventory data needs. The following section provides a summary of the ecoinvent database.

2.7.3.1 Ecoinvent database

The ecoinvent database involves system and unit process versions. While process records describing unit processes include one unit process (a single process step), the ones describing system processes include more than one unit process. For optimum transparency, a system must be designed in unit processes. Below are four datasets existing in SimaPro:

1. “Allocation default, unit processes”
2. “Allocation default, system processes”
3. “Consequential, unit processes”

4. “Consequential, system processes”

An allocation dataset applies the principles of attributional modeling. On the other hand, a consequential dataset applies consequential modeling principles. Moreover, “default” refers to the allocation type employed [259].

Datasets in ecoinvent include activity datasets and impact assessment datasets. “An ecoinvent activity dataset represents a unit process of a human activity and its exchanges with the environment and with other human activities” [290]. Impact assessment datasets are also available in ecoinvent for different impact assessment methods along with their relevant impact categories.

There are exchanges on the input and on output sides of “activity datasets” as seen in Figure 2.21 [290]. Exchanges from and to the environment (natural, social, or economic) that are placed on the input and on output sides of an activity, respectively, are also called elementary exchanges. Other exchanges are intermediate exchanges, such as exchanges between different activities. Intermediate exchanges on the output side of an activity are distinguished as either reference products or by-products/wastes. If there is only one product output of an activity, it is the reference product. An activity with more than one product can have more than one reference product only if the activity is a combined or joint production. On the other hand, activities may have several by-products/wastes. In ecoinvent, reference products and by-products/wastes are activity-specific. A product may be considered a reference product for one activity and a by-product/waste for another activity.

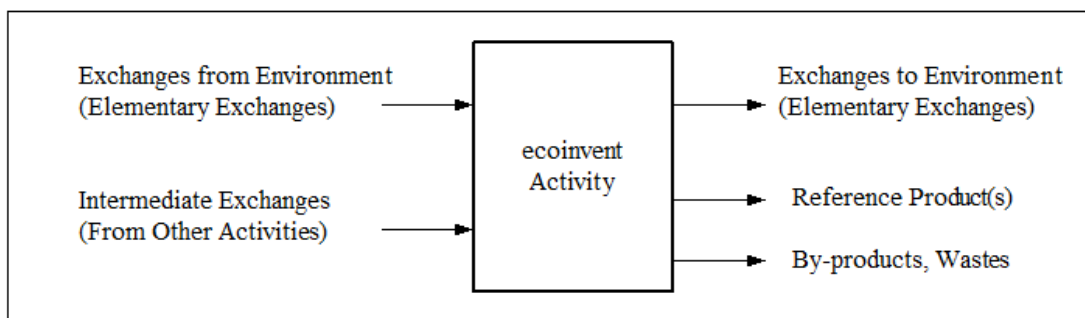


Figure 2.21 : An ecoinvent activity dataset with its exchanges [290].

In ecoinvent, each dataset is described with a geographical, temporal, and technological scope. There are also inter- or extrapolated datasets based on data from other geography or year. These inter- or extrapolations are defined in the dataset with its uncertainty information. Each geographical location is described by a short, unique

name. To ensure completeness, each activity is also defined in “global reference activity dataset” form, with the purpose to be an approximate global average value representing the most recent year for the activity (a dataset with a geographical setting as “global”: GLO). If there is one global and at least one non-global dataset for an activity, time period, and macro-economic scenario, a dataset with a geographical location (“Rest-Of-World”: ROW) is calculated automatically. ROW is the difference between global and non-global datasets.

The focus of the ecoinvent database is to combine these datasets by linking them together using system models, and to construct life cycle inventories. System models use different algorithms and provide rules to link the datasets into contiguous product systems. System models are classified as one of two types:

- I. “System models with partitioning (allocation, attributional)”
- II. “System models with substitution (system expansion, consequential)”

The ecoinvent database can also be reached and queried via the ecoinvent website www.ecoinvent.org [291]. On this website, the database is extensively described and examples from actual applications, as well as their metadata, are available. Moreover, not only the recent version, but also previous versions can be accessed.

Within the context of this thesis research, to have knowledge about life cycle inventories available in SimaPro and the ecoinvent database, the relevant ecoinvent reports were reviewed. Some of these report titles are “applications on wood energy” [292], “combined heat and power” [293], “life cycle inventories of energy systems” [294], and “life cycle inventories of wood as fuel” [295]. “Life cycle inventories of electricity mixes” used in the database was also explained in a report [296]. Looking at these reports and the life cycle inventories from the ecoinvent database, it is seen that CHP production is designed as a joint production in ecoinvent, which means that the relative outputs of joint products (electricity and heat in this case) are fixed.

Generally, as with ecoinvent, all the LCA databases offered in LCA software are comprehensive sources of information. However, it is important to note that this information should not be accepted as provided in databases, but should be adapted to represent the specific conditions of the LCA study. For adaptation purposes, all methodological reports, including major assumptions and calculations made by database producers, should be examined carefully [297]. To adapt data from databases,

the most important issue, and a de-facto standard, is to adapt electricity, heat, and fuel consumption to match those in the region where the LCA is being conducted.

2.8 Cost of CBHBP Production

There are many different biomass sources, conversion paths, and technology options to produce biopower and bioheat. Therefore, cost figures (investment cost and biopower generation cost) vary remarkably depending on the specific feedstock, processes, and local conditions.

For the projects commissioned in the year of 2015, Table 2.7 shows the global weighted average levelized cost of electricity (LCOE) for biopower along with other renewable power technologies. The LCOE of a project represents the cost of electricity when the present value of revenues and costs are equal over its lifetime.

Table 2.7 : Global weighted average levelized cost of electricity (LCOE) for renewable power technologies [7].

	LCOE (cent/kWh) ^a
Biopower	6
Geothermal	8
Hydro	5
Wind (Onshore)	6
Solar Photovoltaic	8

^a cent: US Dollar cent, LCOE: Levelized cost of electricity.

The global weighted average LCOE for biopower is reported to be around 6 cent per kWh, which competes well with fossil fuels having costs between 4.5 cent/kWh and 14 cent/kWh. Actually, improvements in the competitiveness of all renewable-power generation technologies has continued since the past decade [7].

The focus in the following lines is on the solid biomass sources, combustion, and steam cycles. Table 2.8 summarizes the cost figures for the power plants based on combustion with steam turbine technology. Power plant size, efficiency, investment cost per kW, and unit cost per kWh, along with remarks, are provided in the table. The table includes both biopower-only plants and CBHBP plants. The approach to calculate net costs in the case of a cogeneration configuration is to consider a credit displacing the bioheat generated. As seen from the table, there are variations in cost figures. This is mainly due to feedstock quality and cost, geographical conditions,

power plant sizes, and efficiencies, as well as technological options and maturity. Overall, for grate combustion, the cost in the literature ranges from 3000 to 9260 US Dollar (USD) per kW (994 to 5556 Euro (EUR) per kW). The unit cost in cent ranges from 4 to 29 cent/kWh (in EUR: 0.06124 EUR/kWh).

According to the “National Renewable Energy Laboratory” in the USA, the mean installed cost for a CBHBP plant based on combustion is 5792 USD/kW with a standard deviation of 2762 USD/kW. While fixed operation and maintenance (O&M) cost is presented as 98 USD/kW-a with a standard deviation of 29 USD/kW-a; variable O&M cost is presented as 0.04 USD/kWh with a standard deviation of 0.02 USD/kWh [298].

The IEA reports that while unit cost for biopower generation is 11 cent/kWh for biopower-only plants using dedicated steam cycles, the unit cost for CBHBP plants ranges from 4 to 9 cent/kWh [29].

According to the “Energy Information Administration” in the USA, for a biopower plant generating 50 MW_e (net), and using BFB technology with 2000 t/d wood fuel having 50% moisture content; the capital cost, fixed O&M costs, and variable O&M costs are 4985 USD/kW, 110 USD/kW-a, and 0.042 USD/kWh, respectively [299].

In Europe, the specific investment costs for CBHBP plants based on combustion and steam turbine technology, and using solid biomass sources with biopower output less than 250 MW_e, are less than 5000 EUR/kW. For CBHBP plants with output greater than 2 MW_e, steam turbine technology has the lowest investment cost. Also, investment costs decrease with increasing biopower installed capacity due to economies of scale [126].

In a review study [221], the total cost of biopower generation was reported to be between 2.8 and 12.7 cent/kWh for the plants using solid biomass sources and combustion-based technologies. Including gasification and pyrolysis, the average cost was calculated to be 6.9 cent/kWh, which is lower than solar power (24 cent/kWh), about equal to geothermal (6.8 cent/kWh), and more expensive than wind (6.6 cent/kWh), hydro (5.1 cent/kWh), coal (4.2 cent/kWh), and gas (4.8 cent/kWh) [300].

The “International Renewable Energy Agency” (IRENA) reports that the investment

Table 2.8 : Cost figures for biopower and/or bioheat production based on combustion with steam turbine technology (Compiled from the sources indicated).

Plant Size (MW _e)	Efficiency (%)	Cost		Remarks	Year Reported	Reference
		Investment Cost (per kW)	Unit Cost (per kWh)			
		USD ^a 5792		CBHBP ^b , combustion Mean installed cost Standard deviation is ± USD 2762	2017	[298]
5–25	30–35	USD 3000–5000	11 cent ^c 4–9 cent	Biopower-only plants Biomass cost = USD 3/GJ CBHBP ^c	2007	IEA [29]
50		USD 4985		BFB ^d combustion 2000 t/d woody biomass	2016	[299]
2–600			2.8–12.7 cent	Solid biomass sources	2010	[221]
5		USD 3550–6820	7–29 cent	CBHBP, Grate combustion, LCOE ^e Feedstock cost is 40 USD/t	2012	IRENA [301]
25		USD 4920				
		USD 5904				
0.5		USD 9260	9.8 cent	CBHBP, Grate combustion, 100 t/d feedstock	2007	[56]
5.6		USD 4630	5.5 cent	CBHBP, Grate combustion, 600 t/d feedstock		
8.4		USD 4000	7.4 cent	CBHBP, Grate combustion, 900 t/d feedstock		
0.5		USD 20,070	7.7 cent	CBHBP, CFB ^f combustion, 100 t/d feedstock		
5.9		USD 5515	6.6 cent	CBHBP, CFB combustion, 600 t/d feedstock		
8.8		USD 4860	8.4 cent	CBHBP, CFB combustion, 900 t/d feedstock		

Table 2.8 (continued): Cost figures for biopower and/or bioheat production based on combustion with steam turbine technology (Compiled from the sources indicated).

Plant Size (MW _e)	Efficiency (%)	Cost		Remarks	Year Reported	Reference
		Investment Cost (per kW)	Unit Cost (per kWh)			
		USD 3060–8169		Combustion	2014	[302]
			5–20 cent	LCOE, Combustion, USA	2013	[303]
			5–20 cent	LCOE, Combustion, Western Europe		
			6.5–8.6 cent	LCOE, Combustion, India		
5.7	22.3		EUR ^f 0.06124	CBHBP plant in Austria	2015	[35]
10	27	EUR 3700		CBHBP	2012	[304]
30	30	EUR 2800				
80	34	EUR 2200				
0.5–20		EUR 994–5556		CBHBP plants in Finland Start-up years: 1992 to 2002	2004	[33]
2.95–33		EUR 1500–4817		CBHBP plants in Sweden Start-up years: 1990 to 2002	2004	[32,33,203]

^a USD: US Dollar.

^b CBHBP: Combined BioHeat and BioPower.

^c cent: US Dollar cent.

^d BFB: Bubbling Fluidized Bed.

^e LCOE: Levelized cost of electricity.

^f CFB: Circulating Fluidized Bed.

^f EUR: Euro.

cost for CBHBP plants with grate combustion is 4920 and 5904 USD/kW for 5 and 25 MW_e generation, respectively. In general, for CBHBP plants, while investment costs range from 3550 to 6820 USD/kW, LCOE ranges from 7 to 29 cent/kWh [301].

According to the “Environmental Protection Agency” in the USA, unit costs of CBHBP plants with grate combustion technology for the scales of (0.5, 5.6, and 8.4) MW_e are (9.8, 5.5, and 7.4) cent/kWh, respectively. With CFB combustion technology for the scales of (0.5, 5.9, and 8.8) MW_e, the costs are (7.7, 6.6, and 8.4) cent/kWh, respectively. Investment costs are between 4000 and 9260 USD/kW for grate combustion, and between 4860 and 20,070 USD/kW for CFB combustion. It is seen that the investment costs of CFB systems are significantly higher than for stoker systems [56].

In a review report, for biopower technologies based on steam turbines, investment costs are reported to fall between 3060 and 8169 USD/kW [302]. According to the “World Energy Council” (WEC), the LCOE for biopower technologies based on combustion is 5–20 cent/kWh in both the USA and Western Europe, and 6.5–8.6 cent/kWh in India [303].

For an Austrian CBHBP plant producing 5.7 MW_e with 22.3% efficiency, the unit cost was 0.06124 EUR/kWh [35]. For some operational CBHBP plants in Finland and Sweden with startup years between 1990 and 2002, investment costs ranged from 994 to 5556 EUR/kW for scales between 0.5 and 33 MW_e [33,203].

2.9 Literature Review

This section provides the results of selective literature review indicated below:

- Literature review on CBHBP production
- Literature review on LCA of CBHBP and biopower-only production
 - Review articles
 - Research articles

During the literature review, the key search words and their synonyms were identified and then applied to titles, keywords, and abstracts. Some of the keywords were “Life Cycle Assessment, LCA, Life-Cycle, Yaşam Döngüsü Değerlendirmesi, YDD, biomass energy, bioenergy, biomass, CHP, cogeneration, combined heat and power,

bioelectricity, biomass to electricity, sustainability, environmental impact assessment, woody biomass, waste wood, biomass power plants, and biofuel life cycle”. The literature was searched using major national and international academic databases including such as “ULAKBİM, TO-KAT, YÖK Tez Merkezi, TÜBİTAK scientific journals, Science Direct, Environment Complete, Academic Search Complete, Taylor & Francis Online, EBSCOhost, Web of Science, Scopus, ProQuest, Energy and Power Source, and the Directory of Open Access Journals”. To reach studies not published in journals, the “World Wide Web” was searched using search engines. Studies in English and Turkish languages were taken into account for this literature search. In addition, although the literature search was performed without any date limitation, the LCA literature reviewed were published in 2000 or later. This is because the ISO released the first set of LCA standards in the year 2000.

2.9.1 Literature review on CBHBP production

González et al. [30] reviewed available technologies to convert biomass into biopower and/or bioheat production focusing on local wood chips from forests. The aim was to lower transportation needs, and hence to lower cost and the environmental impact of the whole supply chain at micro (less than 50 kW_e) and small (less than 1000 kW_e) scales while being compatible with sustainable forestry practices. In addition, the efficiencies of these technologies for the mentioned scales were compiled. The cost of these technologies was also discussed.

The conversion technologies to produce biopower and/or bioheat from wood chips were classified as primary or secondary conversion technologies. While primary conversion technologies were summarized as direct combustion or gasification; the secondary conversion technologies summarized were ICE, external combustion engine (Stirling engine), steam engine, steam turbine, ORC, gas turbine and BIGCC, micro turbine, other gas turbine based designs (externally-fired gas turbine, evaporative gas turbine), and other designs not currently commercialized and not under development. Efficiencies were reported according to the data for real biopower-only or for cogeneration plants using wood chips. It was stated that for micro scale plants, while electrical efficiencies were between 13 and 25 %, total efficiencies were between 60 and 74 %. For small-scale plants, electrical efficiencies were 12.5–28 %, while total

efficiencies were as high as 96%. It was also noted that better efficiencies could be reached with biomass co-combustion.

Cost is an important driving element for conversion technologies and their deployment. In this context, biomass-to-biopower with combustion and steam turbine was reported to be the most usual technology because it has relatively low investment and O&M costs because of its high commercial availability, maturity, and time in service.

It was concluded that forest biomass, among other renewable energy sources, is an attractive alternative for biopower and bioheat generation. This is because forest biomass is an indigenous energy source in most countries and this has many benefits: reduced GHG emission, more advanced forest management that leads to better environmental protection, creation of green jobs in rural areas, and reduction in risk of wildfires. Added to that, the most viable conversion technology depends on many factors such as plant scale, heating demand, and associated costs.

Bilgen et al. [305] provided a review on biomass potential in Turkey. The focus was on woody biomass sources, biomass energy technology choices, and future policies related to biomass energy in the country. It was emphasized that the development of modern biomass energy technologies is essential for this country.

Jenssen et al. [34] analyzed the concept of “bioenergy villages”. As an example, they used a municipality as a model in a rural area in Germany. It was explained that bioenergy villages aim to maximize the usage of biomass energy sources, and to operate their infrastructure independently. It was also added that a lot of bioenergy villages have been operated in rural areas of Central Europe over the last ten years. The advantages and disadvantages of bioenergy villages were analyzed, and their challenges and possible solutions were presented. It was also emphasized that because bioenergy villages are generally implemented in residential areas, public acceptance is essential for successful project implementations.

In the study, first of all, a model was identified with characteristics such as inhabitants, buildings, and heating and electricity demands. Then, a technology analysis and an assessment were completed to define CO₂ emissions and energy production costs. The analyzed technologies included eleven biomass energy technologies (biogas, district heating, biomass CHP, biodiesel, biomass to liquid). There was also one fossil fuel

technology and also fossil-based reference technologies for heat, electricity, and transportation fuel provisions. CO₂ emissions were taken from LCA studies. Later, based on this technology assessment, technologies were combined into six alternatives which were able to meet the whole energy demand of the model specified. Finally, these alternatives were balanced regarding to CO₂ emissions, land use, and costs.

According to the technology assessments, environmental and economic outcomes indicated that all biomass energy technologies had less CO₂ emissions than with the equivalent fossil-based reference technologies, but hardly achieved lower costs without incentives. In addition, the most cost-effective form of biomass energy was bioheat generation. Added to this, transport fuel production had the highest CO₂ emissions and highest costs. Moreover, using residues was much more favorable in terms of both environmental and economic balances than was growing energy crops. Furthermore, when looking at six combinations, in terms of CO₂ emissions, it was concluded that bioenergy villages could contribute to low carbon supply energy for rural areas. However, it was emphasized that even covering the whole energy demand of a village with biomass, a zero-emission village could not be achieved due to incorporation of up and downstream processes from an LCA perspective. In terms of costs of six combinations, bioenergy villages hardly achieved the results of conventional supply systems without taking into account incentives under current prices in Germany. With regard to land consumption, it was stated that covering energy demands without causing significant land competition was possible. Added to that, municipalities that have large forest areas were seen as excellent candidates to become bioenergy villages because combustion technologies based on wood are accepted as the most sophisticated and low-cost biomass energy technologies.

Overall, for bioenergy villages in Germany, the best current strategies were bioheat, biomass CHP, biopower-only, and transportation fuel production in return. The authors concluded that, assuming the bioenergy village concept was implemented in 50% of the rural area, CO₂ mitigation potential would be approximately 10.1–17.5 % of Germany's annual CO₂ mitigation, which was seen as reasonable for the German energy system.

The economic feasibility of installing a cogeneration unit in an industrial fiberboard plant was analyzed by de Oliveira et al. [216] by developing a valuation model that considered Brazilian conditions. It was explained that forestry industries, having

significant amounts of wood residues, would be able to reduce their energy costs and sell their energy excess by investing in cogeneration units to produce both thermal and electrical energy by extracting the energy value from their biomass residues.

In the reference case of the study, some wood chips were used to produce fiberboard and others as fuel for boilers to generate only thermal energy in the form of steam to be used in the process. The residues were donated to third parties; electrical energy demand was provided from an energy distributor. In the proposed model, a cogeneration unit was installed and fueled with biomass residues from the fiberboard process and natural gas. A connection to a power grid was made to provide the plant the flexibility to sell the surplus electricity production by transferring wood chips from fiberboard production to electricity production when energy prices were high.

It was concluded that the proposed biomass cogeneration investment was feasible even when the wood chips previously used to produce thermal energy were entirely used to produce additional fiberboard. It was also stated that the investment needed to connect the cogeneration unit to the grid increased the value of the plant.

Kelly et al. [215] investigated the suitability of industrial CHP as a low-carbon power generation technology via an LCA study of an available industrial CHP plant in the United Kingdom. The study showed that the application of industrial CHP as a method for utilizing an existing heat demand via CHP-conversion could produce electricity with lower associated energy and carbon impacts. On the other hand, considerable impact savings were achieved when total energy production was compared to total impacts of separate heat and power production.

Yılmaz and Selim [218] reviewed the methods for systems designs of biomass to energy conversion. The types of studies in the review were: energy systems, biomass conversion systems design, and hybrid renewable system (including biomass conversion) design. It was concluded that competitiveness with fossil fuel-based systems could be achieved if renewable systems were designed considering not only technical but also economic, environmental, and social criteria.

Salomón et al. [32] provided an overview of existing small-scale (up to 20 MW_e) biomass CHP plants in Sweden and Finland, which are the countries well known for biomass cogeneration in Europe. Several examples of biomass cogeneration plants having a power output lower than 20 MW_e (and built between 1990 and 2009) were

presented in tables each with their plant name, biopower output (MW_e), bioheat output (MW_{th}), biofuel input (MW), electrical efficiency (%), total efficiency (%), biopower/bioheat ratio, steam values, biofuel used, technology used, and startup year. It was seen that most of the biopower plants using solid biomass sources were based on a conventional steam turbine Rankine cycle. These plants had a grate or FB boiler. Moreover, a review was performed of major energy conversion technologies that are either commercially available, or under research and development, for small-scale biomass cogeneration. Their characteristics (power output range, electrical and total efficiency ranges) were reported, along with possible biofuels that could be used and investment costs. The technologies reported to be commercial (or close to commercialized) were conventional steam turbine Rankine cycle, gas turbine with HRSG, steam engines, micro turbines, ICEs (Otto and Diesel engines), Stirling engines, and fuel cells. Technologies under research and development including ORC were also explained. In this review, the characteristics for a conventional Rankine cycle facility were reported as 0.5–100 MW_e for power output, 20–30 % for electrical efficiency, 85–93 % for total efficiency. This assumes use of mostly solid biomass for possible biofuels and around 1500 EUR/ kW_e for investment cost. For cogeneration applications at smaller scales (less than 1000 kW_e), micro turbines, fuel cells, Stirling engines, and ICEs were reported as the most promising technologies.

It was emphasized that electricity market deregulations present new chances for small-scale distributed power plants and make decentralized generation such as small-scale biomass-fueled CHP facilities a rational alternative choice to centralized power generation. It was added that the increasing popularity of renewables also made small-scale biomass-fueled cogeneration a proper choice. It was concluded that small-scale energy systems would likely be a substantial component of a sustainable energy future.

Raj et al. [98] reviewed renewable-based CHP technology studies, including in the review technologies based on not only biomass but also on solar, fuel cells, and waste heat recovery. The stated aim of the review was to point out aspects of CHP technologies where there was scope for future study.

Dong et al. [122] presented a review on the growth of small-scale ($< 100 \text{ kW}_e$) and micro-scale ($< 15 \text{ kW}_e$) biomass cogeneration systems, which are especially appropriate for applications in commercial buildings, such as industrial buildings,

hospitals, schools, or houses. The relevant major conversion technologies were listed in a table. With a focus on current applications of ORC, comparisons were made between ORC and other technologies. It was emphasized that combustion with a steam turbine is the most widely applied combination, especially for large- and medium-scale biomass cogeneration systems. It was also added that biomass sources are best suited for decentralized, small- and micro-scale cogeneration systems. This is because, small- and micro-scale biomass cogeneration systems can decrease biomass transportation costs and supply bioheat and biopower where needed, and because it is harder to ensure an end-user for the bioheat produced in large-scale cogeneration systems.

Vamvuka et al. [164] analyzed technical, economic, and environmental data of different biomass CHP systems with a focus on European countries. Germany, Austria, Finland, Denmark, Sweden, Switzerland, and Slovenia use more biomass CHP than other countries in Europe. It was stated that steam turbine systems are among the most common technologies used because it is more secure and reliable, with access to good technological expertise. Moreover, steam engine systems are more common for industrial usage. ORC systems have increased investment costs and low maintenance costs. Stirling engine systems have higher investment and maintenance costs than micro-turbine systems. It was emphasized that current trends demand energy systems with good environmental performance, like biomass CHP units. According to their analysis, ORC, combined cycle, and Stirling engine technologies have shown better environmental results in the most recent studies.

Uddin and Barreto [306] analyzed primary energy use, CO₂ emissions, and mitigation costs of large-scale biomass-fueled cogeneration technologies based on steam turbine and BIGCC technologies with CO₂ capture and storage. It was found that if CO₂ is captured from biomass-fueled energy systems, these systems could be negative CO₂ emitters. However, when compared with energy systems in which CO₂ was not captured, CO₂ capture and storage reduced energy efficiency and increased investment and product costs. In addition, BIGCC technologies with CO₂ capture and storage were found very efficient for emissions and energy use compared with other conversion technologies.

Bain [156] provided an overview of biomass CHP technologies in the context of the United States. Co-firing, direct combustion, and gasification applications, and LCA studies on various power generating options were summarized. The lowest cost, and

the nearest-term option, was to use biomass for co-combustion with coal in present boilers, with minor modifications, up to around 15% of the total energy input. The comparative results of LCA studies with fossil-based systems included very low amounts of PM, NO_x, and SO_x emissions, and very small amounts of natural resource consumption.

Gustavsson [307] analyzed costs and primary energy use needed to generate 1.0 MWh electricity and 1.0 MWh heat, as well as handle CO₂ emissions, for different systems based on biomass and fossil sources. It was depicted that CHP plants are more cost- and energy-efficient than those based on either heat pumps or boilers with condensing plants.

Prasad [227] analyzed overall system performance of a biomass-fueled steam engine CHP system. The focus was on the boiler and steam engine as a prime mover. First, the performance of the boiler was studied on a theoretical basis, and then this was combined with actual performance of the steam engine to get overall system performance. A given fuel (sawdust) and its characteristics, excess air to the furnace, and assumed stack temperatures were used to calculate the boiler performance.

The results indicated the effect of several variables on boiler performance and the dependence of design output and efficiency on prime mover input conditions. It was depicted that boiler efficiency decreased with increasing moisture content, excess air, and stack exit temperatures. The amount of electricity produced per mass of feedstock, boiler efficiency, and overall system efficiency were plotted as a function of feedstock moisture content. It was concluded that boiler efficiencies were 84–49 %; steam engine efficiencies were 18–13 %; overall plant efficiencies were 11–8.4 %. The electricity/fuel ratios were 0.7–0.2 kWh/kg for the specific study systems, using biomass feedstocks with moisture contents from zero to 60%, and excess air rates from zero to 200%.

Gustavsson and Johansson [225] studied different ways of using biomass energy in the sectors of electricity, heat, and transportation in a country context in Sweden. The focus was on district heating, and recent technologies like biomass gasification. Performance and costs (capacity, efficiency, investment, and O&M costs) for different biomass energy technologies and conventional systems were estimated. The efficiency (also costs) of using biomass in district heating networks was compared with the

efficiency of biomass-fueled boilers and heat pumps, considering distribution losses. It was concluded that CHP is the most energy efficient choice to produce bioheat and biopower. In addition, biomass is used more efficiently in district heating systems with CHP than in condensing plants or in individual boilers. BIGCC was found to be the most energy efficient choice for using biomass for CHP. However, steam turbines had the lowest heat costs.

Tillman and Jamison [105] carried out a review on CHP cycle fundamentals, considered their adaptability to wood fuels, and examined the technical and economic feasibility of wood-fueled CHP. It was emphasized that while all fuels could be used in CHP mode, wood is a major candidate because it is a renewable source and principally used by forest products industries with requirements for both steam and power.

It was found that, among CHP cycles, the steam turbine topping cycle is the most suitable one for wood fuels. The economics of CHP was studied, including design (wood firing and steam cycle) and financial considerations. Some wood firing considerations were reported as minimizing excess air ratios, adjusting air distribution, and employing economizers and air preheaters to gain energy from stack gases. It was stated that steam cycle considerations are related to the power to heat ratio, which is influenced by steam conditions at the turbine throttle (inlet) and turbine exhaust (outlet), as well as by turbine capacity and efficiency. It was noted that while heat requirements generally reveal outlet steam conditions, site-specific economic evaluations generally assign inlet steam conditions. Thus, a specific system design includes sizing the boiler to a heat sink, and then optimizing the steam conditions of the turbine on a site-specific basis. The benefits of cogeneration, which are capital and fuel savings and decreased environmental impact, were explained with a simplified flow diagram including material and energy balances of a wood-fueled cogeneration system. This also showed a comparison of fuel consumption and emissions using and not using (coal fired) this system. It was presented that for a 5 MW_e wood-fueled CHP plant, annual PM emissions were 12 t (6 t or greater, because with wood a greater amount must be used as fuel), annual SO_x emissions were neglected (17 t or lower), and annual NO_x emissions were 15 t (100 t or lower).

It was concluded that CHP is a conservation tool and does not require any sacrifice in quality of life. It has significant economic advantages with the potential for producing

less costly power. This makes it attractive for areas where power production is inadequate or power is too high in cost.

2.9.2 Literature review on LCA of CBHBP and biopower-only production

First, the literature search showed that there are numerous LCA studies in literature about biomass energy LCAs. Most of these LCAs are focused on biofuels for transport. The LCAs focused on biopower production, were mostly interested in either electricity or heat production alone. During the literature search, only a few LCAs were found concerning both electricity and heat production, and few LCA review studies concerning electricity and/or heat generation from biomass were encountered. In addition, these LCAs were mostly performed for a regional context.

Second, although LCA principles are well known and standardized, it was seen that in practice several methodological choices exist. Standards provide guidelines but allow freedom to LCA practitioners for some methodological issues. This enables LCA applications to be open to interpretation and hence to address different specific questions. On the other hand, subjective choices about such as the system boundary, functional unit, allocation procedures, reference system, carbon cycle modelling, indirect effects, etc. may cause a wide range of final results, even for the same goal and scope. Furthermore, in addition to differences in these methodological choices, the importance of local conditions force LCA practitioners to conduct location specific LCAs. Consequently, the number of LCAs increases year by year. The following subsections provide literature review studies on LCAs of CBHBP production, classified as review or research articles.

2.9.2.1 Review articles

Muench and Guenther [222] conducted a systematic literature review on biopower and bioheat LCAs covering studies in English that were published in the year 2000 or later. After a literature search, they applied practical and methodological screening criteria to identify relevant LCA studies to be analyzed. After that, they first conducted a quantitative analysis to give an overview of the environmental impacts of biopower and bioheat, and found that there is considerable variability in LCA results. Second, they performed a qualitative analysis to identify the sources of variations in these results. They concluded that the first area of variation included regional parameters, varying energy needs for different feedstock, and unstable yield. The second area

included methodological choices made for the LCAs. They identified and discussed the methodological choices that might cause such variations. They proposed ways to take into account during LCA preparations, things that could prevent variation in the methodological choices. Finally, they concluded that ISO framework adherence should be guaranteed and reported, and a higher level of transparency regarding the methodological choices selected is needed.

In their quantitative analysis, Muench and Guenther [222] presented an overview of biomass feedstock utilized, conversion technologies used, LCIA methods considered, and the regions where LCAs were conducted. They found that in terms of feedstocks, lignocellulosic feedstock is remarkable for biopower and bioheat, and for biopower-only LCAs. As a lignocellulosic feedstock, wood residues were used in the greatest number of biopower studies. The conversion technologies among studies include thermochemical and biochemical conversion paths. Most biopower LCA studies assessed thermochemical conversion, direct combustion, or co-firing of biomass, which also had a strong focus on lignocellulosic feedstock. The majority of biopower LCAs were prepared in Europe, with North America second. According to the review, most of the studies applied problem-oriented midpoint impact categories to their LCAs. The most frequently used impact categories in biopower LCAs were GW, ACD, and ETR. The quantitative assessment also focused on these impact categories. There are minor studies that considered other impact categories, such as land use change, HT, OD, and others. Table 2.9 presents GW, ACD, and ETR ranges based on quantitative analysis of the LCAs considered in this review.

In their qualitative analysis, the authors focused on the methodological choices that could cause variations: system boundary, functional unit, allocation, and carbon cycle. They insisted on the use of, at minimum, one energy-output related functional unit. For allocation selection, they developed a process model following ISO 14044 recommendations. With respect to the system boundary definition, they depicted three paths (biomass path, conversion system path, energy service path) that play important roles in a biomass energy system. It was concluded that a biomass path with end-of-life must always be in the assessments. The carbon cycle is another important issue to consider in LCAs. They pointed out that the assumption of carbon neutrality must be made in accordance with ISO 14064 series standards. Moreover, the positive effect on

Table 2.9 : Global warming, acidification and eutrophication ranges of the CBHBP LCAs [222].

(per MJ energy provided)	Global Warming (g CO ₂ eq)			Acidification (g SO ₂ eq)			Eutrophication (g PO ₄ ⁻³ eq)		
	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
BioPower	0.30	38.19	193.00	0.05	1.74	2.32	0.01	0.46	0.60
BioHeat	1.65	8.20	21.39	0.01	0.13	0.27	0.00	0.02	0.04
BioPower and BioHeat	-47.49	-25.18	8.64	0.11	0.18	0.33	0.02	0.30	0.49

GHG emissions of residual biomass, timing of GHG emissions, and soil carbon changes should also be explored in detail.

Turconi et al. [308] conducted a review of LCA studies involving nonrenewable (hard coal, lignite, natural gas, oil, nuclear) and renewable-based power generation technologies (biopower, hydro, solar photovoltaic, and wind). In terms of life cycle environmental impacts, the most critical methodological aspects and the most important technological aspects were identified. To ensure the best data quality, LCA studies were selected based on some criteria. GHG, NO_x, and SO₂ emissions were selected and evaluated with regard to three life cycle paths: fuel provision (from fuel extraction to plant gate), plant operation (O&M and residue disposal), and infrastructure (commissioning and decommissioning). The defined functional unit was 1 MWh of electricity.

While a flue-gas cleaning system and energy recovery efficiency were found to be the most important technological aspects of fossil fuels, the electricity mix used during manufacturing and installation processes was found to be the most important technological aspect of renewable and nuclear power technologies. For biomass-based technologies, origin, type, and quality of biomass feedstock, as well as amount and type of co-products, were also emphasized.

The most critical methodological aspects found were the functional unit definition, LCA data acquisition method applied (process chain analysis or input-output analysis), and emission allocation principle used.

With respect to the three life cycle phases mentioned above, the fuel provision demonstrated the greatest contribution for biomass technologies (71% for GHG, 54% for NO_x, and 61% for SO₂) along with nuclear technologies. On the other hand, plant operation demonstrated the vast amount of life cycle emissions from fossil fuel technologies. Comparing renewables with fossil fuels, the infrastructure caused the highest impact for renewables, and nuclear power followed renewables. In contrast, infrastructure was considered a minor issue for fossil fuels. In the study, it was emphasized that an assessment focused only on GHG emissions may lead to wrong conclusions about the environmental impacts of power generation technologies, so other emissions (such as ACD and ETR) should also be included in LCAs. In addition, it was pointed out that, in terms of biopower, because the fuel provision was found to be the main factor responsible for GHG emissions, neglecting any upstream impacts such as land-use-related emissions associated with biomass (zero burden assumption) might appear to be correct only for residual biomass sources. In this context, the system boundary definition is very important and has a large influence on results, especially for biopower generation technologies.

Moreover, this study showed the variability of reviewed LCA results for power production. The main reasons were summarized as technological differences, local conditions, and methodological aspects. On the other hand, even for the same technology, significant variations were found. For example, the GHG emission factors for different technologies of electricity generation from biomass are 25–130 kg CO₂ eq/MWh for co-combustion, 8.5–118 kg CO₂ eq/MWh for combustion, and 17–117 kg CO₂ eq/MWh for gasification. Table 2.10 presents life cycle emission factors of electricity generation technologies for GHG, NO_x, and SO₂. Emission factors in the table refer to electricity output, kg/MWh. In conclusion, it was recommended that future LCA studies must include transparent statements of data applicability and methodological constraints to improve transparency and usability of the results found.

Cherubini and Stromman [220] performed a review of biomass energy LCA literature, covering a period of five years (2006–2011). They depicted a qualitative interpretation

Table 2.10 : Life cycle emission factors of electricity generation technologies [308].

Energy Source	CO ₂ eq	NO _x	SO ₂
	kg/MWh Electricity Output		
Hard coal	660-1050	0.3-3.9	0.03-6.7
Lignite	800-1300	0.2-1.7	0.6-7
Natural gas	380-1000	0.2-3.8	0.01-0.32
Oil	530-900	0.5-1.5	0.85-8
Nuclear	3-35	0.01-0.04	0.003-0.038
Hydro	2-20	0.004-0.06	0.001-0.03
Solar	13-190	0.15-0.40	0.12-0.29
Wind	3-41	0.02-0.11	0.02-0.09
Biomass	8.5-130	0.08-1.7	0.03-0.94

to point out the key methodological issues that might cause variability in LCA results. The reviewed studies were grouped according to their location and scope, feedstocks and products, and impact categories. It was found that more than half of the reviewed studies were performed in Europe and North America. With respect to the scope of studies, half of them limited their assessment to GHG and energy balance calculations without taking into account other impact categories. Concerning bioheat and biopower production, the number was much lower than biofuels for transport. Lignocellulosic biomass was found to be the most investigated feedstock.

Qualitative interpretation of the results was divided into GHG balance, energy balance, and other environmental impacts. It was stated that the fossil energy need of biomass energy systems was mostly influenced by fossil energy usage during cultivation or processing. It was found that, generally, fossil energy input for transportation biofuels was higher than that of biopower/bioheat generation. In terms of GHG emissions, it was concluded that biomass energy systems generally showed savings when compared with fossil systems. Biopower, if compared with other renewables (hydro, wind, geothermal), generally showed higher GHG emissions. With respect to other environmental impacts, biomass energy crops with intensive agricultural applications and the use of fertilizers, caused increased ETR, ACD, and photo-smog formation.

After qualitative interpretation of the review, it was pointed out that the main methodological choices and assumptions caused broad ranges in the final results of the biomass energy LCAs. These included different functional unit types (input/output

unit related, unit of agricultural land, per year), different LCA methods (attributional/consequential LCA), lack of changes in land use (direct and indirect changes) and residual removal effects, and different allocation approaches.

Evans et al. [221] assessed the sustainability of biopower production. The sustainability indicators used were biopower cost, energy conversion efficiency, limitations, availability, GHG emissions, water and land use, and social impacts. All indicators were assessed over the whole life cycle (biomass growth, collection, transportation, biopower production, and disposal) on a per kWh basis. Assessment included thermal conversion technologies, and forest residues, agricultural residues, and dedicated crops.

In terms of price, waste sources cost the least and had minimal transportation needs. Looking at the investment costs and technology choices, technologies based on combustion were more advantageous over their life cycle compared with gasification or pyrolysis, in spite of their higher operating costs.

Efficiencies varied widely across different technologies. The highest efficiencies (up to 43%) were seen for combined cycle gasification technology, and the average efficiency found for all technologies was 27%.

With respect to GHG emissions, in most cases in the reviewed studies, biopower generation produced low-net-carbon emissions, largely in CO₂ form, with the average carbon emission of 62.5 g CO₂ eq/kWh, and the highest emission of 132 g CO₂ eq/kWh. However, it was emphasized that if not produced in a sustainable way, biopower can emit more CO₂ per kWh than fossil fuels; for example, biopower impacts are seen as negative when vegetation was removed to set up energy crop cultivation. Because changes in land use forms affect GHG emissions, carbon emissions must include land clearing, deforestation, and soil emissions within the assessments. For example, the highest emissions were seen when grasslands and forests were transformed into arable croplands. According to some studies, harvest methods that leave roots in the soil maintain carbon neutrality by leaving sufficient carbon and hence balancing all other emissions, whereas some studies claimed net C negativity because biomass combustion avoids anaerobic decomposition that results in CH₄ emissions.

Technology choices were also questioned. Gasification and pyrolysis showed significantly less emissions than combustion, and gasification insignificantly less emissions than pyrolysis. In addition, looking at different feedstock usage, straw showed the highest emissions while forest residues demonstrated emissions always less than dedicated SRC.

With regard to water use, a significant amount of water was used to cultivate, harvest, transport, and process the biomass. Biomass had a higher overall water use than coal because horticulture involved significant water requirements. On the other hand, concerning power plant operation, biomass had water use similar to that of coal power plants (78 kg/kWh).

In the matters of availability and limitations, feedstock availability was seen as problematic for large-scale biopower production due to biomass source constraints. It was stated that biomass use was land-and-source constrained when supplied by energy crop plantation. Concerning land use, biomass growth may compete with food crops, forest, and urbanization. It was pointed out that destruction of natural forestry and allocation of agricultural land for energy crop plantations is not sustainable. Biomass cultivation is best used to improve degraded or marginal lands.

In terms of social impacts, the review explained that there is a large range of impacts (positive and negative) arising from biopower production. Food competition was seen as a key negative social issue to be considered. The labor requirement was seen as a positive social issue. Direct labor inputs per unit energy were two or three times higher than for coal. The labor requirements for construction and O&M were also higher. However, more occupational injuries were associated with biomass. It was stated that collecting waste wood from poor communities where waste wood is the only source of heating might remove self-sufficiency, and hence efforts must be made to ensure that biomass removal does not disadvantage those communities.

In the review, it was concluded that biopower, when compared with other options, is generally favorable in terms of GHG emissions, efficiency, availability, limitations, and cost. However, considerable attention must be shown to land and water use as well as social aspects. The least sustainability occurred with energy crops competing with food crops or with energy crop plantation using fertilizers in high quantities. Biomass type and growing location share primary importance for its sustainability. Waste

products and crops that are grown on marginal, degraded lands are much more sustainable than are dedicated crops.

Varun et al. [309] presented an LCA of renewable energy systems to produce electricity. Carbon emissions of renewable energy systems, including wind, solar photovoltaic, solar thermal, biopower, and hydropower, were drawn from the literature and compared with those of conventional energy systems, coal, oil, natural gas, and nuclear. It was seen that life cycle emissions of renewable energy systems were very low when compared with those of conventional energy systems. The highest emission was 975.3 g CO₂ eq/kWh, and the lowest emission was 24.2 g CO₂ eq/kWh. Among renewable energy sources, it was observed that small hydropower (run-of-the-river) in which there is no water storage, was the most attractive, but was also highly site dependent. It was also pointed out that C emissions from renewable-based energy systems were not always favorable. For example, solar photovoltaic produced significant life cycle emissions. It was concluded from the study that for an optimum selection of electricity generating sources, various technologies should be used together to balance the overall environmental load. Table 2.11 shows a comparison of life cycle emissions for renewable and conventional electricity production systems.

Table 2.11 : Comparison for life cycle emissions of renewable and conventional electricity production systems [309].

Nonrenewable-based Energy Source	g CO ₂ eq/kWh Electricity Output	Renewable-based Energy Source	g CO ₂ eq/kWh Electricity Output
Coal	975.3	Hydro	3.7-237
Oil	742.1	Solar	53.4-250
Natural gas	607.6	Wind	9.7-123.7
Nuclear	24.2	Biomass	35-178

Fthenakis and Kim [310] reviewed land requirements throughout life cycles of renewable energy alternatives (wind, solar photovoltaic, geothermal, hydropower, and biopower) and conventional energy alternatives (coal, natural gas, and nuclear). In land use assessments, both occupation (direct) and transformation (indirect) usages were taken into account. Although land use requirements change with regional and technological conditions, they found that solar photovoltaic land requirements are the lowest among renewable-based and conventional energy options while biomass cycle

land requirements are the largest. This is because the biomass sources considered in this study are all dedicated crops and compete with agricultural products for land. It was stated that a distinctive characteristic of renewable-based energy sources like solar photovoltaic, wind, and biomass is that they are able to use land statically. Once their infrastructure is constructed, there is no need for further extraction of sources to the power plant. Moreover, solar photovoltaic and wind power plants can be located on degraded lands, and they do not disturb the land by repetitive fuel transportation to the power plants. It was concluded that further investigation is essential to evaluate the impacts on regional and global levels.

Cherubini et al. [311] discussed key issues in biomass energy LCAs influencing their outcomes, and provided GHG and energy balances of some biomass energy chains while presenting a comparison with their fossil-based alternatives and other renewable-based energy systems. In terms of biomass supply, it was stated that using biomass residues and wastes for energy purposes did not usually increase environmental loads, with some exceptions. The exceptions were that removal of biomass residues could decrease carbon storage in carbon pools. In addition, market creation for biomass residues could make major forestry commodities economically more attractive, leading to increase in land use and causing negative environmental impacts. However, it was also explained that increased production of wood products might have positive impacts when substituted for more emission intensive products. In terms of dedicated energy crops, it was stated that an ideal energy crop should have high yield, should need little agrochemical support, should require little irrigation, and should have low moisture content at harvest. It was emphasized that sustainable agriculture is essential for energy crops to be accepted.

The carbon neutrality of biomass energy was also argued, along with its effect on carbon pools. Three different carbon pools were listed in the study. These were vegetation (including roots), litter, and soil pools. When land utilization is changed, these carbon storage pools change until reaching a new equilibrium. Removal of additional forest residues, intensive cultivation, fertilizer application, and converting woodlands or grasslands to energy crop lands are examples that cause changes in the soil carbon pool.

In addition, non-CO₂ GHG emissions such as N₂O, CH₄ occurring in biomass energy systems were discussed in terms of their origin and methods to estimate them.

Moreover, some methodological issues concerning LCA of biomass energy systems such as land use change (direct and indirect), comparison of biomass energy systems with reference fossil energy systems, and functional unit selection were discussed. For biomass energy systems delivering some by-products, it was stated that it is important to consider their non-energy utilization because they can be used to substitute other materials. In this situation, a fossil reference system should be used to define the substituted reference products. It was emphasized that for biomass residues, the results should be calculated per output (such as kWh) to be independent from biomass feedstock types and per input (such as kg of feedstock) to be independent from biomass conversion processes. Because there are important aspects such as assumptions, system boundaries, input values, and allocation methods giving rise to wide ranges in biomass energy LCA studies, it was pointed out that it is crucial to integrate uncertainty and sensitivity analysis into the results of LCA studies.

GHG and energy balances of some biomass energy pathways were given in the study. According to energy balance results, it was reported that biomass energy systems were influenced by a larger cumulative energy requirement than conventional and other renewable systems, although it was not possible to draw general conclusions. It was added that fossil energy input was higher for biofuels than for biopower and bioheat production (usually based on wood combustion). According to GHG balance results, it was stated that GHG emissions to generate a unit biopower were usually 5–10 % of those to generate a unit power from fossil fuels. In addition, it was found that biopower, if compared with other renewables, was comparable with solar photovoltaic power, while it had higher emissions than wind, hydro, and geothermal derived power. It was concluded that biomass energy chains including wastes/residues as feedstock showed the best LCA results.

Weisser [312] reviewed and compared life cycle emissions (GHG) of electricity production technologies for fossil (lignite, coal, and oil), nuclear, and renewable-based energy technologies (photovoltaic, wind, hydropower, biopower). Also considered were carbon capture and storage technologies, and energy storage systems. This literature review showed that renewable and nuclear energy technologies had a lower amount of life cycle emissions than did fossil technologies. For fossil fuels, the largest amount of emissions arose during power plant operation. For renewable fuels, plant operation upstream processes (typically infrastructure) caused the majority of life

cycle emissions. GHG emissions over the entire life cycle of biopower technologies were found to be between 35 and 99 g CO₂ eq/kWh. With respect to carbon capture and storage technologies, it was concluded that, although carbon capture and storage can lead to a substantial decrease in life cycle emissions of fossil fuels, they are still higher than for nuclear and renewable-based power plants. Moreover, carbon capture and storage increases fuel requirements per kWh supplied to grid, and decreases power-plant net efficiency. Concerning energy storage systems, it was emphasized that storage systems could add an important amount to GHG emissions of an electricity system, depending on the electricity source used for energy storage. In this review, five carbon mitigation options were proposed: more efficient fossil fuel conversion, use of lower-carbon fossil fuels (e.g., switching from coal to gas), increase in nuclear power, use of renewable power, and use of carbon capture and storage technologies.

2.9.2.2 Research articles

Perilhon et al. [313] studied an LCA of electricity production through combustion from waste wood (wood chips, barks, edgings) in cogeneration plants: 10 MW_e and 2 MW_e biomass power plants. They focused on biopower production, and bioheat was considered a co-product. Therefore, the functional unit chosen was 1 MJ of biopower, and fuel consumption and emissions were allocated to biopower and bioheat according to the coefficient of allocations calculated for each power plant. Environmental impacts for the 2 MW_e biomass power plant were compared with those of a conventional system (a 2 MW_e diesel power plant). System boundaries included life cycles from wood storage to electricity generation. Necessary data to assess life cycle impacts were taken from the ecoinvent database, an industrial company, and regional (French) regulations on pollutant emissions. The IMPACT 2002+ impact assessment method, which provides an assessment both at midpoint and at endpoint levels, was used. It was assumed that CO₂ emissions are carbon neutral and therefore that CO₂ is reabsorbed during biomass regrowth.

In the study, they concluded that with the assumptions used, biomass CHP plants were more environmentally friendly than was the conventional system considered in the research. There were positive effects on GW and fossil resource depletion, lower impacts on health, and no impact on ecosystem quality. They also emphasized that there are different stages and difficulties of an LCA applied to energy production. For

example, data quality, calculations, assumptions, and choices can all affect an LCA result. Therefore, it is important to specify objectives as precisely as possible, validate the collected data, set up negligibility criteria for data collection, re-use previous studies to limit the work necessary, and prepare detailed reports.

Guest et al. [223] studied LCA of CHP generation through gasification of forest and sawmill residues in a regional perspective for Norway. They compared life cycle impacts of CHP plants having different scales: micro-scale 0.1 MW_e, small-scale 1 MW_e, and medium-scale 50 MW_e. A unit-process based attributional LCA was performed. Two energy output related functional units were chosen: 1 MJ of biopower and 1 MJ of bioheat supplied to end users. Energy distribution was included in the system boundaries of the study; therefore, environmental impacts from biopower and bioheat distribution were also considered. To assess the impacts a midpoint method (CML 2 Baseline 2000) was used. A procedure for allocating between bioheat and biopower was based on energy output: exergy allocation was applied to the study. It was assumed that CO₂ emissions were carbon neutral and hence did not contribute to climate change. The ecoinvent v2.0 database, GEMIS 4.5 database, and practical sources were used as the main data sources.

With regard to GW, while they found 8.8–10.5 g CO₂ eq/MJ for biopower to the end user, they found 2.4–2.8 g CO₂ eq/MJ for bioheat to the end user. They claimed that there is no rationale to discriminate between different scales of CHPs in terms of environmental impacts. Instead, there are several trade-offs between them so that larger scale CHPs are found to be higher in the global impact categories, while smaller scale ones are found to be higher mostly in local categories. However, they suggested that the best environmental choice might be an optimum small-scale cogeneration plant.

Basic uncertainties in this LCA study existed because of CHP plant operational emissions, biomass feedstock supply, and biopower/bioheat distribution distances. They illustrated that CHP plant operation and biomass supply contributed significantly to various important impact categories (GW, ETR, ACD, and PCO). They also illustrated that biopower/bioheat distribution to end users contributed greatly to several impacts (PCO, terrestrial toxicity, ACD, and ETR). Therefore, they pointed out that energy delivery is also very important for LCA studies, and it should be within the system boundaries of electricity and/or district heat LCAs. In the study, they assumed

that the biomass supply was near the CHP plants and they proposed that, in practice, biomass procurement strategies with localized sources should be taken as a high priority for CHP plants.

Kimming et al. [266] conducted a consequential LCA that compared four different scenarios to meet heat and electricity demand of a rural village having 150 houses in Sweden. Three of these scenarios included small-scale biomass-based CHP systems, and the fourth scenario included a large-scale fossil-based (natural gas) CHP system. The biomass-based systems were considered to utilize the biomass (ley, straw, willow) produced at a nearby farm for conversion to bioheat and biopower. Because the LCA study in this research used a consequential approach, a reference system had to be chosen for comparison. Therefore, the four scenarios were compared to a reference system in which only food crops were produced at the farm. The farm also had set aside land. The first conversion scenario for the biomass-based CHP system was anaerobic digestion of ley and straw to produce biogas, and then combustion of biogas in a micro turbine. The second scenario was gasification of straw and willow chips grown on a willow plantation on set-aside land and combustion of the gas produced in an engine. The third scenario was direct combustion of the willow chips in a boiler and use of an external engine. Straw boilers were also used for the first two scenarios to make up for heat output shortages in winters. The objective of the study was to understand which biomass system is preferable with respect to the fossil and primary energy requirements, land use, ACD, and GW. The functional units for the assessments were taken as annual heat and electricity supply to the rural village, which were calculated to be 825 MWh electricity and 2373 MWh heat. Emission data for the CHP production systems were mostly taken from literature. In terms of biomass supply, N_2O and CH_4 from soil and digestion residues were calculated using IPCC Guidelines. A model developed in-country was used to estimate soil carbon content changes. Emissions data from the production on farm land and set aside land were taken from the literature. A sensitivity analysis was also performed so that factors assumed to show significant impacts on the results, were changed to quantify the impacts.

It was found that biomass growth on farmland for energy production could reduce GHG emissions compared with the fossil-based scenario. In terms of biomass CHP systems, soil emissions were found to be most important with respect to GW impact categories. In addition, it was concluded that all biomass-based scenarios show an

increase in ACD compared with the fossil-based scenario due to biomass harvesting operations. According to the results, among biomass-based CHP systems, while fossil and primary energy requirements, and land use are the highest for the first scenario (anaerobic digestion), they are the lowest for the second scenario (gasification). Land use for the second scenario is lower than that of the third scenario (direct combustion). That is because of the lower electrical efficiency of the combustion based CHP plant, compared to that of the gasification based CHP plant. However, an extra boiler is not necessary for the third scenario. On the other hand, it was emphasized that while direct combustion of biomass is a commercial technology, gasification of biomass only exists in demonstration plants. From a sustainability perspective, it was concluded that three biomass systems could be considered environmentally friendly, because GHG emissions from the energy systems were reduced. Moreover, it was indicated that biomass CHP systems could also contribute to a decrease in soil carbon depletion as a result of plantation systems including willow plantations because they are considered a carbon sink.

Recchia et al. [275] conducted a multiple criteria analysis to assess the use of riparian vegetation for energy (cutting operations of grass, reeds, bushes, and trees), and performed LCA for biomass energy chains chosen according to this multi-criteria analysis. First, biomass distribution and availability were estimated with geographical information system tools. After that, different scenarios concerning harvesting, transportation, storage, and final utilization of biomass were defined. Biomass utilization scenarios were defined as small-, medium- and high-scale direct combustion for power production; medium-scaled direct combustion for heat production; anaerobic digesters; gasifiers; and composting plants. After combining all the scenarios, 19 different scenarios for biomass energy were obtained. Each biomass energy scenario was evaluated and a total assessment result was obtained with the help of a decision-ranking matrix and an evaluation criterion defined for logistic, environmental, and economic aspects of scenarios. Looking at the total assessment results obtained through multi-criteria analysis, LCAs were implemented for five of the 19 scenarios. Natural gas or grid electricity was used for all reference cases considered. It was concluded that biomass energy chains requiring constrained forestry mechanization, with medium-scale plants based on direct combustion, and shorter transport distances should be preferred.

Roedl [262] investigated the environmental burdens of short-rotation poplar cultivation on agricultural area and its conversion to energy (bioheat and biopower generation through combustion in cogeneration mode and Fischer-Tropsch diesel production) using LCA methodologies. The study was divided into two parts. The first part of the study assessed the poplar production system: soil preparation, planting, harvesting, storage and drying, and poplar-chip supply to the plant. The functional unit chosen for the first part was 1 t of poplar chips (oven dried). The second part assessed the entire chain of biomass production and energy conversion. The functional units chosen for the second part were 1 MJ biopower, 1 MJ bioheat, and 1 MJ Fischer-Tropsch diesel. For CHP, environmental impacts were allocated between heat and electricity considering their exergy content. Four impact categories were chosen: GW, ETR, ACD, and PCO. To assess these impacts a midpoint method (CML 2001) was used. Soil carbon changes were integrated into the assessment to show land use effect. Indirect land use effects were not included in the assessment because it was assumed that poplar cultivation occurs on set aside lands. CHP operation was assumed to be carbon neutral. Fertilization during biomass production, and machine constructions and infrastructure were not taken into account. Environmental impacts of electricity production using poplar chips were compared with those of natural gas, lignite, and average electricity grid generation in the region (Germany). Primary data were taken from a research project and a CHP plant in Germany, and from literature as well. Background data were taken from the GaBi 4 database.

It was found that in terms of biomass production, ACD (due to mainly NO_x and SO₂ emissions) was the most important impact category. ETR and PCO were less important. It was presented that important impacts of bioheat and biopower generation (combustion) were mainly ACD and ETR, while important impacts of Fischer-Tropsch diesel were ACD, ETR, and to a minor degree, PCO. Comparison of power production using poplar chips with that of conventional systems showed huge differences in terms of ACD and GW: those of conventional systems were much higher. PCO was also higher for conventional systems. However, the ETR of power generation from poplar chips exceeded the potentials of conventional systems. It was also concluded that from an emission-saving perspective, it was beneficial to convert poplar chips into bioheat and biopower, thereby causing less environmental impact than for Fischer-Tropsch diesel.

Butnar et al. [314] studied an LCA of biopower (with feedstocks of poplar and Ethiopian mustard) in a country (Spanish) context to find out if it was environmentally competitive when compared with natural gas electricity or the Spanish electricity mix. They developed 24 different electricity generation scenarios with different power plant scales (10, 25, and 50 MW_e), transport distances (25 and 50 km), and productivities for biomass growth (9 and 13.5 t/ha). System boundaries included biomass cultivation, harvesting, natural drying, transportation to warehouses and power plant, combustion, and transportation of ash. Distribution of electricity was not included in the system boundaries. While primary data were provided from a national project, background data were taken from the ecoinvent database. The carbon neutral assumption was made. The functional unit chosen was per unit output of electricity (1 kWh). The annual biomass amount and cropping area required to supply power plants, were also calculated. The impact categories chosen were GW, ACD, PCO, HT, OD, and abiotic depletion.

The results showed that environmental impacts decreased with increasing biomass productivity. Moreover, an increase between biomass field and power plant showed higher environmental impacts. In addition, it was found that impacts of Ethiopian mustard were 20–60% higher than those of poplar. In terms of power plant capacity, lower impacts were obtained from 10 or 25 MW_e power plants. For GW and ACD impact categories, detailed results were presented. According to these results, it was found that biomass cultivation made an important contribution to these impact categories due to fertilizers usage. Comparison results showed that biomass electricity had a worse environmental profile than natural gas electricity for the categories of ACD, PCO, and HT. However, comparison of biomass electricity with the Spanish electricity mix showed that biomass electricity was cleaner for all impact categories selected in the research. It was explained that this is because the Spanish electricity mix mostly depends on fossil fuels. Butnar et al. [314] found similar results with Gasol et al. [270] who also did an LCA of poplar energy systems producing electricity and heat in comparison with Ethiopian mustard and natural gas, in a regional scenario in Spain.

Caserini et al. [268] conducted LCA studies including different scenarios with the purpose to compare environmental impacts of biomass combustion based on site-specific data from Italy. Scenarios included open fireplaces, conventional wood stoves,

pellet stoves, medium (8 MW_e), and large (100 MW_e) CHP plants. Biomass sources considered were industrial and agricultural wood residues, forest residues, pellets, and energy crops from SRF. While domestic appliances did not include any emission abatement devices, CHP plants included abatement devices (flue gas control systems). The functional unit chosen was 1 t of dry biomass. Impact categories included GW, ACD, photochemical ozone creation, and HT. Emission data for the CHP plants were based on real data. Average emission factors were used for other scenarios.

According to the results, it was concluded that biomass utilization in CHP plants with the help of flue gas treatment systems showed much better environmental impacts than in domestic appliances. The most negative environmental impacts of biomass combustion in domestic appliances were due to PM and other pollutants such as volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH). However, for all scenarios analyzed, the LCA results showed GHG gains in comparison with fossil fuels. In addition, it was stated that, energy crops from SRF showed a worse environmental performance than wood residues, and therefore wood residues (from tree management activities and sawmills) seemed more desirable.

Goglio and Owende [269] performed a screening LCA (a simplified LCA method) for two small-scale electricity generation pathways (gasification and ORC) using willow as the biomass source under conditions in Ireland. System boundaries included crop production, material transport, and electricity conversion phases. They analyzed net energy production per ha, energy output-input ratio, and CO₂ emissions (kg/ha). The functional unit chosen was crop production per ha. Physical allocation to heat and electricity generation was applied. All data were taken from literature and databases. Sensitivity analysis was also implemented. It was concluded that among the key performance factors for small-scale power plants were feedstock logistics, conversion efficiency, crop yields, fertilizer application, chip transportation distance, and drying technique for chips (such as exhaust recycling).

Jungmeier and Spitzer [265] analyzed different biomass energy systems, supplying bioheat only, and also bioheat and biopower, from various agricultural biomass sources, over their life cycles. These included biomass production, processing, fuels, and conversion as system boundaries. Life cycle analysis was performed to compare overall GHG emissions (CO₂, N₂O, CH₄) between biomass and fossil energy systems for a country context in Austria. Land use change and by-product usage were also

included. While the reference use described what happens if biomass is not used for energy purposes, by-product usage described substitution of some products. Emissions associated with these substituted products were subtracted from energy systems as benefits. Fossil energy systems for this research included coal, lignite, light oil, heavy oil, with natural gas CHP and heat-only systems for comparison. The life cycle methodology of the IEA Bioenergy Task “Greenhouse Gas Balances of Bioenergy Systems” was used in this research. GHG emissions were calculated for CHP systems per 0.33 kWh of electricity and per 0.67 kWh of heat, and for heat-only systems per kWh of heat. Data for biomass energy systems were collected from practical experience, as much as possible, and also from literature. Data for fossil energy systems were taken from a national database, TEMIS-A (Total Emission Model of Integrated systems—Austrian situation).

The results demonstrated that GHG emissions of biomass energy systems were lower compared with fossil energy systems considered in the study. It was concluded that if fossil energy systems are replaced with biomass energy systems, it is possible that a considerable reduction of GHG emissions could occur.

Some examples from other LCA studies in the literature include biogas production from marine macro algae and its use in a cogeneration unit [267]; biogas production based on crop residues and its use in cogeneration/trigeneration units [315]; preparing an LCI to investigate environmental loads of a biomass cogeneration plant, over its entire life cycle, which uses waste wood and forest residues as feedstock [194]. Biopower and bioheat production were also taken into account in biorefinery LCAs producing bioethanol, biochemicals, with biopower and bioheat. Biopower and bioheat were produced in a cogeneration unit using lignocellulosic biomass feedstocks such as crop residues [272], switchgrass [273], and straw [274]. LCA studies of biopower generation from bagasse combustion in sugar mills were also reported. Examples are studies by Ramjeawon [264], and Botha and von Blottnitz [271].

3. ASPEN PLUS PROCESS SIMULATION OF COMBINED BIOHEAT AND BIOPOWER PRODUCTION UTILIZING TURKISH OAK (*Quercus cerris* L.) COPPICES

This chapter explains hypothetical TR-Oak chip-fueled CBHBP production processes and their relevant environmental impacts. The chapter subsections are:

- The choice of solid biomass source and sampling
- Characterization of TR-Oak coppices
- Stoichiometric chemical equations for combustion of TR-Oak coppices
- Case studies for CBHBP plants
- Thesis methodology
- Aspen Plus process simulation model for CBHBP plants
- Aspen Plus process simulation model inputs and outputs for Case Study-1, -2, and -3

In summary, this chapter deals first with the details about the choice of the solid biomass source, TR-Oak (*Quercus cerris* L.) coppices, for CBHBP production. Laboratory analysis and characterization results of TR-Oak coppices are provided in a table. Stoichiometric chemical equations for combustion of TR-Oak coppices are provided for comparison. Then, to simulate the CBHBP production process, different CBHBP cases are proposed. The thesis methodology used to develop the Aspen Plus process simulation model, simulate CBHBP cases, and then perform the LCA study with an eco-design approach is explained using a flow diagram. Later, the Aspen Plus process simulation model used to handle these CBHBP cases is presented. The model is validated using the data available in literature. Based on the Aspen model, CBHBP process simulations using TR-Oak (*Quercus cerris* L.) coppices and outputs including the environmental impacts of the CBHBP plants are provided.

3.1 The Choice of Solid Biomass Source and Sampling

Regarding the choice of biomass source, personal communications were made with Marmara Forest Research Institute [71,316,317], which is an institute of GDF. GDF is an organization affiliated with the MoFWA, and is responsible for every forest issue in Turkey (management, protection, enhancement, benefitting from forests in a sustainable way, etc.). It is seen that oak coppice forests in Turkey offer a readily available alternative to utilize for biopower purposes. Around one fourth of all forests in Turkey are made of oak species, the second biggest share after Turkish pine in Turkey [58]. Also, to introduce modern energy forestry in Turkey, the most interesting areas are reported to be the ones where unproductive or poorly productive oak coppice forests are found [13,20].

The biomass feedstock sampling location chosen was the Marmara Region, where the combination of a high enough potential of oak coppice forests and heat demand exists, and which is one of the two regions (Marmara and Mediterranean) in Turkey where systematic coppice forest management activities take place [70,73]. As representative of the Marmara Region, the oak coppice species written below (name in both in Latin and Turkish) was chosen as the biomass source for this thesis research [71,316,317].

- Turkey oak, *Quercus cerris* L., Saçlı meşe, Türk meşesi (TR-Oak)

The samples of TR-Oak were taken from 15 individual 20-year-old trees at breast height, which is 1.3 m above ground, in the middle of June, right after the time when the trees have come into leaf. Samples were collected with the help of those at the “Marmara Forest Research Institute” and “Vize Forest District Directorate” in Kırklareli [317]. The “Vize Forest District Directorate” has the capacity to produce woody biomass in considerable quantities from oak coppice forest management activities [73]. Figure 3.1 shows a picture of the TR-Oak samples.

3.2 Characterization of TR-Oak Coppices

Regarding laboratory analyses, sample preparation, and structural analysis (i.e., lignocellulosic composition) of the samples, were completed in the “Forest Products Chemistry and Technology Laboratory” of “Forest Industry Engineering” at the “Faculty of Forestry” of “Istanbul University”. Proximate, ultimate (elemental), and

(a)



(b)



(c)



(d)

Figure 3.1 : Turkey oak (*Quercus cerris* L.) samples: (a) Stem wood (b) Leaves (c) Stem wood without bark (d) Bark.

thermal analyses were completed at the “Energy Institute of the Scientific and Technological Research Council of Turkey (TÜBİTAK) Marmara Research Center”.

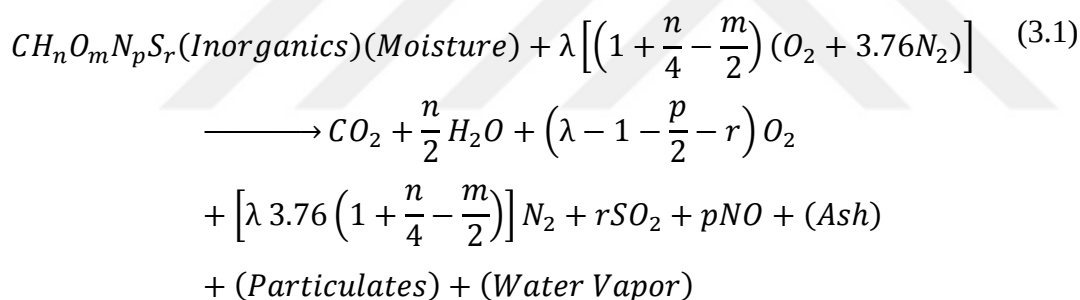
The characterization results of TR-Oak (*Quercus cerris* L.) coppice samples along with empirical formulas are provided in Table 3.1. The methods used for each analysis are also provided in the table. The results are given for stem wood, bark, and whole tree (i.e., the entire above-ground portion of the tree). The results for whole tree were calculated assuming that the bark constitutes 10% of the tree by weight [318-320]. TR-Oak (*Quercus cerris* L.) coppice as a whole tree contains about 50.38% C, 5.85% H,

41.29% O, and a small amount of N and S on a dry basis. The original sample had about 27% moisture on a wet basis (as received). Volatile matter comprised 80.72% of the whole tree on a dry basis. Also, the structural analysis performed for the stem wood shows the chemical composition by class of compounds as holocellulose, which is the entire carbohydrate fraction of the wood (cellulose plus hemicellulose), lignin, alcohol solubility for extractives, and ash for inorganics, on a dry basis. The empirical formulas were found by further calculation, and are presented in the table.

3.3 Stoichiometric Chemical Equations for Combustion of TR-Oak Coppices

This section provides stoichiometric calculations based on TR-Oak combustion, and which are used to compare with stack gas emissions obtained from CBHBP simulations, as provided in the later parts of this chapter.

Taking into consideration the commonly existing major components of C, H, O, N, and S, the general biomass combustion reaction in ambient air can be described by the following stoichiometric chemical equation [173,181,187,321-323].



Here, λ is the excess air ratio that describes the ratio of the locally available air to the stoichiometric amount of air for complete combustion. This equation assumes that chemically bound N and S in the biomass are oxidized to nitrogen monoxide (NO), and SO₂. The combustion reactions were assumed to be as below.

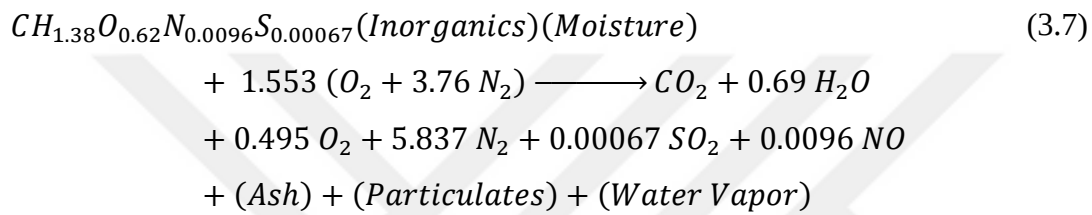
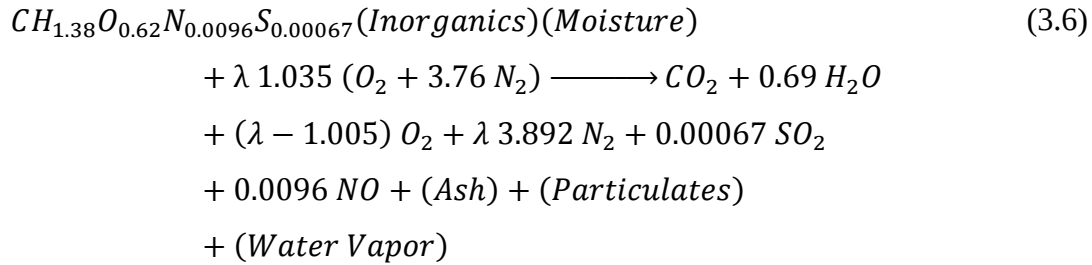


Considering the equations from (3.1) to (3.5), the stoichiometric chemical equation for

Table 3.1 : Characterization of Turkey oak (*Quercus cerris* L.) coppice samples.

Turkey Oak Coppice (<i>Quercus cerris</i> L.)	Stem Wood		Bark		Whole Tree (Calculation)		
	Wet Basis (As Received)	Dry Basis	Wet Basis (As Received)	Dry Basis	Methods	Wet Basis (As Received)	Dry Basis
Proximate Analysis (wt %)							
Moisture	28.47	0.00	13.92	-	ASTM D 7582-15	27.02	-
Ash	0.83	1.16	6.86	7.96	ASTM E 1755-01 (Reapp.2007)	1.43	1.84
Volatile Matter	58.35	81.57	62.91	73.09	ASTM D 7582-15	58.81	80.72
Fixed Carbon	12.35	17.27	16.31	18.95	ASTM D 3172-13	12.75	17.44
Ultimate Analysis (wt %)							
Carbon (C)	35.96	50.27	44.20	51.35	ASTM D 5373-14	36.78	50.38
Hydrogen (H)	4.21	5.88	4.76	5.53	ASTM D 5373-14	4.26	5.85
Nitrogen (N)	0.39	0.54	0.65	0.75	ASTM D 5373-14	0.41	0.56
Sulfur (S)	0.06	0.09	0.08	0.09	ASTM D 4239-14	0.07	0.09
Ash	0.83	1.16	6.85	7.96	ASTM E 1755-01 (Reapp.2007)	1.43	1.84
Oxygen (O)	30.09	42.06	29.54	34.32	ASTM D 3176-15	30.03	41.29
Empirical formula	C ₁ H _{1.39} O _{0.63} N _{0.0092} S _{0.00067}		C ₁ H _{1.28} O _{0.5} N _{0.013} S _{0.00066}		Calculation	C ₁ H _{1.38} O _{0.62} N _{0.0096} S _{0.00067}	
H/C molar ratio	1.39		1.28		Calculation	1.38	
O/C molar ratio	0.63		0.5		Calculation	0.62	
Thermal Analysis (cal/g)							
Lower Heating Value	2864	4222	3485	4137	ASTM D 5865-13 / ISO 1928-09	2926.10	4213.50
Upper Heating Value	3232	4519	3796	4410	ASTM D 5865-13	3288.40	4508.10
Structural Analysis (wt %)							
Holocellulose	75.83				Wise and John, 1952 [324]		
Lignin	19.49				Runkel and Wilke, 1951 [325]		
Alcohol solubility	3.51				TAPPI T 204 om-88 [326]		
Ash	1.17				TAPPI T 211 om-85 [326]		

combustion of TR-Oak (*Quercus cerris L.*) coppice is written in equation (3.6), which is based on the empirical formula of the whole tree in Table 3.1, and in equation (3.7), assuming that λ is equal to 1.5.



3.4 Case Studies for CBHBP Plants

Different cases for CBHBP production were proposed and provided in Table 3.2, which considers scientific studies and current commercial biomass conversion technologies and their applications for CBHBP production, as explained in Chapter 2 [29,30,32-34,36,56,111,120,123,126,148,150,191-205,208-213]. The focus was on the steam turbine system based on direct combustion technology (conventional Rankine cycle), which is the primary approach of most of today's commercial biomass power plants [30,32,56,122,123,164].

Table 3.2 shows the boiler technology for fixed bed (grate) combustion, which is a well proven and mature technology used for industrial biomass combustion systems. Biomass for biopower applications is used mostly for up to medium-scale power plants (20 MW_e) due to scarcity of local feedstock and high transportation costs [29-34,198]. For example, among the existing CBHBP plants with solid biomass in European countries, only 15% have a biopower output greater than 20 MW_e [126]. In the table, 10 MW_e was set as the upper limit for CBHBP plants considering the availability of oak coppices, both to reduce the fuel demand and reduce the strain on the biomass supply chain of the plants.

Table 3.2 : Case studies for Combined BioHeat and BioPower plants.

Combined BioHeat and BioPower Case Studies	Base		Lower Boundary Values for Plant Efficiencies (%)	
	Biopower output (MW _e)	Boiler Technology	Electrical	Total
1	2	Grate		
2	5	Grate	20	80
3	10	Grate		

Although the sizes of available steam turbines applicable to biomass power plants are between 0.05 and 250 MW_e [56,166], the lower limit for the CBHBP plants in this thesis was set as 2 MW_e. This is because steam turbine systems are not economically and technically feasible for the plants with a scale lower than 2 MW_e [167]. A 5 MW_e unit was considered able to make a better comparison with 2 MW_e and 10 MW_e units in terms of technical, environmental and economic aspects. Table 3.2 shows the lower boundary values for plant efficiencies (electrical and total), which were defined based on current commercial biopower plants [32,33,36,191-213]. The efficiency of CBHBP plants is very much dependent on the scale, technology, and configuration used in the plants [29,30,32,36,123,126]. For the selected power plants that are currently in operation, and based on direct combustion of solid biofuels with a steam turbine technology, as presented in Table 2.6 in Chapter 2, CBHBP electrical efficiencies are mostly above 20%, while CBHBP total efficiencies are mostly above 80%. That is why the lower boundary values for CBHBP electrical and total efficiencies were defined as 20% and 80%, respectively.

3.5 Thesis Methodology

Figure 3.2 shows a block diagram of the methodology followed in the thesis. The main steps of the methodology for the proposed CBHBP case studies include the studies of Aspen Plus process simulation software for the process simulation model development, validation and CBHBP simulation, and the studies of SimaPro software for the CBHBP LCA. The CBHBP simulation and LCA studies consider eco-design parameters. The LCA study also takes into account sensitivity of data variations other

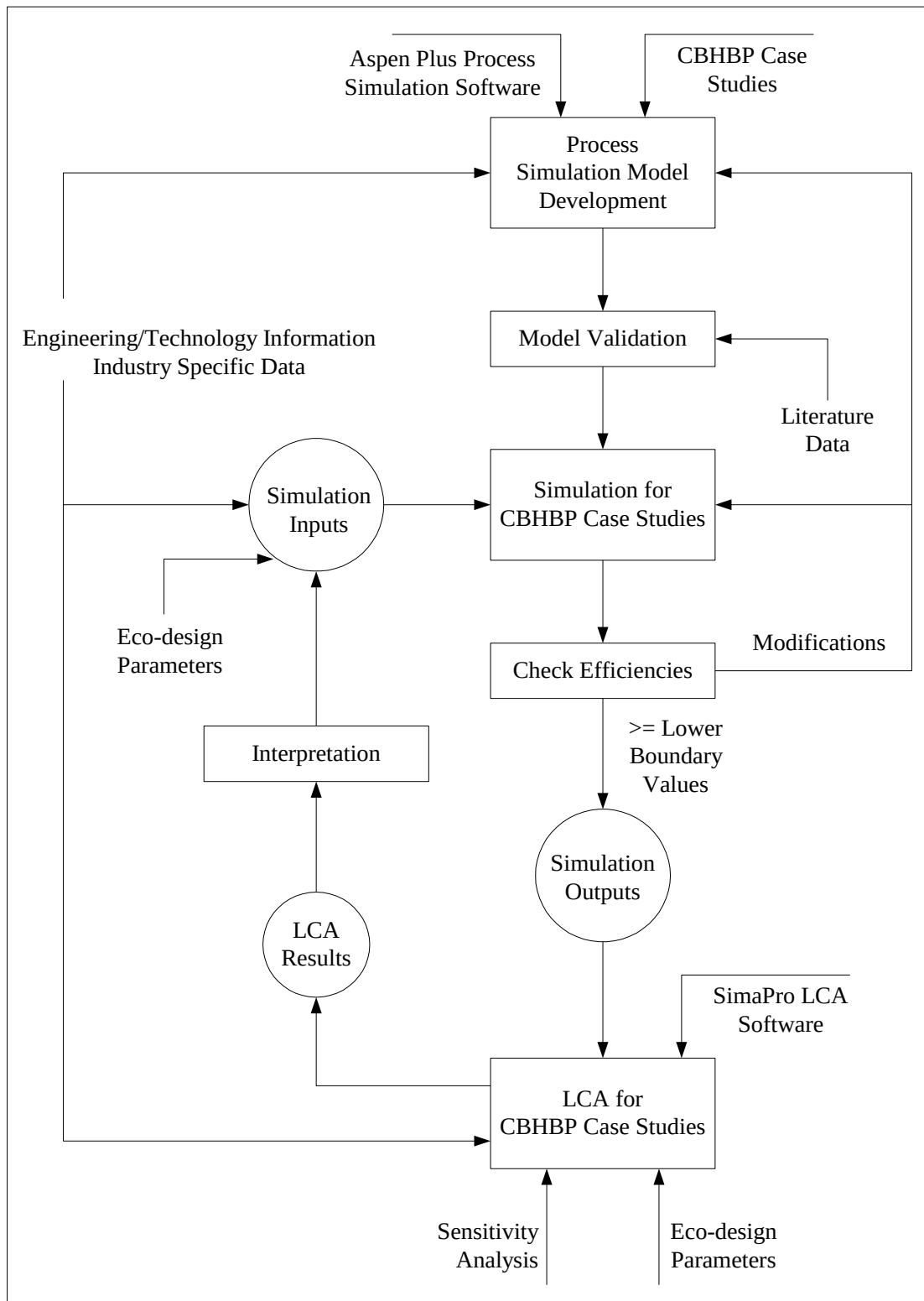


Figure 3.2 : Thesis methodology (Aspen Plus process simulation model development and validation, simulation, and SimaPro LCA for CBHBP case studies).

than influence of eco-design parameters on the LCA results. The purpose of this methodology was to achieve an environmentally friendly conclusion with industry specific values for the defined plant sizes of the proposed CBHBP case studies, which are in line with the corresponding commercial applications.

As seen in Figure 3.2, the methodology of this thesis research considers relevant scientific knowledge, such as engineering and technology information, and sectoral background. The sectoral background includes the industry specific data that has either been obtained from personal communications or compiled through research articles, reports, or websites of current commercial CBHBP plants, and from technology and equipment suppliers.

Figure 3.2 illustrates how that, after an Aspen Plus process simulation model for CBHBP case studies was developed, the model was validated with literature data. Each time a CBHBP simulation based on its Aspen Plus process simulation model was run, a thermodynamic evaluation was performed. It is checked if the specified electrical and total efficiencies in Table 3.2 were met. If so, the results of the CBHBP simulation were recorded; if not, first the necessary modifications on CBHBP simulation and if needed on Aspen Plus process simulation model were performed. Then, the thermodynamic evaluation was repeated until the specified electrical and total efficiencies were met. In case any modifications were made on the Aspen Plus process simulation model, the validation was also repeated.

This methodology exhibits an iterative process in that the simulation and LCA studies for CBHBP production are interrelated. Figure 3.2 shows that eco-design parameters have effects on both simulation inputs and the LCA study, which uses the simulation outputs. Based on the simulation outputs, the relevant process parameters, requirements, and environmental impacts of the CBHBP case studies were quantified and were used as the LCI. Each time an eco-design parameter for CBHBP was introduced, the Aspen Plus process simulation was run considering the parameter, and the SimaPro LCA results were updated. On the other hand, the simulation inputs were determined based on the interpretation of the LCA results in addition to the eco-design parameters.

3.6 Aspen Plus Process Simulation Model for CBHBP Plants

This section provides detailed information on the simulation model of CBHBP plants developed using Aspen Plus V8.4 software, and the validation of the model with operating data based on commercially available CBHBP plants taken from the literature [56,166].

The Aspen Plus process simulation model basically simulates a typical steam Rankine cycle CBHBP production using TR-Oak chips as biofuel and grate combustion as the conversion technology as explained in Chapter 2 and depicted in Figure 2.12.

The Aspen Plus V8.4 process simulation model for grate combustion is provided in Figure 3.3. To simulate CBHBP production, the Aspen process simulation model was divided into two sections: primary conversion (grate combustion) side and secondary conversion (steam turbine side).

The model is based on the following main assumptions:

- Operation is steady-state
- Steam is modeled as pure water
- Air is modeled as a mixture of oxygen (21%) and nitrogen (79%)
- Ambient temperature is 25 °C and pressure is 1.01325 bar
- Pressure-drops through piping and equipment are negligible

Following are the system description and details of the Aspen process simulation model.

3.6.1 Properties environment

The properties environment in the Aspen Plus software contains the components considered, and the methods used for calculating the properties in the model. These are explained below.

3.6.1.1 Components

Biomass and ash are defined as non-conventional (NC) components; carbon as a solid component; and others as conventional components. NC components are

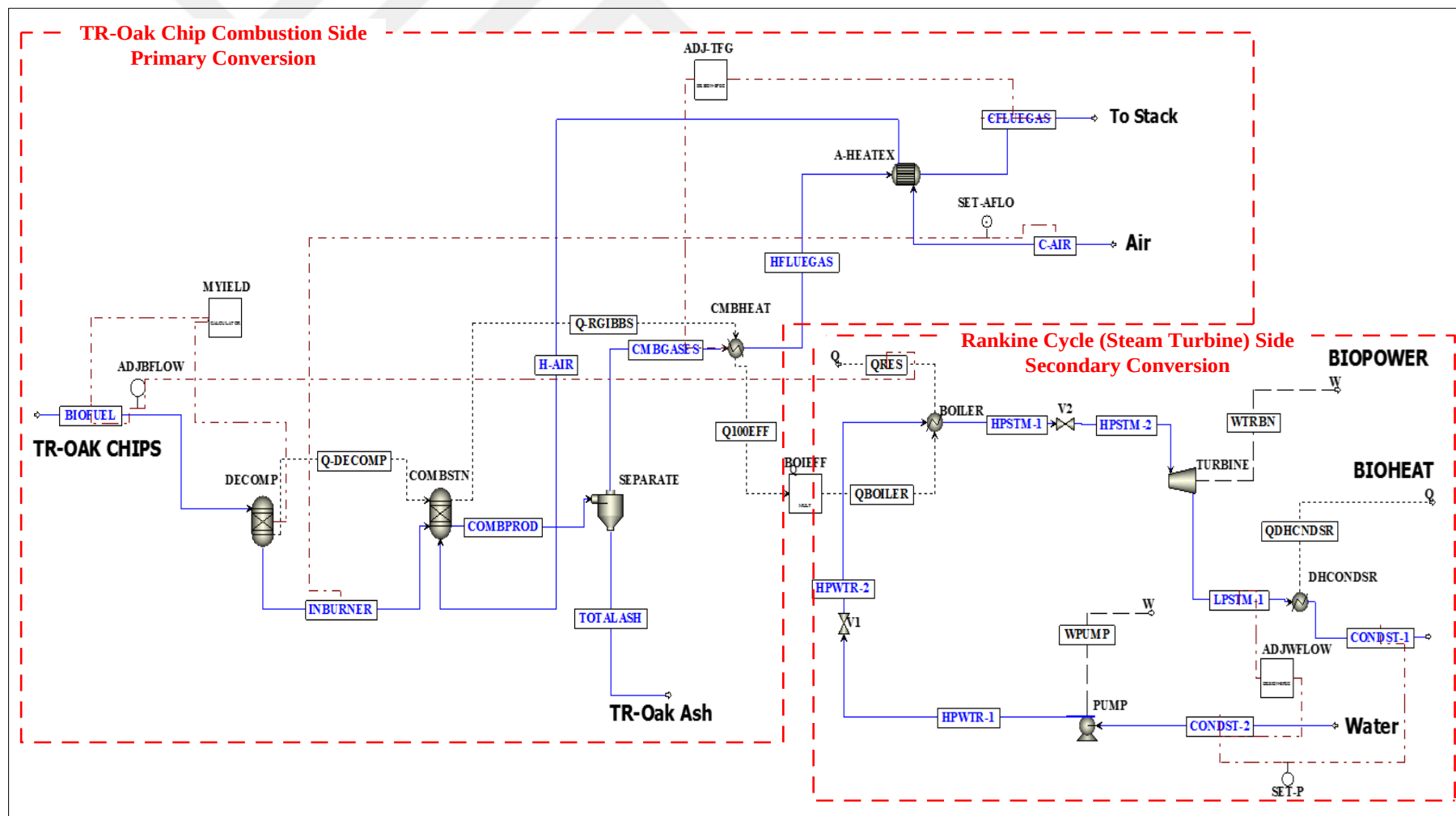


Figure 3.3 : The Aspen Plus V8.4 process simulation model for TR-Oak chip-fueled CBHBP production.

heterogeneous solids that cannot be characterized by a molecular formula. They are characterized in terms of component attributes (empirical factors) each representing the composition of individual ingredients [327]. TR-Oak (*Quercus cerris L.*) coppice sample that was characterized by laboratory analysis (as explained in Section 3.1) was used in the model as the biofuel feedstock. Complete and incomplete combustion, as well as NO_x formation, were taken into account when specifying the components of the combustion gases. The components considered in this Aspen model are depicted in Figure 3.4.

	Component ID	Type	Component name	Alias
▶	BIOMASS	Nonconventional		
▶	ASH	Nonconventional		
▶	C	Solid	CARBON-GRAPHITE	C
▶	H2O	Conventional	WATER	H2O
▶	O2	Conventional	OXYGEN	O2
▶	N2	Conventional	NITROGEN	N2
▶	H2	Conventional	HYDROGEN	H2
▶	CO	Conventional	CARBON-MONOXIDE	CO
▶	CO2	Conventional	CARBON-DIOXIDE	CO2
▶	NO	Conventional	NITRIC-OXIDE	NO
▶	NO2	Conventional	NITROGEN-DIOXIDE	NO2
▶	N2O	Conventional	NITROUS-OXIDE	N2O
▶	S	Conventional	SULFUR	S
▶	SO2	Conventional	SULFUR-DIOXIDE	O2S
▶	SO3	Conventional	SULFUR-TRIOXIDE	O3S
▶				

Figure 3.4 : The components considered in the Aspen Plus V8.4 process simulation model.

3.6.1.2 Methods

The next step in making the model is to assure that an appropriate thermodynamic property method has been chosen for the components. More than one property method is required for the model. The PR-BM property method (Peng Robinson cubic equation of state with the Boston-Mathias alpha function) was used as the base method for the properties of the biomass combustion section of the model. For the steam cycle section, in cases where only water is present in the stream, the STEAM-TA property method (ASME 1967 Steam Tables) was used.

To calculate the physical properties of the NC components, the HCOALGEN and DCOALIGT models were used to calculate enthalpy and density, respectively. Aspen Plus uses component attributes to represent NC components in terms of a set of identifiable constituents that are needed to calculate physical properties. Therefore, HCOALGEN used the proximate analysis, ultimate analysis, and sulfur analysis to calculate the enthalpy of the biofuel feedstock. Moreover, the heat of combustion option code in the HCOALGEN model, which is a gross calorific value expressed on a dry mineral-matter-free basis, makes a user input value possible. All of these values were taken from the laboratory analysis results for TR-Oak (*Quercus cerris L.*) coppice and entered into the simulation model as mentioned above [327-330].

3.6.2 Simulation environment

The simulation environment in the Aspen Plus software contains the flowsheet of the model, and various features used to create the flowsheet. Among these features, stream classes, unit operation blocks, and design specifications of the model are explained below.

3.6.2.1 Stream class

To define the structure of the simulation streams, a stream class including CISOLID (Conventional Inert Solid), NC, and MIXED substreams was defined. While the CISOLID substream was used for carbon components in the model (because the decomposition of TR-Oak chips forms carbon, which is a homogeneous solid with a defined molecular weight), the NC substream was used for TR-Oak chips and ash components in the model because they are heterogeneous solids that have no defined molecular weight. The MIXED substream is a default stream class for all streams having components of conventional types. Therefore, in the model, the stream class “MIXCINC” was chosen for the components, which includes mixed (conventional), CISOLID, and NC substreams.

3.6.2.2 Unit operation blocks

TR-Oak chip combustion was modeled using RYield and RGibbs reactors as unit operation blocks in Aspen Plus. As the TR-Oak chip enters the combustor, it is devolatilized into carbon, hydrogen, oxygen, sulfur, and nitrogen. Because the TR-Oak chip is a non-conventional component, this is accomplished in Aspen Plus using

an RYield block that decomposes the TR-Oak chip into its constituent elements followed by an RGibbs block to model the combustion reactions.

The “RYield” reactor model (DECOMP) was used to decompose the TR-Oak chip into its constituent elements based on its ultimate analysis as shown in Table 3.1. RYield in Aspen Plus is used to simulate a reactor with a known yield and does not require reaction stoichiometry and kinetics. In the simulation, a “Calculator” block (MYIELD calculator) was built up to calculate the actual mass yield distribution (after RYield reactor) from the component attributes of TR-Oak chips in the feed stream. The purpose of the calculator block is to perform a parametric calculation of mass yields to be able to run different biomass feed streams easily. The operating conditions selected for the reactor were 298 K and 101.325 kPa. A heat stream was added between the RYield and RGibbs reactors to carry the heat of reaction from the RYield to the RGibbs block.

The “RGibbs” reactor model (COMBSTN) was used to model the combustion reactions. RGibbs in Aspen Plus uses the Gibbs free energy minimization method to model reactions that come to phase equilibrium and chemical equilibrium. Therefore, the equilibrium composition of the products resulting from the many reactions that can occur can be determined. The reaction stoichiometry does not need to be specified when using RGibbs reactor model. Operating pressure for the reactor was defined as 101.325 kPa. The furnace exit temperature was modeled to be defined as a simulation input considering typical combustion temperatures reported for biomass combustion systems [178-180,182,183].

Air preheating is crucial to ensure efficient combustion. Prior to the RGibbs block, the combustion air is preheated from ambient state to a recommended temperature by the hot flue gases from combustion, which was also modeled to be defined as a simulation input. Heat recovery from the hot flue gases was modeled using a “Heater” exchanger block (A-HEATEX). With a design specification in the model, the temperature for cold flue gases (CFLUEGAS) to the stack was modeled to be kept at a defined value to prevent the condensation of water vapor in the flue gases [178,180,189]. As a practical matter, in a boiler the combustion gases are used to heat the feed water to form saturated water in the economizer, saturated steam in the evaporator, and superheated steam in the superheater. In the Aspen model, the temperature of the hot

flue gases (HFLUEGAS) represents the temperature of the combustion gases leaving the economizer.

A “Calculator” block (SET-AFLO calculator) was built up to calculate the amount of stoichiometric oxygen required for complete TR-Oak chip combustion. Therefore, the air molar flow rate (kmol/h) was calculated based on the constituent elements entering the RGibbs reactor and the basic combustion reactions, as provided in Section 3.1. These consider the stoichiometric equation explained and λ assumed. In this case, λ greater than ‘1’ is always required. The optimal value of λ depends on the biomass fuel, combustor design and operational conditions. For the Aspen model in this thesis, a value typical for biomass combustion applications was modeled, to be defined as a simulation input during combustion in the RGibbs block [148,178-181].

The “SSplit” solid separator block (SEPARATE) was used to model the separation of the TOTALASH stream, which is a solid product of combustion, from combustion gases (CMBGASES). The SSplit block in Aspen Plus is used to split its feed stream, combustion products in this case (COMBPROD), into two or more streams according to substream specifications. TOTALASH includes all solid emissions from the power plant modeled, which are the bottom ash (ash fraction produced in the combustion chamber), the boiler and cyclone fly ash (fine ash particles carried with flue gases and precipitated in the boiler section and in cyclones), the filter fly ash (second finer fly ash fraction carried with flue gases and precipitated in filters), and the flue dust or PM (the finest fly ash fraction, which is emitted with the flue gases) [331].

Two “Heater” exchanger blocks (CMBHEAT on the grate combustion side and BOILER on the steam turbine side) were tied together by pushing the duty from the fuel side of the boiler to the steam side where the steam is generated. Boiler efficiency (efficiency of the biomass combustion side in the model) was modeled to be defined as a simulation input based on correctly installed and maintained modern biomass boilers [176,177].

For turbine operation, a “Compr” pressure changer block (TURBINE); to model heat utilization, a “Heater” exchanger block (DHCONDSR); to model pump operation, a “Pump” pressure changer block (PUMP); to model piping pressure-drops (if any), two “Valve” pressure changer blocks (V1, V2), were used on the steam side of this simulation.

Using the model, the back-pressure from the steam turbine (TURBINE block) can be set at a defined value as a simulation input (for LPSTM-1). Isentropic and mechanical efficiencies can be entered as well. Moreover, in the PUMP block, the discharge pressure appropriate for the boiler feed pressure can be defined as a simulation input.

In the simulation, on the steam side, the material flow was not modeled as a cycle, instead the flowrate, composition, and conditions of the inlet and outlet streams were set to be the same (streams CONDST-1 and CONDST-2), which effectively closes the cycle.

Emissions and wastes from the model include combustion gases and solids (TOTALASH). The amount of combustion gases (CMBGASES stream) are calculated by the model. Figure 3.5 lists the names of the combustion products. Taking into account these combustion products, NO_x control technologies are not required because prompt and thermal NO_x formation are minimized by keeping the furnace exit temperature low enough to reduce the fixation of prompt and thermal nitrogen. In addition, desulfurization technologies are not needed because TR-Oak chips contain only a negligible amount of sulfur. Therefore, SO₂, sulfur trioxide (SO₃) emissions are not of concern [150].

	Component	Valid phases
▶	C	PureSolid
▶	H2O	Mixed
▶	O2	Mixed
▶	N2	Mixed
▶	H2	Mixed
▶	CO	Mixed
▶	CO2	Mixed
▶	NO	Mixed
▶	NO2	Mixed
▶	N2O	Mixed
▶	S	Mixed
▶	SO2	Mixed
▶	SO3	Mixed

Figure 3.5 : Combustion products of the Aspen Plus V8.4 process simulation model.

As explained above, TOTALASH includes all solid emissions from the plant. These are bottom ash from combustion, fly-ash from boiler and emission control units (cyclone and filter), and flue dust released to the environment. Because the particle

size distribution of TOTALASH is unknown, emission control units, which are cyclone and filter, are not included in the Aspen model. Instead, the amounts of bottom ash, fly-ash, and flue dust (PM), are assumed considering the average percentage of the different ash fractions to the total ash amount (TOTALASH). This was done using literature data from measures in various power plants [331], typical PM emission factors determined for wood combustion plants with cyclone and filter from real-life operation [228], and the “AP 42 Emission Factor Database” [332].

3.6.3 Design specifications

Below are the explanations of the design blocks included in the model.

- The first “Design-Spec” block (ADJBFLOW) is included in the model to calculate the necessary mass flow rate (kg/h) of biofuel feedstock by varying the amount of duty produced on the fuel side to be equal to the duty needed in the boiler on the steam side.
- The second “Design-Spec” block (ADJ-TFG) is included in the model to set the temperature of the flue gases released to the atmosphere at a defined value as a simulation input by changing the temperature of the hot flue gases (HFLUEGAS) from the “Heater” exchanger block (CMBHEAT) on the fuel side.
- The third “Design-Spec” block (ADJWFLOW) is included in the model to set the back-pressure of the LPSTM-1 stream from the steam turbine at a defined value as a simulation input by changing the mass flow rate of the live steam (CONDST-2).

3.6.4 Validation of Aspen Plus process simulation model

For validation purposes, the Aspen model was compared with the operating data from commercially available CBHBP plants taken from the literature [333,334]. This literature data was chosen to validate the model because all the operation data needed for the steam turbine side of the simulation is available. Hence, the validation of the steam turbine side of the model was made using this published data. In addition, the grate combustion side of the model was validated using results from the stoichiometric model explained in Section 3.2.

The Aspen Plus flowsheet model of the CBHBP plant with the design parameters explained above, is depicted Figure 3.6. It includes the operation data of the mentioned commercially available CBHBP plant [333,334] in its related blocks and streams, and also the outputs of the simulation.

Table 3.3 shows a comparison of the literature and simulation data used in the flowsheet depicted in Figure 3.6. The table summarizes the steam turbine and CBHBP parameters taken from the literature mentioned above. In addition, the data used as input for the simulation, the output data of the simulation, and some calculated values for efficiencies are presented.

As seen in Table 3.3, the simulation results of this thesis study are in good agreement with the literature data except for the percentage error of power production, which is 5.5%. However, the 3000 kW of power production given in the literature was reported as the nominal (maximum) power production. If the efficiencies of either turbine or generator were improved 1–3 percent, all data would be well-suited.

For the grate combustion side of the model, it was assumed that the TR-Oak chips characterized during this thesis study is the biofuel feedstock used. Therefore, the grate combustion side of the model was validated by comparing the emission data from the Aspen simulation model, CFLUEGAS stream, with the stoichiometric model explained in Section 3.2. The Aspen simulation model consumes the TR-Oak chips necessary to provide the amount of the fuel input in Table 3.3.

The results are in good agreement with those provided in Table 3.4. They are reported on a dry basis. It is seen that mass flows of H_2O and CO_2 fit with the simulation results. Mass flow of O_2 is less than that of the calculation result because the reactions assume that the combustion products are H_2O , CO_2 , NO , and SO_2 . However, in the simulation, the amount of combustion products defined was calculated to ensure chemical and phase equilibrium under the given operating conditions. Therefore, some of the oxygen content was spent in the formation of other combustion products (CO , NO_2 , N_2O , and SO_3). NO formation in the simulation is less than in the calculation because the combustion reactions assume that all N_2 in the biofuel used is converted to NO . The calculation assumes that all S is converted into SO_2 ; in the simulation, it was observed that some S is converted to SO_3 .

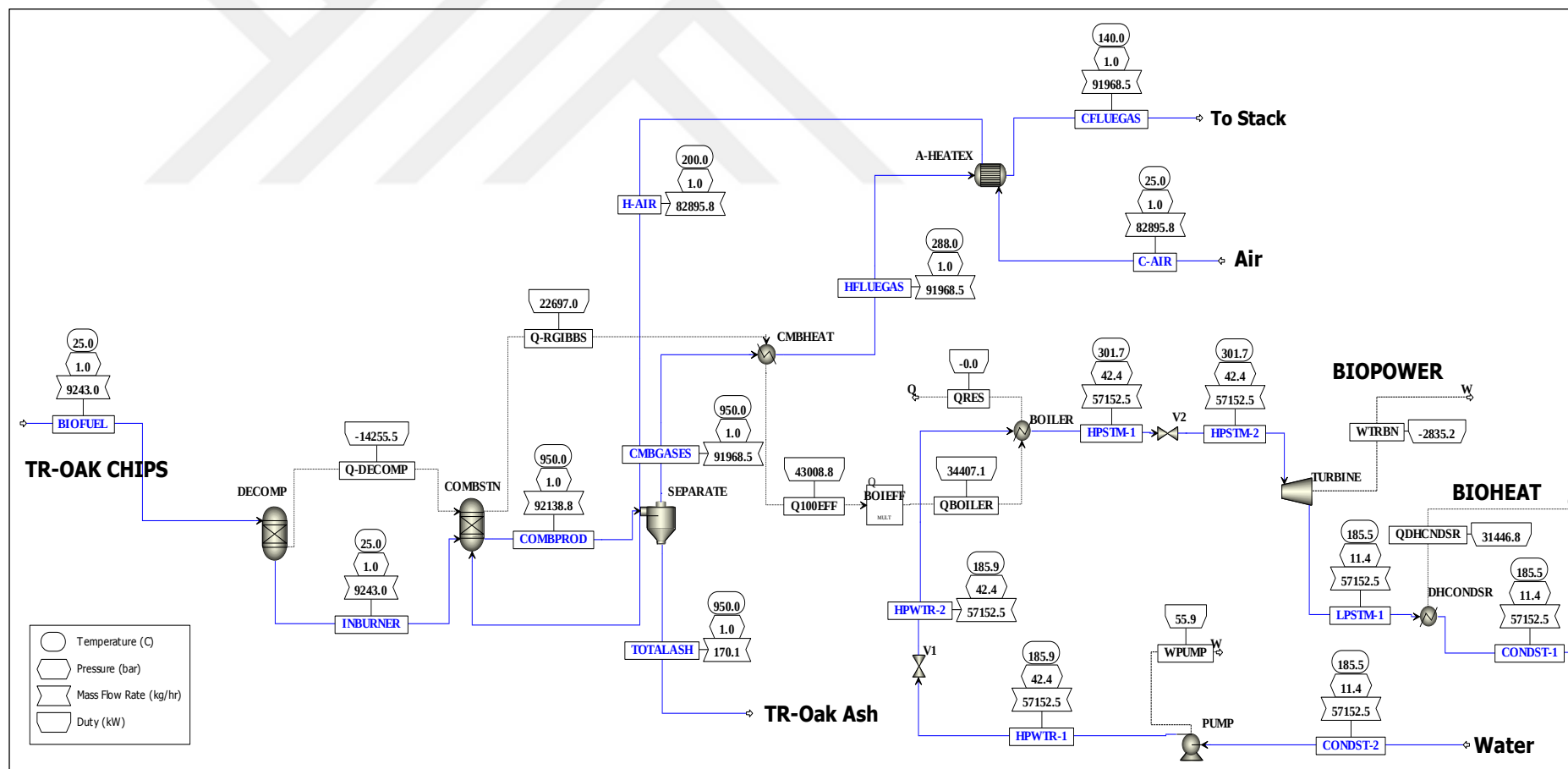


Figure 3.6 : Validation of the Aspen Plus V8.4 process simulation model for TR-Oak chip-fueled CBHBP plant.

Table 3.3 : Aspen Plus V8.4 process simulation and validation data for the steam side of the model [333,334].

Steam Turbine and CBHBP Parameters	Literature Data [333,334]		Aspen Plus Process Simulation (SI Units)	
	FPS Units (given)	Simulation Units (converted)	Input	Output
Nominal Electric Capacity		3000 kW		2835 kW
Turbine Type		Back Pressure		
Typical Application		Paper mill		
Turbine Isentropic Efficiency		70%	70%	
Generator/Gearbox Efficiency		94%	94%	
Steam Flow	126,000 lbs/h	57,153 kg/h	57,153 kg/h	
Inlet Pressure	600 psig	42.38 bar	42.38 bar	
Inlet Temperature	575 F	302 °C	302 °C	
Outlet Pressure	150 psig	11.36 bar	11.36 bar	
Outlet Temperature	366 F	186 °C		186 °C
Boiler Efficiency		80%	80%	
Fuel Input	147.4 MMBtu/h	43,199 kW		43,009 kW
Steam to Process	107 MMBtu/h	31,359 kW		31,447 kW
CBHBP Electrical Efficiency		6.90%		6.59%
Total CBHBP Efficiency		79.50%		79.72%
Power / Heat Ratio		0.1		0.09
Heat / Fuel Ratio		0.72		0.73
Electricity / Fuel Ratio		0.07		0.07

Table 3.4 : Aspen Plus V8.4 process simulation and validation data for the fuel side of the model.

Air emissions	Mass flow (kg/h)	
	Calculation	Aspen Plus Process Simulation Output
H ₂ O	4828.053	4828.048
O ₂	6435.941	6415.374
N ₂	63,587.904	63,633.700
H ₂	0	4.341E-05
CO	0	1.260E-03
CO ₂	17,061.699	17,061.680
NO	111.083	12.731
NO ₂	0	1.578E-01
N ₂ O	0	1.075E-03
S	0	2.235E-16
SO ₂	1.662E+01	1.577E+01
SO ₃	0	1.057

3.7 Aspen Plus Process Simulation Model Inputs and Outputs for Case Study-1, -2, and -3

This section provides descriptions of the CBHBP plants simulated along with their process parameters, as well as their simulation inputs and outputs. The simulations are based on the newly developed Aspen Plus process simulation model that was explained in the previous section.

For all cases, the TR-Oak chips had moisture content of 30 % and the boiler efficiency was 90 % [176,177]. The superheated steam is fed into a back pressure steam turbine. The isentropic efficiency for turbine was 85% [184]. The exhaust pressure of the turbine was set to 1.3 bar [185,335], suitable for a low temperature water system used in district heating, which is known as a system easily adaptable to alternate fuel sources such as biomass [336-338]. To produce useful heat, low pressure (1.3 bar), low temperature (107 °C) steam leaving the turbine is led to a heat exchanger to produce hot water for heating within the district. After that, the condensed steam is returned to the boiler by pressurizing to the appropriate boiler feed pressure with a pump. The isentropic efficiency for the pump was set at 90% [184]. During combustion, the excess-air ratio, λ , was 1.5, which means an excess of air (50%) was defined during combustion [148,178-181]. In the simulation, the combustion air is preheated from

ambient state (25 °C) to 200 °C in a heat exchanger (air preheater) by recovering the heat of the combustion gases leaving the economizer. The temperature of the combustion gases leaving the furnace was 950 °C [178-180,182,183], and the flue gas exhaust temperature before the stack was kept at 140 °C [178,180,189].

3.7.1 Case Study-1

For the proposed CBHBP plant in CS-1, the Aspen simulation flowsheet with its operation data is shown in Figure 3.7. The overall process parameters of the CBHBP plant along with its simulation inputs and outputs, and the relevant calculations, are listed in Table 3.5. Aspen simulation mass and energy balances are provided in Appendix A. Below are the details of the simulation inputs and outputs, and calculations that are provided in Table 3.5.

The cogeneration plant produced 2000 kW biopower and 6956 kW bioheat during its maximum load conditions. The thermal power input was 9936 kW. The CBHBP electrical and total efficiency was 20% and 90%, respectively. The power over heat ratio calculated was 0.29. The resulting flow rate of the TR-Oak chips needed to supply 9936 kW thermal power input was 3273 kg/h with moisture content of 30%, and 2291 kg/h on a dry basis. The TR-Oak-chip mass flow per kWh biopower production was calculated to be 1.15, which is in line with the values reported (0.79–1.53) for different biomass sources [339].

The total air input was calculated to be 20,548 kg/h for an excess air ratio of 1.5. The temperature of the combustion gases leaving the economizer was calculated to be 277.5 °C. The mass flow rate of the flue gases was 23,778 kg/h. The volumetric flow rate of the flue gases under stack operating conditions (140 °C and 1.01325 bar), and under normal conditions (0 °C and 1.01325 bar), were 28,124 m³/h and 18,591 Nm³/h, respectively. TR-Oak ash (solid waste), and PM emissions of the CBHBP plant were determined to be 42 kg/h. The steam was superheated in the boiler to the temperature of 420 °C. The pressure of the superheated steam was 40 bar. The mass flow rate of the live steam was 11,464 kg/h. The pressure between the two stages of the turbine was 40 bar and 1.3 bar (back pressure). The pump increased the water pressure to 40 bar. The feedwater temperature before the boiler was 107.5 °C.

Table 3.5 : CBHBP process parameters, Aspen Plus V8.4 process simulation inputs and outputs, and calculations for Case Study-1.

CBHBP Case Study-1 Process Parameters	Unit	Simulation Input	Simulation Output	Calculation
System Parameters				
Biopower production	kW _e	2000		
Bioheat production	kW _{th}		6956	
Thermal power input	kW _{th}		9936	
CBHBP electrical efficiency ^a	%			20
CBHBP thermal efficiency ^b				70
CBHBP total efficiency ^c	%			90
Power/Heat ratio				0.29
TR-Oak chips mass flow				
Per hour, moisture content=30%	kg/h		3273	
Per hour, dry	kg/h			2291
Per kWh biopower, dry	kg/kWh			1.15
Grate Combustion Side				
Excess air ratio		1.5		
Air input	kg/h		20,548	
Combustion air temperature	°C	200		
Furnace exit temperature	°C	950		
Combustion gases to stack				
Temperature	°C	140		
Flow rate	kg/h		23,778	
Flow rate, 140°C, 1.01325 bar	m ³ /h		28,124	
Flow rate, 0°C, 1.01325 bar	Nm ³ /h			18,591
Total ash (including PM)	kg/h		42	
Steam Turbine Side				
Live steam flow	kg/h		11,464	
Turbine (Back pressure)				
Inlet pressure	bar	40		
Inlet temperature	°C	420		
Outlet pressure	bar	1.3		
Outlet temperature	°C		107	
Isentropic efficiency	%	85		
Boiler (Grate) efficiency	%	90		
Pump				
Isentropic efficiency	%	90		
Work	kW		14	
Steam cycle efficiency ^d	%			20

^a CBHBP electrical efficiency is equal to biopower production divided by thermal power input.

^b CBHBP thermal efficiency is equal to bioheat production divided by thermal power input.

^c CBHBP total efficiency is equal to the total of biopower and bioheat production divided by thermal power input.

^d Steam cycle efficiency is equal to the difference between biopower production and pump work divided by thermal power input.

3.7.2 Case Study-2

For the proposed CBHBP plant in CS-2, the Aspen simulation flowsheet with its operation data is shown in Figure 3.8. The overall process parameters of the CBHBP plant, along with its simulation inputs and outputs and calculations, are listed in Table 3.6. The Aspen simulation mass and energy balances are provided in Appendix A. Below are the details of the simulation inputs and outputs, and the calculations that are provided in Table 3.6.

The cogeneration plant produced 5000 kW biopower and 14,735 kW bioheat under its maximum load conditions. The thermal power input was 21,872 kW. The CBHBP electrical and total efficiency was 23% and 90%, respectively. The power over heat ratio was calculated to be 0.34. The resulting flow rate of the TR-Oak chips needed to supply 21,872 kW thermal power input was 5044 kg/h (dry basis) or 7205 kg/h (moisture content 30%). The TR-Oak-chip mass flow per kWh biopower production was calculated to be 1.01.

Total air input was calculated to be 45,233 kg/h for an excess air ratio of 1.5. The temperature of the combustion gases leaving the economizer was calculated to be 277.5 °C. The mass flow rate of the flue gases was 52,345 kg/h. The volumetric flow rate of the flue gases under stack operating conditions (140 °C and 1.01325 bar), and normal conditions (0 °C and 1.01325 bar), were 61,913 m³/h and 40,925 Nm³/h, respectively. TR-Oak ash (solid waste), and PM emissions of the CBHBP plant were determined to total 93 kg/h. The steam was superheated in the boiler to the temperature of 480 °C. The pressure of the superheated steam was 65 bar. The mass flow rate of the live steam was 24,334 kg/h.

The pressure between the two stages of the turbine was 65 bar and 1.3 bar (back pressure). The pump increased the water pressure to 65 bar. The feedwater temperature before the boiler was 107.8 °C.

3.7.3 Case Study-3

For the proposed CBHBP plant in CS-3, the Aspen simulation flowsheet with its operation data is shown in Figure 3.9. The overall process parameters of the CBHBP plant, along with its simulation inputs and outputs and calculations, are listed in Table 3.7.

Table 3.6 : CBHBP process parameters, Aspen Plus V8.4 process simulation inputs and outputs, and calculations for Case Study-2.

CBHBP Case Study-2 Process Parameters	Unit	Simulation Input	Simulation Output	Calculation
System Parameters				
Biopower production	kW _e	5000		
Bioheat production	kW _{th}		14,735	
Thermal power input	kW _{th}		21,872	
CBHBP electrical efficiency ^a	%			23
CBHBP thermal efficiency ^b				67
CBHBP total efficiency ^c	%			90
Power/Heat ratio				0.34
TR-Oak chips mass flow				
Per hour, moisture content=30%	kg/h		7205	
Per hour, dry	kg/h			5044
Per kWh electricity, dry	kg/kWh			1.01
Grate Combustion Side				
Excess air ratio		1.5		
Air input	kg/h		45,233	
Combustion air temperature	°C	200		
Furnace exit temperature	°C	950		
Combustion gases to stack				
Temperature	°C	140		
Flow rate	kg/h		52,345	
Flow rate, 140°C, 1.01325 bar	m ³ /h		61,913	
Flow rate, 0°C, 1.01325 bar	Nm ³ /h			40,925
Total ash (including PM)	kg/h		93	
Steam Turbine Side				
Live steam flow	kg/h		24,337	
Turbine (Back pressure)				
Inlet pressure	bar	65		
Inlet temperature	°C	480		
Outlet pressure	bar	1.3		
Outlet temperature	°C		107	
Isentropic efficiency	%	85		
Boiler (Grate) efficiency	%	90		
Pump				
Isentropic efficiency	%	90		
Work	kW		50	
Steam cycle efficiency ^d	%			23

^a CBHBP electrical efficiency is equal to biopower production divided by thermal power input.

^b CBHBP thermal efficiency is equal to bioheat production divided by thermal power input.

^c CBHBP total efficiency is equal to the total of biopower and bioheat production divided by thermal power input.

^d Steam cycle efficiency is equal to the difference between biopower production and pump work divided by thermal power input.

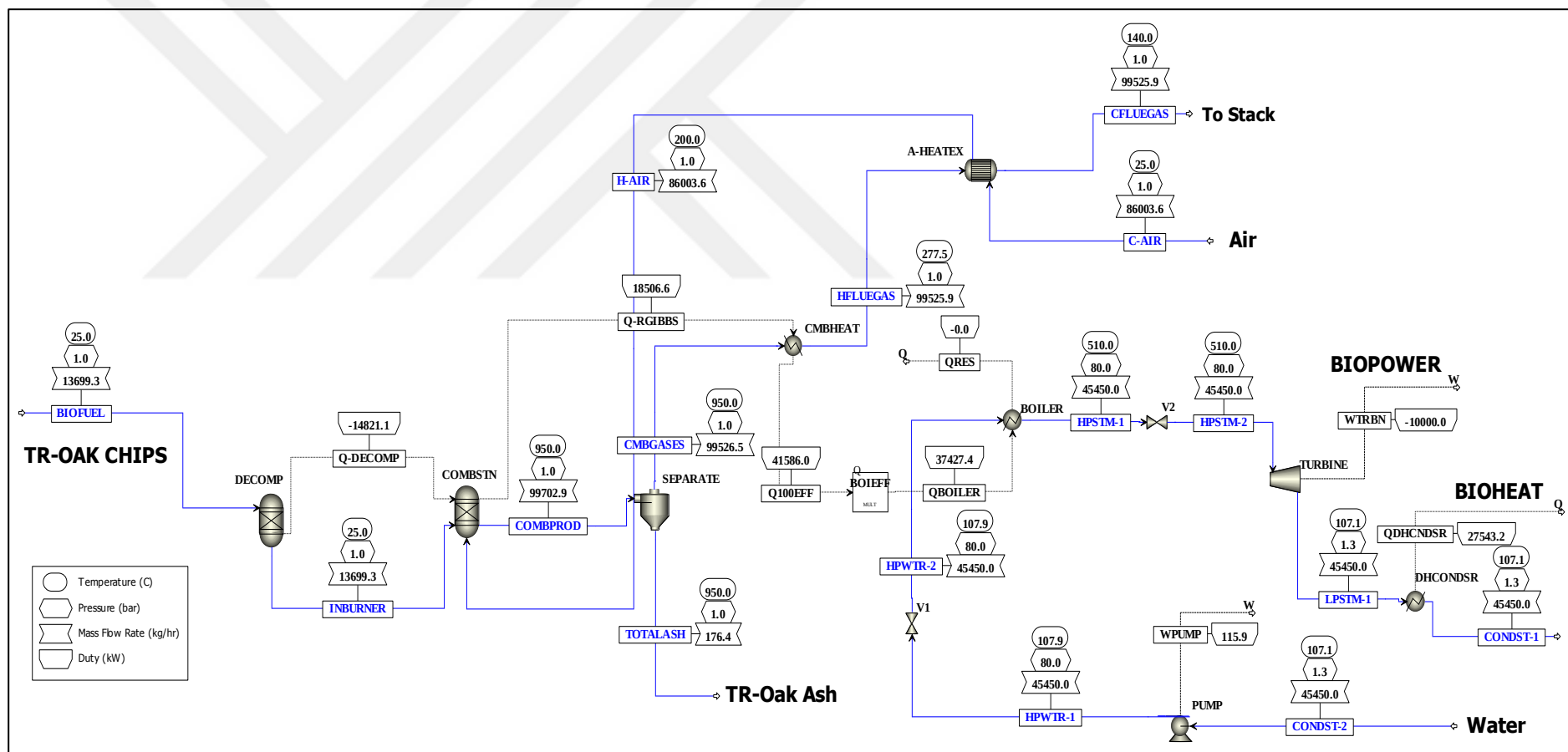


Figure 3.9 : Aspen Plus V8.4 process simulation flowsheet of TR-Oak chip-fueled CBHBP plant for Case Study-3.

Table 3.7 : CBHBP process parameters, Aspen Plus V8.4 process simulation inputs and outputs, and calculations for Case Study-3.

CBHBP Case Study-3 Process Parameters	Unit	Simulation Input	Simulation Output	Calculation
System Parameters				
Biopower production	kW _e	10,000		
Bioheat production	kW _{th}		27,543	
Thermal power input	kW _{th}		41,586	
CBHBP electrical efficiency ^a	%			24
CBHBP thermal efficiency ^b				66
CBHBP total efficiency ^c	%			90
Power/Heat ratio				0.36
TR-Oak chips mass flow				
Per hour, moisture content=30%	kg/h		13,699	
Per hour, dry	kg/h			9589
Per kWh electricity, dry	kg/kWh			0.96
Grate Combustion Side				
Excess air ratio		1.5		
Air input	kg/h		86,004	
Combustion air temperature	°C	200		
Furnace exit temperature	°C	950		
Combustion gases to stack				
Temperature	°C	140		
Flow rate	kg/h		99,526	
Flow rate, 140°C, 1.01325 bar	m ³ /h		117,717	
Flow rate, 0°C, 1.01325 bar	Nm ³ /h			77,813
Total ash (including PM)	kg/h		176	
Steam Turbine Side				
Live steam flow	kg/h		45,450	
Turbine (Back pressure)				
Inlet pressure	bar	80		
Inlet temperature	°C	510		
Outlet pressure	bar	1.3		
Outlet temperature	°C		107	
Isentropic efficiency	%	85		
Boiler (Grate) efficiency	%	90		
Pump				
Isentropic efficiency	%	90		
Work	kW		116	
Steam cycle efficiency ^d	%			24

^a CBHBP electrical efficiency is equal to biopower production divided by thermal power input.

^b CBHBP thermal efficiency is equal to bioheat production divided by thermal power input.

^c CBHBP total efficiency is equal to the total of biopower and bioheat production divided by thermal power input.

^d Steam cycle efficiency is equal to the difference between biopower production and pump work divided by thermal power input.

Aspen simulation mass and energy balances are provided in Appendix A. Below are the details of the simulation inputs and outputs, and calculations, provided in Table 3.7.

The cogeneration plant produced 10,000 kW biopower and 27,543 kW bioheat during its maximum load conditions. The thermal power input was 41,586 kW. The CBHBP electrical and total efficiency was 24% and 90%, respectively. The power over heat ratio was calculated to be 0.36. The resulting flow rate of the TR-Oak chips needed to supply 41,586 kW thermal power input was 9589 kg/h (dry) and 13,699 kg/h (moisture 30%). The TR-Oak-chip mass flow per kWh biopower production was calculated to be 0.96.

Total air input was calculated to be 86,004 kg/h, for an excess air ratio of 1.5. The temperature of the combustion gases leaving the economizer was calculated to be 277.5 °C. The mass flow rate of the flue gases was 99,526 kg/h. The volumetric flow rate of the flue gases under stack operating conditions (140 °C and 1.01325 bar), and normal conditions (0 °C and 1.01325 bar), was 117,717 m³/h and 77,813 Nm³/h, respectively. TR-Oak ash (solid waste), and PM emissions of the CBHBP plant was determined to total 176 kg/h. The steam was superheated in the boiler to the temperature of 510 °C, and the pressure of the superheated steam was 80 bar. The mass flow rate of the live steam was 45,450 kg/h. The pressure between the two stages of the turbine was 80 bar and 1.3 bar (back pressure). The pump increased the water pressure to 80 bar. The feedwater temperature before the boiler was 107.9 °C.

3.7.4 Environmental impacts from CBHBP Plants

Environmental impacts from the CBHBP plants include stack gas emissions (combustion gases and PM), solid wastes (bottom and fly ash), and other wastes. For all cases, the combustion gases were assumed to be cleaned first in a multi-cyclone. Further particle removal includes the application of advanced ESP or fabric filters for each case study. NO_x control technologies are not required because the prompt and thermal NO_x formation were minimized by keeping the furnace exit temperature at 950 °C, low enough to reduce the fixation of prompt and thermal nitrogen. In addition, desulfurization technology was not needed because TR-Oak chips contain a negligible amount of sulfur. Therefore, SO₂ and SO₃ emissions were of no concern [150]. All

process emissions explained below are the base values used for LCA studies of the CBHBP plants considered.

3.7.4.1 Stack gas emissions

Stack gas emissions include the combustion gases to the stack and PM, which is the finest fly-ash fraction (which is emitted with the combustion gases). Stack gas emissions were quantified as combustion gases of the CBHBP plants by the Aspen Plus process simulation. Table 3.8 presents the amount of the combustion-gas emission mass-flow rates (as kg/h), concentrations, and mass flows per MJ TR-Oak chips input (mg/MJ). The concentrations are valid for all cases, and calculated as mg/m³ for stack gas temperature and pressure (140 °C and 1.01325 bar), mg/Nm³, and ppmv (parts per million in volume) based on the Aspen Plus process simulation outputs. Appendix B provides the procedure followed to calculate the concentrations. The mass flows of combustion gases per MJ TR-Oak chips input were calculated taking into account the lower heating value of whole-tree TR-Oak chips. In addition, for comparison purpose, Table 3.8 includes the emissions determined with the help of stoichiometric calculations using both the assumed combustion reactions and ultimate analysis of TR-Oak chips (explained in Chapter 3).

Analyzing the combustion gas emissions obtained using the simulation in Table 3.8, it is seen that the mass flow rates of H₂O and CO₂ fit the results of the stoichiometric calculation. The mass flow of O₂ is less than that of the stoichiometric calculation because the combustion reactions assume that the combustion products are H₂O, CO₂, NO, and SO₂. However, in the simulation, the amount of the defined combustion products was calculated to ensure chemical and phase equilibrium under the given operating conditions.

Therefore, some of the O₂ content was spent in formation of the other combustion products (CO, NO₂, N₂O, and SO₃). Also in the simulation, some of the H₂ remained in the combustion products. CO formation was minor in the simulation, and was not a concern in the combustion reactions. Modern biomass combustion systems drastically reduce incomplete combustion products to levels close to zero [181,228,340]. NO formation in the simulation was less than the stoichiometric calculation because the

Table 3.8 : Stack gas (combustion gases) emissions of the CBHBP plants: Aspen Plus V8.4 process simulation, and stoichiometric calculation for comparison.

Stack Gas (Combustion Gases) Emissions	Aspen Plus Process Simulation			Calculation Based on Aspen Plus Process Simulation				Stoichiometric Calculation		
	Mass Flow Rate (kg/h)			Concentration ^a			Mass Flow (Per MJ TR- Oak Chips) ^b	Mass Flow Rate (kg/h)		
	Case Study 1	Case Study 2	Case Study 3	mg/m ³	mg/Nm ³	ppmv	mg/MJ	Case Study 1	Case Study 2	Case Study 3
H ₂ O	2179	4796	9119	77,464	117,189	145,711	53,940	2179	4796	9119
O ₂	1590	3501	6656	56,541	85,537	59,878	39,371	1596	3512	6677
N ₂	15,773	34,723	66,019	560,830	848,434	678,421	390,517	15,762	34,698	65,972
H ₂	2.027E-05	4.461E-05	8.483E-05	7.206E-04	1.090E-03	1.211E-02	5.018E-04	-	-	-
CO	3.232E-04	7.115E-04	1.353E-03	1.149E-02	1.739E-02	1.390E-02	8.002E-03	-	-	-
CO ₂	4229	9310	17,701	150,372	227,485	115,785	104,707	4229	9310	17,701
NO	3.156	6.947	13.208	112.206	169.747	126.718	78.131	27.534 ^c	60.614 ^c	115.247 ^c
NO ₂	3.780E-02	8.321E-02	1.582E-01	1.344	2.033	9.900E-01	9.358E-01	-	-	-
N ₂ O	2.575E-04	5.669E-04	1.078E-03	9.156E-03	1.385E-02	7.050E-03	6.376E-03	-	-	-
S	5.939E-17	1.308E-16	2.486E-16	2.112E-15	3.195E-15	2.232E-15	1.470E-15	-	-	-
SO ₂	3.9170	8.6220	16.393	139.260	210.676	73.662	96.970	4.120	9.069	17.243
SO ₃	2.537E-01	5.585E-01	1.062	9.020	13.646	3.818	6.281	-	-	-

^a mg/m³ is reported for stack gas temperature and pressure (140°C and 1.01325 bar).

^b Based on lower heating value of whole tree TR-Oak chips.

^c Calculated for NO_x, which represents the total of NO and NO₂.

combustion reactions assume that all N_2 in the TR-Oak chips was converted to NO. That is why the N_2 amount in the simulation was higher than in the stoichiometric calculation. In the simulation, it was observed that air nitrogen (thermal and prompt N_2) was in the combustion products because the furnace temperature was far below 1200–1300 °C. On the other hand, while 87.76% of the fuel N_2 was in the combustion products, only 12.24% of fuel N_2 caused NO_x (NO and NO_2) and N_2O formation. The calculations for the combustion reactions assumed that all S was converted to SO_2 . In the simulation, it was observed that 95% of S was converted to SO_2 and the rest was converted to SO_3 . Only a minor amount of sulfur was left in the combustion products.

PM emissions were determined by considering the emission factor for PM-10 as reported in “AP 42, Compilation of Air Pollutant Emission Factors” [332], which suggested an emission factor rating of ‘D’. Appendix B provides the related information and calculation procedure. Table 3.9 presents the amount of PM-10 emission mass-flow rate (kg/h), concentrations, and mass flow per MJ TR-Oak chips input (mg/MJ). The concentrations are valid for all cases, and were calculated as mg/m^3 under the conditions of the stack gas temperature and pressure (140 °C and 1.01325 bar), and as mg/Nm^3 based on the Aspen Plus process simulation outputs. Appendix B provides the procedure followed to calculate the concentrations. The mass flow of PM-10 per MJ TR-Oak chip input was calculated taking into account the lower heating value of whole tree TR-Oak chips.

The PM-10 mass flow rate in the table corresponds to 1.6% of the total ash formation of the CBHBP plants, which is an output of the Aspen Plus process simulation. In addition, from the literature, considering the average percentage of different ash fractions to the total ash formation of the CBHBP plants, the percentage for flue dust reported was between 0.1 to 3.0 for different power plant technologies and biofuel feedstocks used [331]. In other words, for this simulation, a PM-10 percentage that is 1.6% of the total ash formation is in line with the values reported in literature. The rest, 98.4%, represents the boiler bottom and fly ash amounts, which are the bottom ash produced in the combustion chamber (the boiler and cyclone fly-ash which are ash particles carried with combustion gases and precipitated in boiler section and in cyclones), and the filter fly-ash (ash particles precipitated in filters). The mass flow of PM-10 per MJ TR-Oak chip input was 16.7 mg/MJ, which is in line with correctly operated modern biomass combustion systems. Today, wide ranges of PM emission

factors are reported for biomass combustion systems, variations which mainly depend on the particle-removal equipment used. With simple ESP applications, while typical PM emission factors are reported between 25–50 mg/MJ, achievable PM emission factors for correctly operated modern biomass combustion systems are reportedly between 15–35 mg/MJ [228].

Table 3.9 : PM-10 emissions of the CBHBP plants calculated using AP 42 [332] and the Aspen Plus V8.4 process simulation outputs.

Case Study	PM-10 Emission ^a			
	Mass Flow Rate (kg/h)	Concentration ^b		Mass Flow (Per MJ TR-Oak Chips) ^c
		mg/m ³	mg/Nm ³	
1	0.674			
2	1.484	23.971	36.264	16.692
3	2.822			

^a AP42 emission factor rating is D.

^b mg/m³ is reported for stack gas temperature and pressure (140°C and 1.01325 bar).

^c Based on lower heating value of whole tree TR-Oak chips.

Table 3.10 shows the calculated air pollutant concentrations for each CS under reference conditions. The reference conditions were 0 °C, 1 atm, 6% volumetric oxygen, and dry basis for the stack gases, as stated in the “Industrial air pollution control regulation” of Turkey [341]. Table 3.10 also includes the limit values from this regulation, which are set for solid-fuel combustion plants with thermal power up to 50 MW. To convert the pollutant concentrations in mg/m³ to mg/Nm³ at 6% O₂ and dry basis, correction factors for oxygen and moisture were calculated. The formulas and procedure are provided in Appendix B. NO_x represents the total of NO and NO₂, SO_x represents the total of SO₂ and SO₃.

3.7.4.2 Solid wastes

Solid wastes represent the mineral content remaining after the combustion process, and include the bottom ash produced in the combustion chamber, the boiler and cyclone fly-ash (ash particles carried with flue gases and precipitated in the boiler section and in the cyclones), and the filter fly-ash (ash particles collected upon the filters).

Table 3.10 : Air pollutant concentrations of the CBHBP plants and national limits for Turkey.

	Air Pollutant Concentrations (mg/Nm ³ , 6% O ₂ , dry basis)					
	CO	CO ₂	NO _x ^a	N ₂ O	SO _x ^b	PM
Case Studies	0.021	285,492	215.583	0.017	281.552	45.511
Limits ^c [341]	200	-	-	-	2000	150

^a NO_x represents the total of NO and NO₂.

^b SO_x represents the total of SO₂ and SO₃.

^c Limits from the “Industrial air pollution control regulation of Turkey” for thermal energy input ≤ 50 MW.

The total ash formation (including PM) was computed by the Aspen simulation and is presented in Table 3.5 to 3.7. Table 3.11 in this section shows the total boiler bottom and fly-ash produced for each CBHBP plant. The amounts in Table 3.11 are based on the assumption that 1.6% of the total ash formation represents the PM emissions, and that the rest comprises the solid waste, boiler bottom, and fly-ash. The table also provides the percentage of biofuel feedstock (by weight) which is left as solid waste.

Table 3.11 : Solid waste (TR-Oak ash) amounts of the CBHBP plants.

Case Study	TR-Oak Ash	
	Mass Flow Rate (kg/h)	Weight % of TR-Oak Chip Input
1	41.482	
2	91.317	1.81
3	173.625	

3.7.4.3 Other wastes

Other wastes include all emissions and wastes other than stack gas emissions and solid wastes. Waste water (boiler blowdown and steam leakages) and waste lubrication oil are two types of emissions of concern with CBHBP plants. Although much of the water required for the CBHBP plants is used in a closed system, there is a wastewater stream caused by the boiler blowdown and steam leakage. Typical blowdown flow rates are reportedly between 4% and 8% of the boiler feedwater (live steam) flow rate [342]; although some studies assume values of 0.25% and 1% [343]. For this simulation, a blowdown flow rate of 4% was assumed, including steam leakage. Table 3.12 presents the amount of wastewater for each CBHBP plant, which is based on the assumption

mentioned and the Aspen process simulation output. Lubrication oil use and waste lubrication oil were not within the scope of the Aspen process simulation for the CBHBP plants; so they were adapted from the literature [291], and provided in Chapter 4.

Table 3.12 : Waste water flow rate of Combined BioHeat and BioPower plants.

Case Study	Waste Water Flow Rate (kg/h) ^a
1	459
2	973
3	1818

^a 4% of the live steam flow rate which is an output of the Aspen Plus process simulation.

4. LIFE CYCLE ASSESSMENT OF COMBINED BIOHEAT AND BIOPOWER PRODUCTION UTILIZING TURKISH OAK (*Quercus cerris* L.) COPPICES

This chapter presents the “goal and scope definition” and “inventory analysis” phases of the LCA study conducted, as well as the eco-design parameters determined. The LCA study was conducted for the case studies of CBHBP plants utilizing TR-Oak (*Quercus cerris* L.) coppices as biomass feedstock. The case studies were explained and simulations of them described in Chapter 3. The results of the LCA study are presented in Chapter 5.

The purpose of this chapter is to explain all the methodological choices determined and inventory data prepared for the LCA study in detail, and as transparently as possible. Below are the subsections of this chapter:

- Goal and scope definition of the LCA study
- Inventory analysis of the LCA study
- Eco-design parameters of the LCA study

4.1 Goal and Scope Definition of the LCA study

The subsections below provide all the methodological choices determined for this LCA study, which takes into account LCA standards [37-40], SimaPro software [285] and its related tutorials and manuals [259,344], and literature about CBHBP and biopower-only LCA studies including any recommended decisions that should be made at the beginning of an LCA study [246].

4.1.1 Goal

The goals of the LCA study were:

- To establish a baseline of information in terms of environmental aspects of CBHBP generation processes considered in the study. This baseline mainly

consists of resource requirements and environmental loadings from the processes that were analyzed, and a sensitivity analysis showing the effects of variations in key assumptions and choices

- To rank the relative contribution of top stressors (substances) and processes in the system boundary (i.e., which substances/processes contribute the most impacts)
- To present an eco-design approach by showing relative environmental consequences between alternative variables, which are feedstock and process conditions in this study, used to produce CBHBP
- To compare environmental loadings of CBHBP with a fossil-based alternative
- To identify data gaps
- To provide information and direction to investors, policymakers, and academicians

4.1.2 Scope

Following is the scope of the LCA study, in which all the methodological choices are identified. These include the system boundary, functional unit, modeling approach, allocation principle, impact assessment methods, impact categories, and required specificity.

4.1.2.1 System boundary

The system boundary of the LCA study is illustrated in the flow diagram in Figure 4.1. In the figure, the operations are grouped under the names listed below.

- Harvesting
- Collecting and forwarding
- Storage and natural drying
- TR-Oak chip production
- TR-Oak chip transport
- TR-Oak chip feedstock preparation

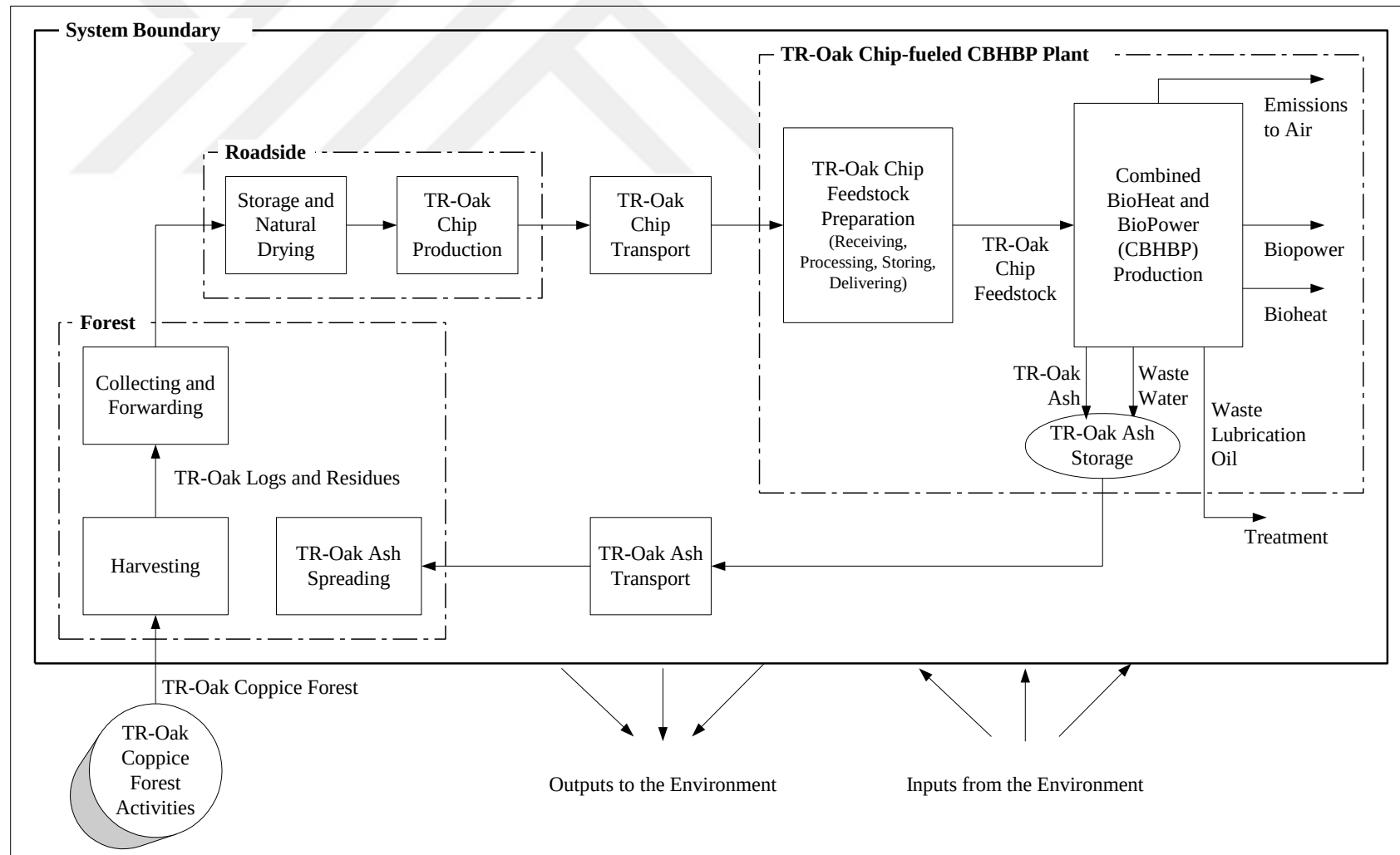


Figure 4.1 : System boundary of the LCA study conducted for TR-Oak chip-fueled CBHBP production.

- CBHBP production
- TR-Oak ash storage
- TR-Oak ash transport
- TR-Oak ash spreading

The system boundary begins with harvesting of TR-Oak coppices from the TR-Oak coppice forest (i.e., raw material acquisition). TR-Oak coppice forest activities are out of the system boundary. Therefore, cultivation processes are not taken into consideration; the activities after cultivation and wood growth are taken into account. The harvesting operation is followed by collecting and forwarding operations. Uncomminted TR-Oak logs and residues are collected, forwarded, and then stored at a roadside landing for natural drying to take place. After at least one summer period of storage and natural drying, TR-Oak chip production occurs at the roadside landing, and is directed into a transportation vehicle to eliminate the need for chip storage. Next, TR-Oak chips are transported to the CBHBP plant. TR-Oak chip feedstock preparation and CBHBP production take place in the CBHBP plant. TR-Oak chip feedstock preparation includes receiving, processing (sizing, grinding, and others, such as magnetic separation, conveying, etc.), storing, and delivering of TR-Oak chip feedstock for CBHBP production. Combustion coupled with a steam turbine (with conventional Rankine cycle), is the technology applied for CBHBP production in the study. Because CBHBP production is the core system considered in the LCA study, the major emissions and wastes are shown in the system boundary. TR-Oak ash utilization includes TR-Oak ash storage, transport, and spreading. After TR-Oak chips are combusted in the CBHBP plant, TR-Oak ash and wastewater are stored; then returned to the TR-Oak coppice forest floor. TR-Oak ash spreading occurs over the same area where the harvest was made previously. The system boundary ends at the grid where biopower is supplied, and at district heating network where bioheat is supplied. The environmental impacts from energy transmission, which belongs to the energy service life cycle, is not included in this study. Construction and decommissioning data, which includes the production and disposal of all materials used in the machinery infrastructure up to the system boundary, are taken into account. Transport operations are included in the system boundary wherever needed, and road transport is applied for them all.

4.1.2.2 Functional unit and modeling approach

Three energy-output-related functional units were chosen for this LCA study: 1 kWh biopower, 1 kWh bioheat, and 1 kWh useful energy (combined, i.e., both biopower and bioheat). During the LCA study, all mass and energy flows were normalized according to the functional units. In addition, the modeling approach used in the thesis study is a unit process-based attributional LCA. System model with partitioning (allocation, attributional) is the system model used to conduct a unit process-based attributional LCA.

4.1.2.3 Allocation procedure

CBHBP production is a multifunctional process resulting in more than one product, in this case, biopower and bioheat. Allocation is unavoidable because the life cycles of biopower and bioheat are interconnected. Therefore, combined bioheat and biopower production was designed as a joint production in the LCA study [292-296], which means that the outputs of the (joint) products (biopower and bioheat) were fixed. Consequently, exergy-based allocation, a physical causality for allocation, was the allocation approach chosen for the LCA study.

4.1.2.4 Impact assessment methods and impact categories

To choose an impact assessment method, all methods available in SimaPro software [277,285] were reviewed and compared considering the methods applied to CBHBP and biopower-only LCAs in the literature. The following lines explain the methods chosen along with the reasons for choosing these methods.

First, to elaborate a problem-oriented (midpoint) approach, CML-IA [345] was chosen as the midpoint impact assessment method to be used in the LCA study. CML-IA is a method developed by the “Centre of Environmental Science (CML)” of “Leiden University” in The Netherlands [345]. CML-IA has two versions available SimaPro: baseline and non-baseline. The baseline version (CML-IA baseline), having the most common impact categories used in LCA studies, was the version chosen.

Next, to elaborate a damage-oriented (endpoint) approach, ReCiPe Endpoint [346] was chosen as the endpoint impact assessment method for the weighting needed in the LCA study. The acronym ReCiPe represents the initials of the main contributors in its development, which are the “National Institute for Public Health and the Environment

(RIVM)”, “Radboud University”, “CML”, and “PRé Consultants” in The Netherlands [346]. ReCiPe Endpoint has three perspectives available in SimaPro. These are individualist, hierarchist, and egalitarian perspectives. The hierarchist perspective, “ReCiPe Endpoint (H)”, which relies on the most agreed policy principles, was the perspective chosen.

Normalization factors for the CML-IA baseline method; and normalization and weighting factors for the ReCiPe Endpoint (H) method, were selected as the world average values. Both methods were used as implemented in the SimaPro software [285]; no customization was done.

The reasons for choosing the methods above are summarized below.

- CML-IA is the most used midpoint impact assessment method for biomass energy life cycles. Using this method allows the study to be compared with other studies in the literature.
- CML-IA includes the most used impact categories for CBHBP generation, which are GW, ACD, and ETR.
- NO and NO₂ emissions are among the simulation outputs of the study. Impact assessment methods use different approaches to calculate the impact of NO and NO₂ emissions. CML-IA has separate characterization factors for NO and NO₂ emissions to calculate their impact on PCO, ACD, and ETR. However, for example, ReCiPe Midpoint splits NO_x into NO and NO₂ only to calculate their impact on marine ETR.
- ReCiPe Endpoint is the successor of Eco-indicator 99 method which has been the most applied endpoint approach used in biomass energy LCAs [222,247,249,277,278]. Now, SimaPro no longer supports Eco-indicator 99 [277,285] because it has been replaced by ReCiPe Endpoint [277,346,347].
- Both CML-IA and ReCiPe Endpoint include the values of the world averages for normalization and weighting, respectively [285,345,346].

At midpoint level, Table 4.1 shows an overview of the connections between environmental problems and midpoint impact categories, along with the characterization factors and units used in the CML-IA baseline method. The midpoint impact categories include:

Table 4.1 : CML-IA baseline method: An overview of the connections between environmental problems and midpoint impact categories along with characterization factors and units [277,285,345,347].

Environmental Issue	Midpoint Impact Category (Characterization)		Characterization Factor ^b
	Name	Unit ^a	
Photochemical oxidation	Photochemical oxidation	kg C ₂ H ₄ eq ^c	Photochemical oxidant creation potential
Acidification	Acidification	kg SO ₂ eq	Acidification potential
Eutrophication	Eutrophication	kg PO ₄ ³⁻ eq ^d	Eutrophication potential
Climate change	Global warming	kg CO ₂ eq	Global warming potential
Ozone layer depletion	Ozone layer depletion	kg CFC-11 eq ^e	Ozone depletion potential
Human toxicity	Human toxicity	kg 1,4-DB eq ^f	Human toxicity potential
Ecotoxicity	Fresh water aquatic ecotoxicity	kg 1,4-DB eq	Fresh water aquatic ecotoxicity potential
	Marine aquatic ecotoxicity	kg 1,4-DB eq	Marine aquatic ecotoxicity potential
	Terrestrial ecotoxicity	kg 1,4-DB eq	Terrestrial ecotoxicity potential
Depletion of abiotic resources	Abiotic depletion	kg Sb eq ^g	Abiotic depletion potential-elements
	Abiotic depletion (fossil fuels)	MJ	Abiotic depletion potential-fossil fuels

^a The impact category unit is the unit of the impact category indicator result.

^b The characterization factor unit is the impact category unit per kg emission or per kg extraction.

^c C₂H₄: ethane, ^d PO₄³⁻: phosphate, ^e CFC-11: trichlorofluoromethane, ^f DB: dichlorobenzene, ^g Sb: antimony.

- photochemical oxidation (PCO)
- acidification (ACD)
- eutrophication (ETR)
- global warming (GW)
- ozone layer depletion (OD)
- human toxicity (HT)
- fresh water aquatic ecotoxicity (FWET)
- marine aquatic ecotoxicity (MET)
- terrestrial ecotoxicity (TET)
- abiotic depletion for elements (ADE)
- abiotic depletion for fossil fuels (ADF)

The units of the impact categories are also the units of the impact category indicator results. Characterization factors are expressed as impact category units per kg emission or per kg extraction [277,285,345,347].

At endpoint level, Table 4.2 shows an overview of the connections between environmental problems and endpoint impact categories along with the units used in the ReCiPe Endpoint (H) method. The intermediate endpoint impact categories are aggregated into three endpoint (damage) categories:

- damage to human health
- damage to ecosystem diversity (ecosystems)
- damage to resource availability (resources)

These three categories are further aggregated into a single score using an indicator having a unit called point (Pt). To assess damage to human health, “Disability-adjusted Life Years” (DALY) is a unit commonly used in LCAs. To calculate DALY, years of life lost and disabled are summed, which is derived from human health statistics reported for a wide range of diseases. To assess damage to ecosystem diversity, ReCiPe Endpoint (H) gives the species diversity over time (species·yr). The damage

Table 4.2 : ReCiPe Endpoint (H) method: An overview of the connections between environmental problems and endpoint impact categories along with units [277,285,346,347].

Environmental Issue	Intermediate Endpoint Impact Category (Characterization)		Endpoint Impact (Damage) Category Name		
	Name	Unit	Human health (DALY) ^a	Ecosystems (species.yr) ^b	Resources (surplus cost)
Ozone layer depletion	Ozone depletion	DALY	+		
Particulate matter	Particulate matter formation	DALY	+		
Photochemical oxidation	Photochemical oxidation formation	DALY	+		
Human toxicity	Human toxicity	DALY	+		
Ionizing radiation	Ionizing radiation	DALY	+		
Climate change	Climate change - human health	DALY	+		
	Climate change - ecosystems	species.yr		+	
Acidification	Terrestrial acidification	species.yr		+	
Ecotoxicity	Fresh water ecotoxicity	species.yr		+	
	Marine ecotoxicity	species.yr		+	
	Terrestrial ecotoxicity	species.yr		+	
Eutrophication	Fresh water eutrophication	species.yr		+	
Land use	Agricultural land occupation	species.yr		+	
	Urban land occupation	species.yr		+	
	Natural land transformation	species.yr		+	
Depletion of abiotic resources	Metal depletion	USD ^c			+
	Fossil depletion	USD			+
Single Score (Pt) ^d					

^a DALY: disability-adjusted life years, ^b species.yr: loss of species during a year, ^c USD: US Dollar, ^d Pt: point.

*+ means that a connection is established with intermediate endpoint impact category.

to ecosystems diversity is calculated by taking the sum of “Potentially Disappeared Fraction of Species” (PDF) integrated over area and time multiplied by the species density for terrestrial, fresh water, and marine water systems. The damage to resource availability is expressed as the surplus costs (USD) of future resource extractions [277,285,346,347].

4.1.2.5 Required specificity

The approach to determine the required specificity is first to make a screening LCA and then to set up a data collection approach. The screening LCA was carried out using the data available in the literature. By doing so, it became possible to see what kind of data is needed, how much data is available, and what data is missing. The missing data was filled in with the data provided in the SimaPro software (i.e., from the ecoinvent database). Contribution analysis and/or sensitivity analysis was done to see how important this missing data is for overall LCA. Below are the steps implemented to determine the required specificity and to set up a data collection approach for the thesis.

- A CBHBP plant with known system parameters and steam turbine parameters was searched and an example was taken from the literature [333,334]
- Mass and energy balances were prepared for this CBHBP example
- A screening LCA was carried out in SimaPro software considering the basic methodological choices presented in this chapter
- An attempt was made to understand what kind of data was needed, how much data was available or missing, and how important the missing data was

As a result, the basic foreground and background data needed to carry out the LCA study were determined. This process also constructs the base of the inventory analysis phase of the LCA study. Being sensitive to the LCA results, the required specificity makes foreground data essential for biomass feedstock characteristics, and the CBHBP system parameters and operation data. In this context, the LCA study for this thesis considered the biomass feedstock in the oak coppice forests in Turkey, and the CBHBP system parameters and operation data based on the process simulation models explained in Chapter 3. To repeat, the process simulation models built within Aspen Plus for this thesis study take into account scientific studies, current commercial

biomass conversion technologies, and their applications for CBHBP production. All foreground and background data are presented in the inventory analysis section of this chapter.

4.2 Inventory Analysis of the LCA study

This section provides the inventory data prepared for the LCA study. The inventory data is based on the “goal and scope definition” explained in the previous section.

The subsections are organized under the headings below to provide an explanation of the data sources used, the data usage approach applied, and the collected inventory including general data and assumptions, which were needed for the LCA study.

- Data sources and data usage approach
- LCA inventory general data, and assumptions
- LCA inventory for TR-Oak chip supply chain
- LCA inventory for TR-Oak chip-fueled CBHBP plants and TR-Oak ash utilization

4.2.1 Data sources and data usage approach

The foreground inventory data of the LCA study was based on the biofuel feedstock characterization and Aspen Plus process simulation models. Experiments were carried out to characterize TR-Oak (*Quercus cerris L.*) coppices as biofuel feedstock for CBHBP production. Because there are presently no real operational plants using woody biomass chips to produce biopower and bioheat in Turkey, current commercial CBHBP plants worldwide were reviewed and CBHBP process simulations utilizing TR-Oak (*Quercus cerris L.*) coppices were performed. Therefore, the CBHBP plant data was provided from these process simulation outputs and other industry specific average technology data of the related CBHBP plants reviewed. The TR-Oak coppice characterization results and CBHBP simulation inputs and outputs are given in Chapter 3. Besides the Turkish specific settings, other data sources were literature, various databases, information systems, reports at national [21,348-350] and international levels, and ecoinvent [291] and other international LCA databases. The ecoinvent database [291], offered in SimaPro software [285], was used in the LCA study for background inventory data needs.

It is important to mention that whenever data was taken from a data source to be used in the LCA study, the approach followed in the thesis was not to use it as presented in the data source, but to properly adapt it to represent the specific conditions in this LCA study. First, if they existed, all relevant methodological reports were examined carefully for adaptation purposes. Then, an assessment was made considering the specific conditions of the study. This assessment answers questions such as, “How can the data be adapted?”, “How can the data be scaled?”, and “Are regional conditions significant for the data?”.

When using the ecoinvent database as a reference in the LCA study, “ecoinvent 3 – allocation, default – unit” was the ecoinvent library used. Hence, the ecoinvent dataset used was “allocation default, unit processes” [285,291]. In terms of the geographical scope of the datasets in ecoinvent, the GLO datasets, which represent general global geography, are preferred. Beside global datasets, the database contains non-global datasets, which are either Regional such as European (RER), country specific, or ROW datasets calculated automatically as the difference between global and non-global datasets. The use of global datasets in this study was found to be meaningful, productive, and acceptable, because the biomass energy applications in European countries are highly developed and operated at an advanced level. Besides, while using global datasets as a reference, one major adaptation for foreground processes and local conditions is made. Because processes are considered to be occurring locally in Turkey, Turkish-produced electricity is assumed to be used as input, which is a de-facto standard for adapting data from the ecoinvent database. As was found in the database, by simulating electricity consumption of related processes, electricity consumption was calculated according to the Turkish electricity mix and used in the study. In terms of activity types of the datasets in ecoinvent, market datasets, which include inputs of transport data with its associated activities; and losses in trade and transport in addition to inputs from production data; are preferred. Besides market datasets, the database contains transformation datasets, which contain all the inputs except for the transport data. The use of market datasets in this study is considered rational because it is recommended to use market datasets when specific suppliers are not known [291].

4.2.2 LCA inventory general data, and assumptions

The items below are the explanations of the general data, and assumptions for the LCA study, respectively.

- The Turkish electricity mix, which was applied to all processes in the LCA study, is constituted according to the distribution of Turkey's gross electricity production by energy sources at the end of 2015 [351], as depicted in Table 4.3.

Table 4.3 : Turkish electricity mix used in the LCA study [351].

Energy Source	Electricity Production (GWh)	Share (%)
Natural Gas	99,218.7	37.90
Coal - total	76,165.60	29.09
Imported coal	39,986.0	15.27
Hard Coal+Asphaltite	4,843.9	1.85
Lignite	31,335.7	11.97
Hydro - total	67,145.90	25.65
Dam	47,514.1	18.15
Natural lake and run of river	19,631.8	7.50
Wind	11,652.5	4.45
Others - total	7600.70	2.91
Geothermal	3,424.5	1.31
Liquid Fuels	2,223.9	0.85
Biomass	1,350.3	0.52
Waste heat	407.9	0.16
Solar	194.1	0.07
TOTAL	261,783.3	100

Natural gas, coal, and hydro were the main energy sources used in Turkish electricity production at the end of 2015. The share of natural gas, coal, hydro, and wind were (37.90, 29.09, 25.65, and 4.45) %, respectively. Although geothermal, liquid fuels, biomass, waste heat, and solar, which are classified as others, have a small share (2.91% in total), they are also included in the study. To represent the Turkish electricity mix, the associated market data in ecoinvent was taken as a base and customizations were made according to Table 4.3. The customized data describes

electricity production (high voltage), the transmission network, and electricity losses during transmission. During customization, imported coal, hard coal, and asphaltite were designated as hard coal; liquid fuels were designated as oil; biomass was designated as biogas; and waste heat was designated as industrial waste heat (blast furnace gas and coal gas). For electricity production with natural gas, four different datasets were assumed: conventional power plants with or without cogeneration, and combined cycle power plants with or without cogeneration. Electricity imports were not taken into consideration in the country mix.

- For heat requirements of the processes, global datasets were used because there is no definite country-specific information available.
- Moisture content, density, heating value, and other material properties of TR-Oak coppices were assumed to be homogeneous, and thus the variations in these properties were assumed to be negligible.
- It was assumed that TR-Oak coppices were harvested, and then TR-Oak logs and residues were collected and forwarded to a roadside landing with a moisture content of 50% by weight [148,151]. At the roadside landing, natural drying occurred from an initial average moisture content of 50% to about 30% by weight [57,73,136,147,148,151,262,352,353]. Therefore, TR-Oak logs and residues were chipped at 30% moisture content for the production of whole tree TR-Oak chips. TR-Oak chips were transported to the CBHBP plant at 30% moisture content, and prepared as feedstock to be used in the conversion unit. Table 4.4 summarizes the moisture content assumptions for the operations considered in the system boundary.
- Bulk density of TR-Oak chips (for whole tree TR-Oak chips) was taken as 330 kg/m^3 as a mean value for a moisture content of 30% [73,179,353-355].
- Bulk density of boiler bottom ash was taken as 200 kg/m^3 (mean value) [356].

Table 4.4 : Moisture content assumptions used in the LCA study [57,73,136,147,148,151,262,352,353].

Place	Operation	Moisture Content (% by weight)
Forest	Harvesting	50
	Collecting and forwarding	50
Roadside	Storage and natural drying	50 (before) / 30 (after)
	Chipping	30
Transport	TR-Oak chip transport	30
CBHBP plant	TR-Oak chip feedstock preparation	30
	CBHBP production	30

- Dry matter losses were included at every step of the LCA study. While 4% losses for operations in forests (harvesting, collecting, and forwarding) were assumed, those for each of storage and natural drying, chipping, and the CBHBP plant were assumed to be 2% [136,138,223,357]. Table 4.5 summarizes dry matter loss assumptions for the operations considered within the system boundary.
- This research assumes a continuous supply of TR-Oak chip feedstock from sustainable forest management activities resulting in an equal rate of TR-Oak coppices growth each year.

Table 4.5 : Dry matter loss assumptions used in the LCA study [136,138,223,357].

Place	Operation	Dry Matter Losses (% by weight)
Forest	Harvesting	-
	Collecting and forwarding	4%
Roadside	Storage and natural drying	2%
	Chipping	2%
Transport	TR-Oak chip transport	-
CBHBP plant	TR-Oak chip feedstock preparation	2%
	CBHBP production	-

- TR-Oak chip combustion was assumed to be a carbon-neutral process as a result of the sustainably managed forest activities. TR-Oak chip combustion does not contribute to increased atmospheric CO₂, because the amount of CO₂ released during TR-Oak chip combustion is balanced by the

CO₂ removed from the atmosphere by photosynthesis when the TR-Oak coppice was grown.

- Considering scientific studies and current commercial CBHBP applications, 20 years was chosen as the technical lifetime of these TR-Oak chip-fueled CBHBP plants [56,298,358].
- It was assumed that the CBHBP plants would operate continuously for 8000 h per year, seven days per week, and three shifts per day. One month was excluded for maintenance and vacations. This resulted in an availability factor of 91.3% for the plants, which indicates operational time without interruptions. The load factor for the plants was assumed to be 85%, which is a ratio of the gross production of a power plant over a time period, to its production if it had operated at full capacity over that time period. The capacity factor for the power plants, which is a factor of the power plant availability and load factor, was calculated to be 77.63% [111,166,358,359]. Table 4.6 summarizes the operational performance factors of the CBHBP plants proposed, and considers scientific studies and current commercial CBHBP applications.

Table 4.6 : The operational performance factors of TR-Oak chip-fueled CBHBP plants [56,111,166,298,358,359].

Place	Unit	Value
Technical lifetime	a	20
Operational hours per year	h/a	8000
Availability factor ^a	%	91.3
Load factor	%	85
Capacity factor ^b	%	77.63

^a Availability factor is equal to operational hours divided by nominal full load hours per year (8760 h/a).

^b Capacity factor is equal to availability factor times load factor.

- Table 4.7 shows the allocation factors calculated and the basic data used in the calculations for each CBHBP plant CS [34,194,223,262,360]. Here, 1 kWh biopower has an exergy content of '1'. For bioheat, the exergy content was calculated to be 0.26 using the Carnot factor, which depends on the steam temperature (temperature of the steam released into the district heating system) and the surrounding temperature. The temperature

assumed for the steam released into the district heating system was 107 °C, which is an output from the Aspen Plus simulation. The surrounding temperature is taken as 10 °C considering the average winter temperatures of the Marmara Region in Turkey [361]. The calculations for the Carnot factor, and allocation factors for biopower and bioheat, were made according to the formulae explained in Appendix C, which also includes the average temperature calculation.

- It was assumed that the bioheat produced in TR-Oak chip-fueled CBHBP plant was used for district heating (space heating and hot water) in residential houses or buildings in the vicinity. The district heating system chosen should be a low-temperature water system, which is compatible with the TR-Oak chip-fueled CBHBP simulation. However, district heating design is outside the scope of this thesis research.

Table 4.7 : Allocation factors calculated and the basic data used in the calculations for each case study [34,194,223,262,360,361].

		Case Study 1	Case Study 2	Case Study 3
Allocation factors ^a	Biopower	0.53	0.57	0.59
	Bioheat	0.47	0.43	0.41
Temperature (°C)	Steam ^b		107	
	Surrounding ^c		10	
Exergy content	Biopower ^c		1	
	Bioheat ^a		0.26	

^a Calculation, ^b Aspen simulation, ^c Known.

4.2.3 LCA inventory for TR-Oak chip supply chain

Harvesting of TR-Oak coppices in forests is the boundary for the beginning of TR-Oak chip supply-chain system. A harvester, which is a type of heavy forestry vehicle, is used for harvesting operations. The harvester has a mechanism that drives a chainsaw powered through a hydraulic drive. It is employed in logging operations (cut-to-length or whole tree extractions) for felling, delimbing, and crosscutting of TR-Oak coppices. Stump lifting was not included in this study. Next, a forwarder is used for collecting and forwarding operations. The forwarder hauls the oak logs and residues to a forest roadside landing, where natural drying takes place. At the roadside landing,

uncomminuted TR-Oak logs and residues are stored in big stockpiles under top cover in the most wind-exposed location for at least one summer period (i.e., with good air flow to promote rapid drying). The tops of the stockpiles are covered either during the stockpiling or, at latest, before the rainy season. It was assumed that a cover made of a biobased material is laid onto the stockpiles using the forwarder, and that emissions during stockpiling are negligible. The stockpiles are made as high as possible (i.e., 5 m), but not too close to each other because this would slow down the drying process. On the other hand, TR-Oak logs and residues that come out during spring and summer are left drying in the forest before forwarding to the stockpiles because they dry as fast in the forest as in the stockpiles. A mobile chipper is used for chipping operations at the roadside landing. Chipping of naturally dried oak logs and residues is carried out essentially year-round. Road transport is applied and a truck is used for oak chip transportation. TR-Oak chip storage is not necessary at the roadside because streams of the TR-Oak log and residue chips are directed into truck trailers and immediately transported to the CBHBP plant. The boundary of TR-Oak chip supply-chain system ends at the CBHBP plant gate.

Unless data specific to Turkish conditions was obtained, the inventory data for the TR-Oak chip supply chain was mainly based on the collection of representative average values from the literature, from biomass energy companies, from previous practices and lessons learned, and from the ecoinvent database because there was no operating commercial application in Turkey.

The unit processes designed in SimaPro software for TR-Oak chip supply chain of the LCA study are illustrated in Figure 4.2 with all the inputs from the environment and all the outputs to the environment including the reference products, materials, fuels, emissions, wastes, transport, and infrastructure (construction and decommissioning). In addition, all the inventory data as inputs and outputs is provided in Appendix D. The following lines summarize the unit processes designed, and provide the basic inventory data prepared for the TR-Oak chip supply chain of the LCA study.

The unit processes for forest machinery operations (harvesting, collecting and forwarding, chipping) mainly include input regarding the machinery infrastructure (i.e., production, maintenance, disposal); transport of machinery to the forest site; input of diesel fuel and lubricant; and emissions into the air from diesel consumption.

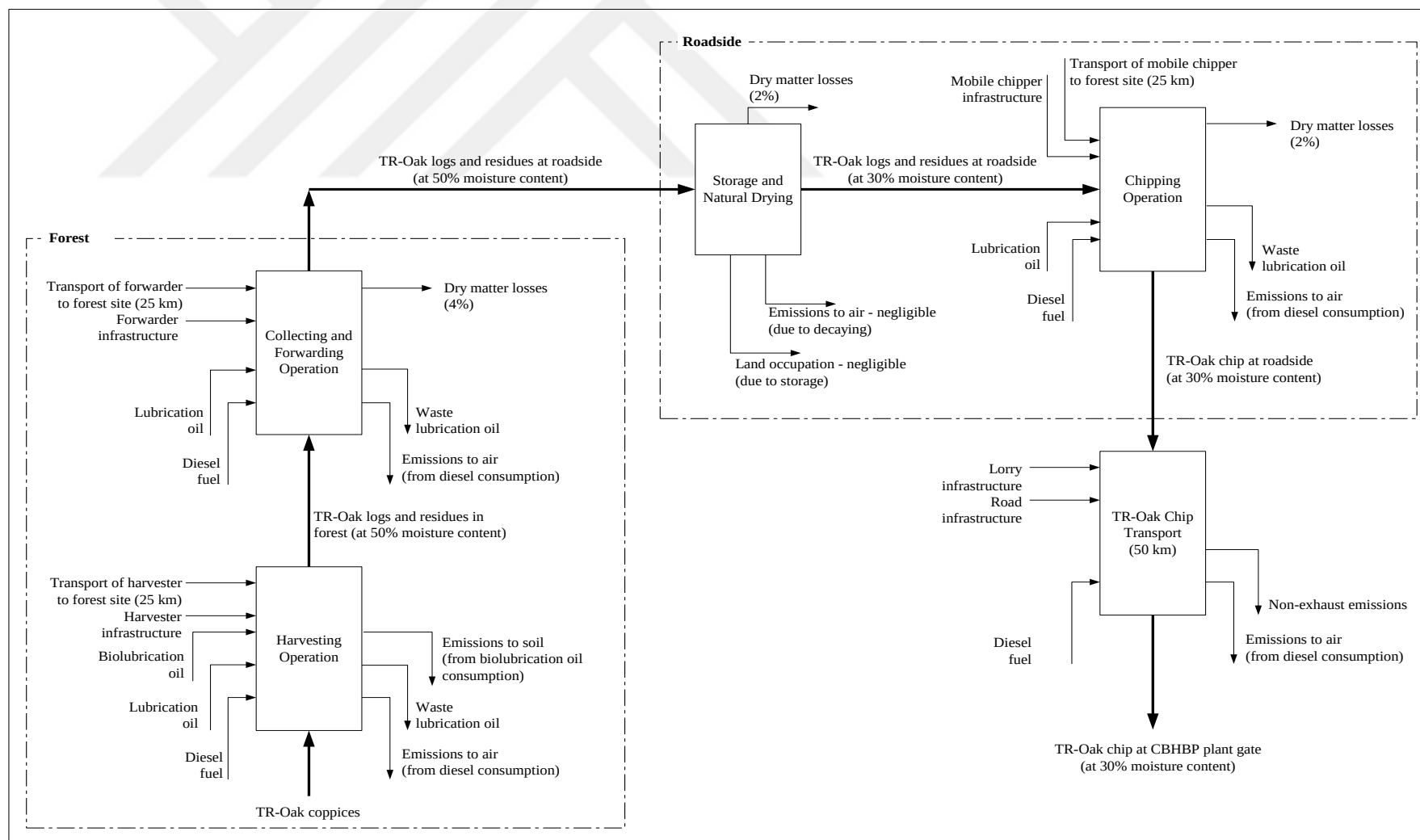


Figure 4.2 : Unit processes designed in the SimaPro software for the TR-Oak chip supply chain of the LCA study.

While lubrication oil is used as diesel engine oil and hydraulic oil for all the machinery, biolubrication oil was assumed to be used by the harvester for lubricating its chain saw. Therefore, in the forest, the oil waste that passes from the chainsaw to the soil is biodegradable. For every process, the moisture content and dry matter losses were considered as provided in the previous section. It was assumed that dry matter losses do not cause emissions, due to their being a part of natural processes. Moreover, because storage and natural drying take place prior to chip production, the decay process of the storage piles, and therefore emissions, were assumed to be negligible [136,223]. Land occupation due to storage was not taken into account because it is part of the forestry activities. The inventory data for truck transport include production, maintenance, and end of life of trucks; road infrastructure; diesel fuel consumption; and emissions into air from diesel consumption (i.e., the entire transport life cycle). Non-exhaust emissions due to tires, brakes, and road wear were also included. Data on forest machinery infrastructure and transport life cycle were from the ecoinvent database [285,291]. The input of diesel fuel, lubricant, and biolubrication oil was based on literature [135,362] and the ecoinvent database [285,291]. Data on diesel fuel emissions into the air was obtained from literature [363] and the ecoinvent database [285,291]. Data on waste lubricating oil, and emissions to the soil due to biolubrication oil consumption was from the ecoinvent database [285,291].

Table 4.8 shows the basic inventory data and assumptions used in the LCA study for harvesting, collecting and forwarding, and chipping operations. The inventory for each forest machinery operation was prepared for per productive machine hour. The working hours of each operation needed for TR-Oak chip supply chain was calculated based on the productivities reported, and the TR-Oak chips required for the CBHBP plant. In general, the values for productivity of forest machinery are variable as a result of different field conditions, operators, and stand characteristics. In this study, productivity (dry) was taken as (6 [57,364-367], 9 [134,364,365], and 22 [134,368]) t/h for the harvester, forwarder, and mobile chipper, respectively. It was assumed that all forest machinery operated at the maximum rated production capacity. The average engine power outputs were (100, 110, and 350) kW for the harvester, forwarder, and mobile chipper, respectively [285,291]. In this study, the harvester and forwarder were medium sized equipment, but the chipper was a high-power model mounted on a lorry,

Table 4.8 : Basic inventory data and assumptions used in the LCA study for harvesting, forwarding, and chipping operations [57,134,135,285,291,362,364-368].

Forestry Machine	Unit	Operation		
		Harvesting	Collecting and Forwarding	Chipping
Name		Harvester	Forwarder	Mobile chipper
Engine power	kW	100	110	350
Weight	kg	14,000	11,049	29,000
Daily transport distance to forest site ^a	km	25	25	25
Productivity (dry)	t/h	6	9	22
Daily utilization time ^a	h	8	8	8
Diesel fuel consumption	l/h	12	11	70
Lifetime ^a	a	20	20	20

^a Assumption.

the type most often used for roadside chipping operations. The forwarder had a load capacity of 10–12 t [285,291]. Diesel engines provided power for all the forest machinery. The density of the diesel fuel was 0.84 kg/l. While the average diesel consumption of the harvester and forwarder was 12.8 and 11 l/h, respectively, that for the chipper was 70 l/h [135,285,291,362]. The average daily transport distance of the forest machinery to the forest site was 25 km. In addition, all machinery was assumed to work eight productive hours per day. The technical lifetime of each machine was assumed to be 20 years.

Table 4.9 shows the basic inventory data and assumptions used in the LCA study for transportation vehicles. Truck choices were based on the load amount and also the receiving system of TR-Oak chip feedstock preparation yard in the CBHBP plant. In this study, a lorry (truck) of the size class 16–32 t gross vehicle weight (the most used type), with Euro 5 Emission Class was employed using the module available in the ecoinvent database. The average distance chosen between the roadside landing and the CBHBP plant was 50 km, considering previous biomass energy practices, lessons learned, and the literature.

Table 4.9 : Basic inventory data and assumptions used in the LCA study for the transportation vehicle [285,291,363].

	Unit	Transportation Vehicle
Name		Lorry
Size class	t	16-32
Average load factor	t	5.79
Service life	km/vehicle	540,000
Diesel consumption	kg/tkm	0.0375
Transport distance ^a	km	50

^a Assumption.

4.2.4 LCA inventory for TR-Oak chip-fueled CBHBP plants and TR-Oak ash utilization

This section includes the inventory data of the TR-Oak chip-fueled CBHBP plant comprising TR-Oak chip feedstock preparation and CBHBP production (i.e., the data after the TR-Oak chips are received onsite in trucks). Therefore, the inventory for the CBHBP plant starts at the gate of the plant and ends with the production of biopower and bioheat.

The conceptual configuration for TR-Oak chip feedstock preparation is based on a manual system. The system starts with receiving TR-Oak chips at the CBHBP plant gate. After trucks unload the oak chips, front-end loaders move and stack the oak chips on storage piles in an open storage area (i.e., long-term storage area). In this thesis, because chips were directed into the delivery truck, foreign materials such as gravels and rocks that could be picked up if chips were scraped off the ground to load into the truck, did not cause a problem. In addition, the open storage area in the preparation yard was assumed to be paved to prevent incidental scraping up of foreign materials with the oak chips. After receiving, onsite processing starts. Common processing steps are magnetic separation, sizing, and grinding, as well as conveying. TR-Oak chips are conveyed over a magnetic separation belt to remove metals and other noncombustible materials. The sizing operation separates oversized chips. The oversized chips are sent to the grinding operation to be properly sized. The processed TR-Oak chips are conveyed into a short-term (buffer) storage silo to be stored until the furnace needs the feedstock. From the silo, TR-Oak chips are metered and discharged to a surge bin. From the surge bin, TR-Oak chips are pneumatically transported to the furnace section of the boiler. No external dryers are used. The oak chips dry more in the combustion section of the boiler.

For CBHBP production, the following lines summarize the conceptual design used in the LCA study. Combustion takes place after the TR-Oak chip feedstock is pneumatically transported into the furnace section of the boiler. The boiler was assumed to be a grate boiler. Direct combustion produces hot combustion gases, which then produces steam with high pressure and temperature in the heat exchange section of the grate boiler. The thermal energy in the high-pressure and high-temperature steam enters the turbine and is converted to mechanical energy or shaft power. The mechanical energy from the steam turbine is used to drive a generator and produce biopower. The lower pressure and lower temperature steam leaving the steam turbine flows into heat exchangers to produce bioheat. An ESP is used for PM control. TR-Oak ash utilization includes oak ash storage, transport, and spreading. TR-Oak ash, which represents the bottom ash discharged from the grate, and fly ash collected from the cyclone separators and ESPs, are combined in a TR-Oak ash storage silo. TR-Oak ash is discharged from the silo through a conditioner (mixed with waste water) into trucks for transport. TR-Oak ash is utilized as a fertilizer by spreading it back on the

TR-Oak coppice forest floor. The average distance was assumed to be the same as for TR-Oak chip transport. Moreover, the vehicle used in the TR-Oak ash transport was the same as used in the TR-Oak chip transport. The TR-Oak ash spreading area in the forest was assumed to be equal to the harvest area, and was calculated based on the TR-Oak coppice forest productivity and TR-Oak chip feedstock requirement of the CBHBP plant. Ash spreading is done by a forwarder with a spreader attached to it (the forwarder is used to collect and forward oak logs and residues to the roadside landing). The LCA inventory did not consider the transmission and distribution of the biopower and bioheat produced to end users.

The unit processes designed in the SimaPro software for the TR-Oak chip-fueled CBHBP plant of the LCA study are illustrated in Figure 4.3. This includes all the inputs from the environment and all the outputs to the environment, including the reference products, materials, fuels, emissions, wastes, transport, and infrastructure. In addition, all the inventory data as inputs and outputs is provided in Appendix D. The following lines summarize the unit processes designed, and provide the basic inventory data prepared for the TR-Oak chip-fueled CBHBP plant and TR-Oak ash utilization for the LCA study.

The unit processes for TR-Oak chip feedstock preparation include the input of infrastructure (construction and decommissioning) for machinery (front-end loader and sizing and grinding equipment), and the TR-Oak chip storage silo; the use of diesel fuel; and emissions into the air from diesel consumption. The TR-Oak chips at the plant gate have a moisture content of 30%, which reduces dry matter losses considerably and facilitates long-term storability [132,148]. Therefore, decay in the storage areas, and therefore emissions, were assumed negligible. Material loss at the CBHBP site was assumed to be 2% [136,138,223,357], as provided in Table 4.5.

Table 4.10 provides the basic inventory data and assumptions used in the LCA study for feedstock preparation. The front-end loader was assumed to be an agricultural tractor suitable for boiler size applications up to 10 t/h feedstock input [151] (based on the ecoinvent dataset in SimaPro). Diesel consumption was taken from literature [151]. Air emissions from diesel combustion was calculated based on the emission factors

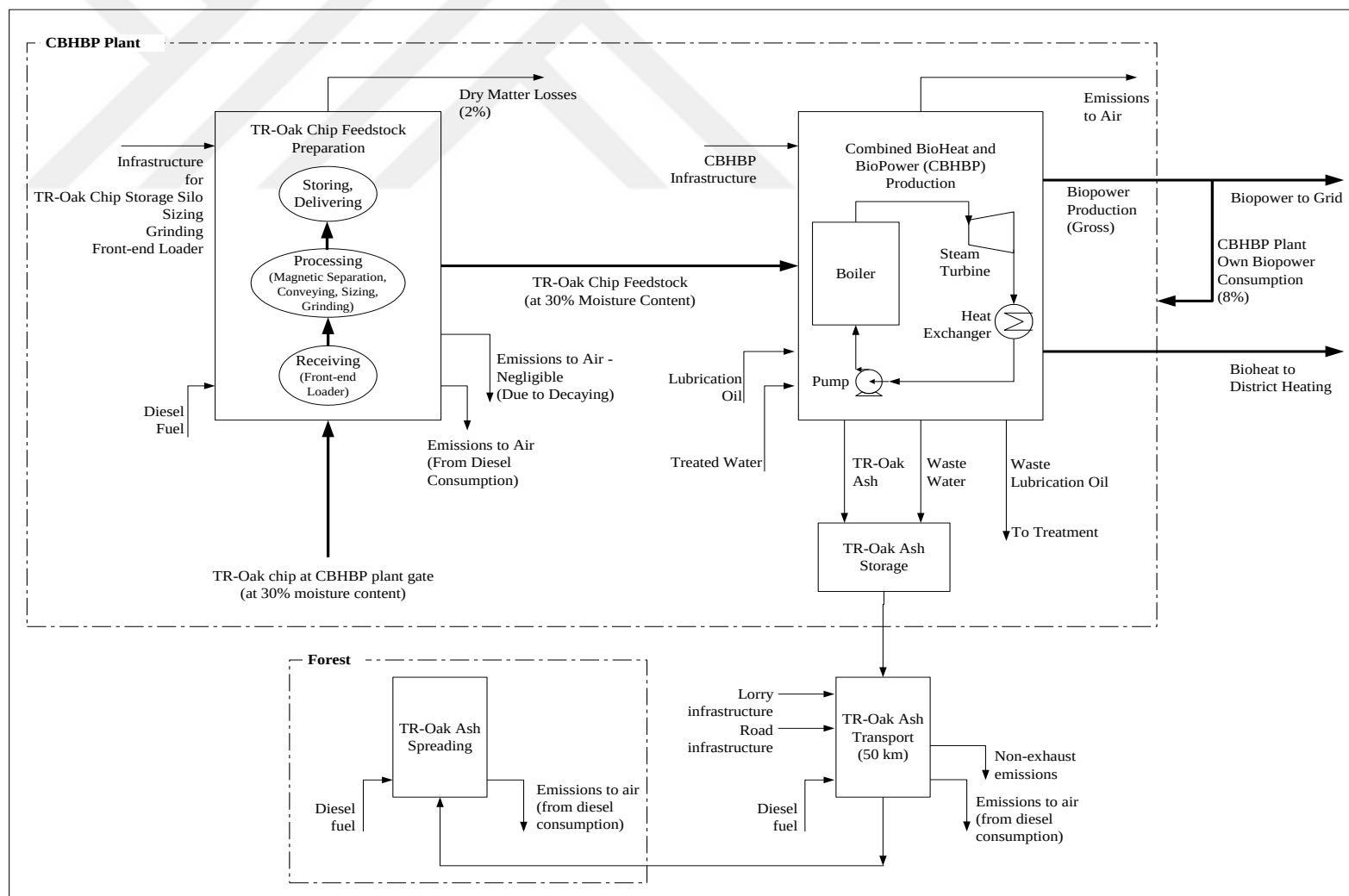


Figure 4.3 : Unit processes designed in the SimaPro software for the TR-Oak chip-fueled CBHBP plant of the LCA study.

Table 4.10 : Basic inventory data and assumptions used in the LCA study for feedstock preparation [148,150,151,285,291,369-372].

Equipment	Unit	Operation		
		Receiving	Sizing	Grinding
Name		Front-end loader	Disc screen	Hammer mill
Weight	kg	3000	3500	3300
Capacity (dry)	t/h	10	40	3
Average daily utilization time	h	8 ^a	8 ^a	8 ^a
Electricity consumption	kWh/t	-	^b	^b
Fuel consumption	l/h	3.8	-	-
Lifetime	a	20 ^a	20 ^a	20 ^a
Quantity	piece			
Case Study-1		1	1	1
Case Study-2		2	1	1
Case Study-3		3	1	1

^a Assumption, ^b Included in the own biopower consumption of the CBHBP plant.

reported [372] and in the ecoinvent database [291]. While a disc screen with a capacity of 40 t/h was used for sizing, a hammermill with a capacity of 3 t/h was used for grinding [148,151].

It was assumed that 1% of the feedstock [150] was bigger than the required dimension and needed grinding. The agricultural machine module of ecoinvent was used for construction data on the sizing and grinding equipment [285,291]. The use of electricity for sizing, grinding, and other operations such as magnetic separation and conveying in the feedstock preparation yard, was assumed to be included in the biopower consumption of the CBHBP plant. The lifetime for all machinery was assumed to be 20 years. The quantity of feedstock preparation equipment was calculated based on TR-Oak chip feedstock requirement of the CBHBP plant for each case study. The decisions were made in such a way as to meet minimum requirements for feedstock preparation.

A silo able to provide a 24-hour supply was chosen for short-term storage from which the oak chips were fed into the furnace. To meet the daily TR-Oak chip feedstock requirement of the CBHBP plant, the TR-Oak chip feedstock storage silo was designed in SimaPro assuming a vertical cylinder of steel with height two times the diameter. The material used for construction of the silo is taken as steel since, in general, silos

with diameters of 6.5–12 m are reportedly more cost effective when steel is used [369]. Table 4.11 provides the characteristics of the TR-Oak chip feedstock storage silos for the daily supply in each case study. The volumes were calculated using the assumed TR-Oak chip density, as provided in Section 4.2.2.

Table 4.11 : Characteristics of the TR-Oak chip feedstock storage silos for daily supply for each case study.

TR-Oak Chip Feedstock Storage Silo	Unit	Case Study 1	Case Study 2	Case Study 3
Quantity	piece	1	1	2
Dimensions (diameter/height)	m	5/10	6.5/13	6/12, 6.5/13
Volume	m ³	196 ^b	417 ^b	756 ^b
Wall thickness	mm	5 ^a	5 ^a	5 ^a
Steel requirement	kg	7700 ^b	13,000 ^b	24,000 ^b

^a Assumption, ^b Calculation.

The unit process for the TR-Oak chip-fueled CBHBP production considered in the LCA study was based on the Aspen Plus process simulation studies of the CBHBP plants utilizing TR-Oak coppices, as explained in Chapter 3. Therefore, LCI data of the CBHBP production was developed using the outputs of the Aspen Plus process simulations and TR-Oak chip feedstock characterization studies. The remaining data gaps were filled using the ecoinvent database and literature. The TR-Oak chip feedstock requirement was calculated running the Aspen Plus process simulation. Much of the water required for the CBHBP plant was used in a closed system. Consequently, the water requirement was primarily due to boiler blowdown and steam turbine leakages. It was assumed that water use was 4% of the total steam production [343] provided from the simulation. It was assumed that all water was treated water supplied from a water treatment unit in the power plant. An ecoinvent database entry [291] was used for the consumption of chemicals and emissions for the treatment of water used in the plant. Non-process use of water was not considered because this amount was small relative to the process use of water. Data on the infrastructure for CBHBP unit and ESP was from the ecoinvent database [291]. For the CBHBP infrastructure, the dataset for a CBHBP unit was used after scaling according to each CS. Scaling factors used for the CBHBP infrastructure are provided in Appendix D. The ESP infrastructure belongs to a typical ESP designed for PM collection from wood boilers. The dataset includes the most important materials used for the construction of

the CBHBP unit and ESP, the transport of these materials, the energy needed for their fabrication, the area occupied, and the disposal of the unit. The lubrication oil use of the plant was adapted from the ecoinvent database [291] after scaling to the amount of the reference product. Waste lubrication oil was sent for treatment. On-site biopower consumption for the auxiliary electricity requirement of the CBHBP plant (the difference between gross and net generation) was assumed to be 8% of the gross biopower production, considering CBHBP practices worldwide [214,343,359,373]. The on-site biopower consumption included the demand from CBHBP plant process requirements (for both TR-Oak chip feedstock preparation and CBHBP production), supplied by the power plant itself, as well as the demand during start-up and shut-down periods of the plant. CBHBP plant operational emissions to air (combustion gases) were taken from the simulation outputs. PM emissions to air and TR-Oak ash (bottom and fly ash) data were based on the simulation outputs and the AP42 emission factors database [332]. Boiler blowdown water was used for ash cooling and dust control [150,343], which eliminates discharge of the stream to the wastewater stream. The basic process parameters and requirements for the CBHBP case studies are provided in Table 4.12.

For TR-Oak ash storage, a steel silo of 15 days capacity was designed in SimaPro assuming a vertical cylinder of steel, with height two times the diameter. Table 4.13 provides the characteristics of the TR-Oak ash storage silos of 15 days capacity for each CS. The volumes were calculated using the assumed TR-Oak ash density provided in Section 4.2.2.

To address concerns that collecting forest residues removes soil nutrients, the TR-Oak ash was returned to the TR-Oak coppice forest floor and utilized as a fertilizer [56,148,150,151,173,374]. TR-Oak ash was assumed to be transported 50 km. TR-Oak coppice forest productivity was taken as 30 dry t/ha [69,317,375,376]. Based on the TR-Oak chip feedstock requirement of the CBHBP case studies, ash spreading area, which is equal to the harvest area, was calculated using TR-Oak coppice forest productivity. Ash spreading productivity chosen was 0.7 ha/h, based on the literature [377]. Table 4.14 summarizes the TR-Oak ash utilization steps and their related LCA inventory data.

Table 4.12 : Major process parameters, requirements, emissions, and wastes of TR-Oak chip-fueled CBHBP production.

CBHBP Production	CBHBP Production Case Studies			
	Unit	1	2	3
System parameters		Table 3.5, Figure 3.7	Table 3.6, Figure 3.8	Table 3.7, Figure 3.9
Operational performance factors		Table 4.6	Table 4.6	Table 4.6
Annual biopower production	GWh/a	13.6	34	68
Annual bioheat production	GWh/a	47.3	100	187
TR-Oak chip requirement (dry)	t/day	55	121	230
Own biopower consumption	kWh	160	400	800
Water consumption	kg/h	459	973	1818
Lubrication oil consumption	kg/kWh	11.8E10-6	11.8E10-6	11.8E10-6
Stack gas emissions (except PM)	kg/h	Table 3.8	Table 3.8	Table 3.8
PM-10 emissions	kg/h	Table 3.9	Table 3.9	Table 3.9
TR-Oak ash	kg/h	Table 3.11	Table 3.11	Table 3.11
Waste water	kg/h	Table 3.12	Table 3.12	Table 3.12
Waste lubrication oil	kg/kWh	11.8E10-6	11.8E10-6	11.8E10-6

Table 4.13 : Characteristics of the TR-Oak ash storage silos of 15 days capacity for each case study.

TR-Oak Ash Storage Silo	Unit	Case Study 1	Case Study 2	Case Study 3
Quantity	piece	1	1	1
Dimensions (diameter/height)	m	4/8	5/10	6/12
Volume	m ³	100 ^b	196 ^b	339 ^b
Wall thickness	mm	5 ^a	5 ^a	5 ^a
Steel requirement	kg	5000 ^b	7700 ^b	11,000 ^b

^a Assumption, ^b Calculation.

Table 4.14 : TR-Oak ash utilization inventory data [69,317,375-377].

Ash Utilization Steps	Unit	Case Study 1	Case Study 2	Case Study 3
TR-Oak ash storage ^a	kg/h	Table 3.11	Table 3.11	Table 3.11
TR-Oak ash transport ^b	km	50	50	50
TR-Oak ash spreading area ^c	ha	0.08	0.19	0.35

^a Aspen Plus process simulation output, ^b Assumption, ^c Calculation.

4.3 Eco-design parameters of the LCA study

A schematic of the eco-design approach applied to the LCA study is shown in Figure 4.4. The objective was first, to demonstrate the effect of the most fundamental CBHBP design parameters on the LCA results.

In this thesis work, each time an eco-design parameter for CBHBP was introduced, an Aspen Plus process simulation was run considering the parameter, and the LCA results were updated. After interpretation of the results, a new eco-design parameter for CBHBP could be introduced and the CBHBP simulation could be run accordingly.

The eco-design parameters determined were:

- Feedstock properties
- Process conditions

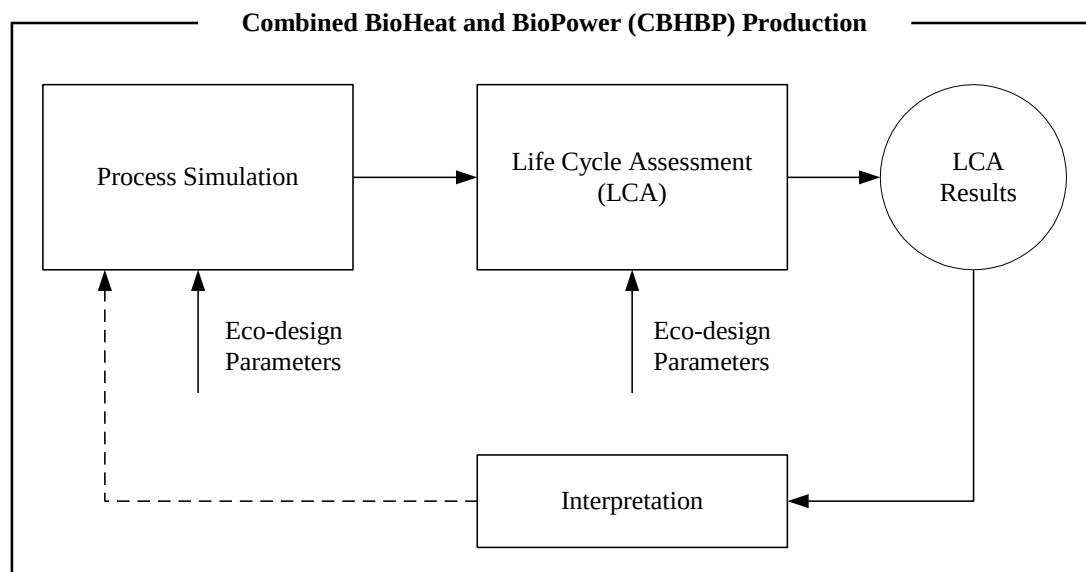


Figure 4.4 : Schematic of Life Cycle Assessment with an eco-design approach.

As known, LCA results are affected by feedstock properties and process conditions. In the thesis study, the biomass feedstock has been specified, and hence its properties are specific. However, the most changeable property of the biomass feedstock is its moisture content. Therefore, the moisture content was selected as a feedstock property to examine.

The excess air ratio and furnace temperature are essential factors for achieving complete combustion (thereby reducing pollutants) in biomass combustion systems. Hence, among the process conditions, the excess air ratio and furnace temperature were chosen to explore.

Table 4.15 provides all the eco-design parameters examined. The numbers in bold are the base values used for the case studies of CBHBP plants. For each eco-design parameter shown in the table, all the inventory data as inputs and outputs is provided in Appendix D.

Table 4.15 : Eco-design parameters determined for the LCA study.

Eco-design Parameter	Values					
Mositure content (%)	20	30^a	40	50		
Excess air ratio	1.2	1.5^a	1.8	2.0	2.2	2.5
Furnace temperature (°C)	850	900	950^a	1000	1100	1200

^a Base values used for the case studies of CBHBP plants.



5. COST OF COMBINED BIOHEAT AND BIOPOWER PRODUCTION UTILIZING TURKISH OAK (*Quercus cerris* L.) COPPICES

This chapter describes the method followed in the cost study and cost inventory data prepared to estimate costs of the TR-Oak (*Quercus cerris* L.) chip-fueled CBHBP plants, incorporating the data previously presented for each of the three case studies.

The costs presented in this chapter are realistic because they have been calculated on the basis of current commercial CBHBP applications, but, of course they do not represent actual costs for a specific project in Turkey. Naturally, the cost for each project would need to be calculated specifically.

5.1 The Method Followed in the Cost Study

First of all, for the cost study of the CBHBP plants, there was communication with biomass energy sector leaders, both domestic and international suppliers, to determine real market prices. Oral communications and correspondence were done to reach the costs related to this issue. Unfortunately, suppliers showed little interest in non-profit academic work because of the working principles they assess within their scope of consulting; therefore, real market prices were not determined.

At this stage, to provide insight for investors and public-sector decision makers involved in CBHBP production technologies, and hence to facilitate decision making, it was aimed to provide CBHBP production representative cost estimates on the basis of current commercial CBHBP applications worldwide.

It is known that investment and biofuel feedstock costs are important factors influencing biopower production cost. To estimate investment cost as well as fixed and variable O&M costs for the CBHBP plants, the “System Advisor Model” (SAM 2017.1.17) [378] was taken as the base. SAM is a performance and financial model of the “National Renewable Energy Laboratory” in the USA, and is used to facilitate decision making based on current, commercial, renewable power and/or heat applications.

To estimate TR-Oak chip cost at the CBHBP plant gate, a demonstration study carried out by GDF in Turkey was found and taken as a base [73]. Therefore, it is thought that the best available cost solution for TR-Oak chip cost at the CBHBP plant gate was used in the study.

5.2 Cost Inventory Data for Case Study-1, -2, and -3

Table 5.1 shows a summary of the technical and cost related data used in the cost estimates of TR-Oak chip-fueled CBHBP plants.

The technical data listed in Table 5.1 is from tables previously presented for CBHBP simulations, as provided in the remarks column. The cost related data is summarized below.

- The annual capital recovery factor (10.2%) [56], was used to calculate the annual capital recovery cost (annuity) by multiplying it by the investment cost. A 20-year utilization period at 8% interest rate, resulted in an annual capital recovery factor of 10.2% [35,56].
- TR-Oak chip cost at CBHBP plant gate (35 USD/t) was based on a demonstration study carried out by GDF in Turkey [73], as mentioned before.
- Biopower sale price was calculated based on the feed-in tariffs in the YEK law [25]. The price applicable to biopower production plants is 13.3 cent/kWh without possible domestic production incentive for components produced in Turkey and a cogeneration premium. The possible tariff calculated was 17 cent/kWh with the addition of 3.7 cent/kWh domestic production incentive, including the cogeneration system premium (i.e., 0.8 cent/kWh for the boiler, 2.0 cent/kWh for the steam turbine, 0.5 cent/kWh for the generator, and 0.4 cent/kWh for the cogeneration system premium).
- Bioheat was sold to a district heating network. The bioheat sent to the district heating network was assumed to substitute for natural gas. Hence, the bioheat sale price taken was the natural gas price for residential heating (~2.5 cent/kWh) [379].

Table 5.1 : A summary of technical and cost related data used in the cost estimates of the TR-Oak chip-fueled CBHBP plants.

	Unit	Case Study-1	Case Study-2	Case Study-3	Remarks
Technical Data					
Biopower production	kW _e	2000	5000	10,000	Tables 3.5, 3.6, 3.7
Bioheat production	kW _{th}	6956	14,735	27,543	Tables 3.5, 3.6, 3.7
TR-Oak chip requirement at 30% moisture	kg/h	3273	7205	13,699	Tables 3.5, 3.6, 3.7
Load factor	%	85			Table 4.6
Annual operating hours	h	8000			Table 4.6
Annual TR-Oak chip requirement at 30% moisture	t/a	22,256	48,994	93,153	Calculation
Annual biopower production	kWh/a	13,600,000	34,000,000	68,000,000	Table 4.12
Annual bioheat production	kWh/a	47,303,105	100,198,105	187,293,949	Table 4.12
Cost Related Data					
Annual capital recovery factor	%	10.2			[35,56]
TR-Oak chip cost (at CBHBP plant gate)	USD/t	35			[73]
Biopower sale price	cent/kWh	17			[25]
Bioheat sale price	cent/kWh	2.527814			[379]
Fixed O&M cost	USD/kW-a	120			[298,299,302], SAM [378]
Variable O&M cost	USD/kWh	0.04			[298,299], SAM [378]
Boiler	USD/kW	750			SAM [378]
Turbine and generator	USD/kW	510			SAM [378]
Feedstock handling equipment	USD/kW	330			SAM [378]
Other equipments	USD/kW	270			SAM [378]
Balance of plant	USD/kW	480			SAM [378]

- O&M costs associated with the operation of the CBHBP plants included fixed and variable costs. Labor, insurance, scheduled maintenance, planned equipment replacement, etc. composed the fixed O&M costs. On the other hand, variable O&M costs included ash utilization, non-biomass fuel costs, unplanned maintenance and equipment replacement, etc. Based on the current commercial CBHBP applications and SAM 2017.1.17, which is a performance and financial model to facilitate decision making, the fixed O&M cost chosen was 120 USD/kW per year, and the variable O&M cost chosen was 0.04 USD/kWh [298,299,302,378].
- Direct capital requirements for basic equipment (boiler, turbine, generator, feedstock handling equipment) were calculated based on the cost per installed biopower (USD/kW) provided as default cost values in SAM [378]. Other equipment and balance of plant was handled similarly. While other equipment represents that other than the basic equipment mentioned above, the balance of plant accounts for plant related costs not associated with its specific components.
- By calculating direct capital requirements based on the cost per installed biopower, the impact of economies of scale for the CBHBP plants considered were not taken into account. This is an issue to be taken into consideration during a real cost estimate study.
- Direct capital requirements were 750 USD/kW for boiler, 510 USD/kW for steam turbine and generator, 330 USD/kW for the feedstock handling equipment, 270 USD/kW for other equipment, and 480 USD/kW for the balance of plant.

6. RESULTS AND DISCUSSION

This chapter deals with “impact assessment” and “interpretation” phases of the LCA study conducted, and cost estimates for the CBHBP plants fueled with TR-Oak chips. The CBHBP plants were based on the simulated case studies explained in Chapter 3. While the “impact assessment” phase includes all the LCA results showing the related environmental impacts, the “interpretation” phase includes discussion of the results. Further interpretation of the LCA study is provided in Chapter 7.

After defining the “goal and scope”, and completing the “inventory analysis” phase of the LCA study (as explained in Chapter 4), the LCI (provided in Appendix D) was prepared using SimaPro software. Then, the results below were obtained following the CML-IA baseline V3.03 and ReCiPe Endpoint (H) V1.12 impact assessment methods provided in the SimaPro software.

Below are the subsections of this chapter:

- LCA results and discussion for Case Study-1, -2, and -3
- Sensitivity analysis on LCA results
- Effect of eco-design parameters on LCA results
 - Effect of feedstock properties on LCA results
 - Effect of process conditions on LCA results
- Comparison of LCA results for TR-Oak chip-fueled CBHBP production and Turkish lignite-fueled power production
- Cost results and discussion for Case Study-1, -2, and -3

6.1 LCA Results and Discussion for Case Study-1, -2, and -3

This section first provides comparative characterization results of midpoint impact categories calculated for CS-1, CS-2, and CS-3. Then, comparative characterization results for the annual environmental impacts are presented for each CS. After comparison of characterization results of the most used impact categories with

information from the literature, the section continues with comparative normalization results of midpoint impact categories. Later, comparative weighting results of endpoint impact categories for CS-1, CS-2, and CS-3 are shown. Finally, in terms of environmental impacts, contribution analyses based on characterization and weighting results of the LCA study are provided. To see the top stressors on the impacts, the contribution of different substances to the characterization results is presented in a table. To understand the relative importance of the different stages considered in the system boundary, the contribution of each stage to the LCA results was analyzed for midpoint and endpoint impact categories and shown in detail for each CS. The results are presented and discussed in the following lines.

6.1.1 Comparative characterization results of midpoint impact categories

For characterization and normalization of the environmental impacts, all midpoint impact categories already provided via the CML-IA baseline impact assessment method were considered in this study. These are photochemical oxidation (PCO), acidification (ACD), eutrophication (ETR), global warming (GW), ozone layer depletion (OD), human toxicity (HT), fresh water aquatic ecotoxicity (FWET), marine aquatic ecotoxicity (MET), terrestrial ecotoxicity (TET), abiotic depletion (elements), ADE, and abiotic depletion of fossil fuels (ADF). All the results were obtained for the functional units related to the production of 1 kWh biopower, 1 kWh bioheat, and 1 kWh energy (combined, i.e., biopower and bioheat).

For characterization, characterization factors provided in the impact assessment method (CML-IA baseline), and specific to each impact category mentioned above, were used to convert each amount of emitted substance into an equivalent amount of reference substance (as explained in Chapter 4). The names of the characterization factors are also provided in Chapter 4.

Characterization (impact category indicator) results of every CS and their cross comparisons are provided in Figure 6.1 and Table 6.1 for 1 kWh biopower production; in Figure 6.2 and Table 6.2 for 1 kWh bioheat production; and in Figure 6.3 and Table 6.3 for 1 kWh energy (biopower and bioheat) production.

In the figures, while x-axis represents the name of the midpoint impact categories,

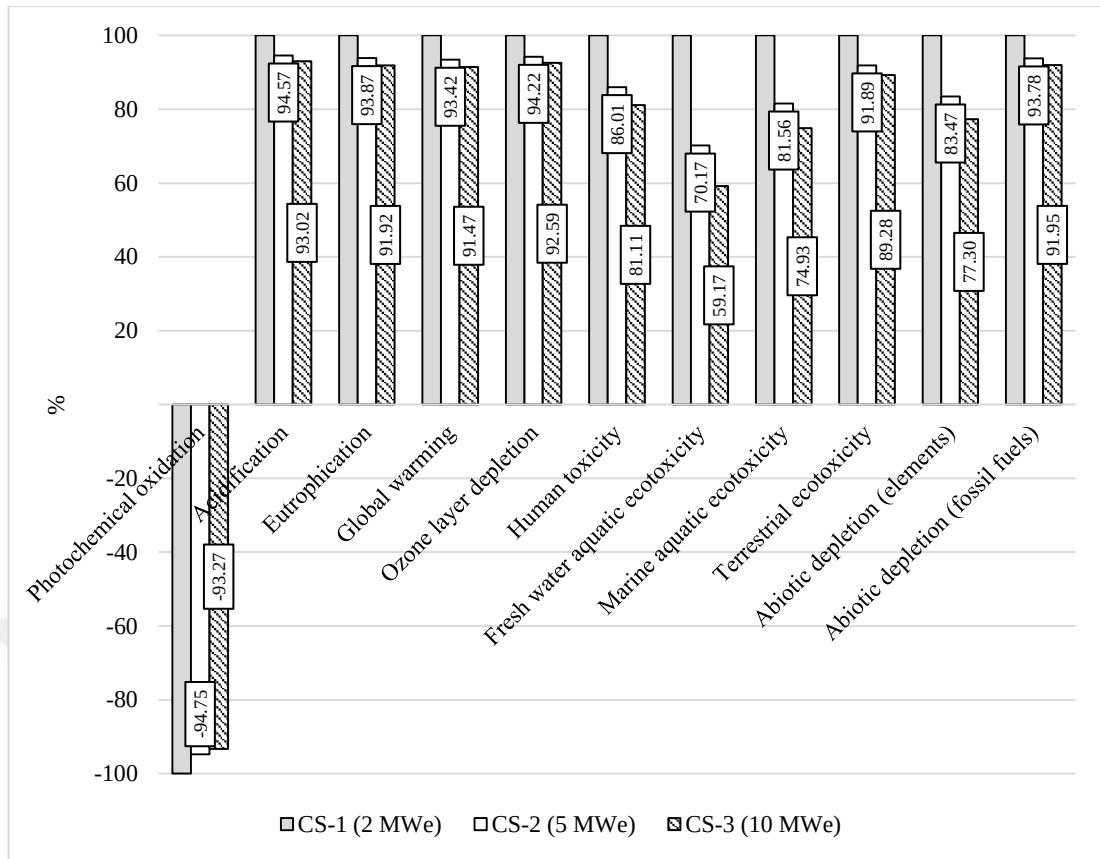


Figure 6.1 : Comparative midpoint characterization results of 1 kWh biopower production for CS-1, -2, -3 (2 MWe, 5 MWe, and 10 MWe, respectively).

Table 6.1 : Characterization results of 1 kWh biopower production for CS-1, -2, -3 (2 MWe, 5 MWe, 10 MWe, respectively).

Midpoint Impact Category	Unit	CS-1	CS-2	CS-3
Photochemical oxidation	kg C ₂ H ₄ eq	-3.2567E-04	-3.0859E-04	-3.0375E-04
Acidification	kg SO ₂ eq	2.3024E-03	2.1773E-03	2.1418E-03
Eutrophication	kg PO ₄ ³⁻ eq	2.2964E-04	2.1556E-04	2.1108E-04
Global warming	kg CO ₂ eq	4.3794E-02	4.0912E-02	4.0058E-02
Ozone layer depletion	kg CFC-11 eq	7.8047E-09	7.3533E-09	7.2260E-09
Human toxicity	kg 1,4-DB eq	1.0906E-02	9.3807E-03	8.8459E-03
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	1.0478E-02	7.3523E-03	6.1998E-03
Marine aquatic ecotoxicity	kg 1,4-DB eq	10.8539	8.8528	8.1330
Terrestrial ecotoxicity	kg 1,4-DB eq	8.3047E-05	7.6312E-05	7.4144E-05
Abiotic depletion (elements)	kg Sb eq	6.2442E-08	5.2120E-08	4.8265E-08
Abiotic depletion (fossil fuels)	MJ	6.6684E-01	6.2537E-01	6.1313E-01

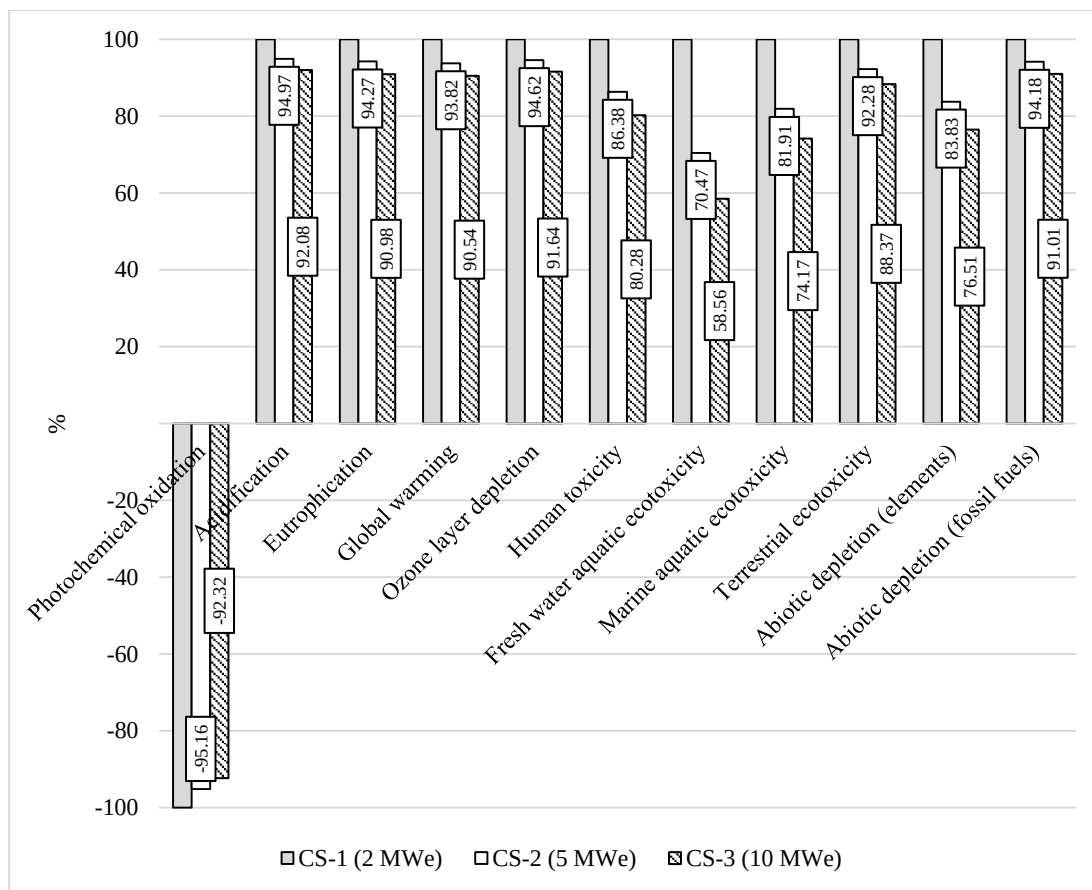


Figure 6.2 : Comparative midpoint characterization results of 1 kWh bioheat production for CS-1, -2, -3 (2 MWe, 5 MWe, and 10 MWe, respectively).

Table 6.2 : Characterization results of 1 kWh bioheat production for CS-1, -2, -3 (2 MWe, 5 MWe, 10 MWe, respectively).

Midpoint Impact Category	Unit	CS-1	CS-2	CS-3
Photochemical oxidation	kg C ₂ H ₄ eq	-7.6388E-05	-7.2691E-05	-7.0520E-05
Acidification	kg SO ₂ eq	5.4004E-04	5.1290E-04	4.9725E-04
Eutrophication	kg PO ₄ ³⁻ eq	5.3863E-05	5.0777E-05	4.9005E-05
Global warming	kg CO ₂ eq	1.0272E-02	9.6373E-03	9.3002E-03
Ozone layer depletion	kg CFC-11 eq	1.8306E-09	1.7322E-09	1.6776E-09
Human toxicity	kg 1,4-DB eq	2.5582E-03	2.2097E-03	2.0537E-03
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	2.4578E-03	1.7319E-03	1.4394E-03
Marine aquatic ecotoxicity	kg 1,4-DB eq	2.5458	2.0854	1.8882
Terrestrial ecotoxicity	kg 1,4-DB eq	1.9479E-05	1.7976E-05	1.7214E-05
Abiotic depletion (elements)	kg Sb eq	1.4646E-08	1.2278E-08	1.1206E-08
Abiotic depletion (fossil fuels)	MJ	1.5641E-01	1.4731E-01	1.4235E-01

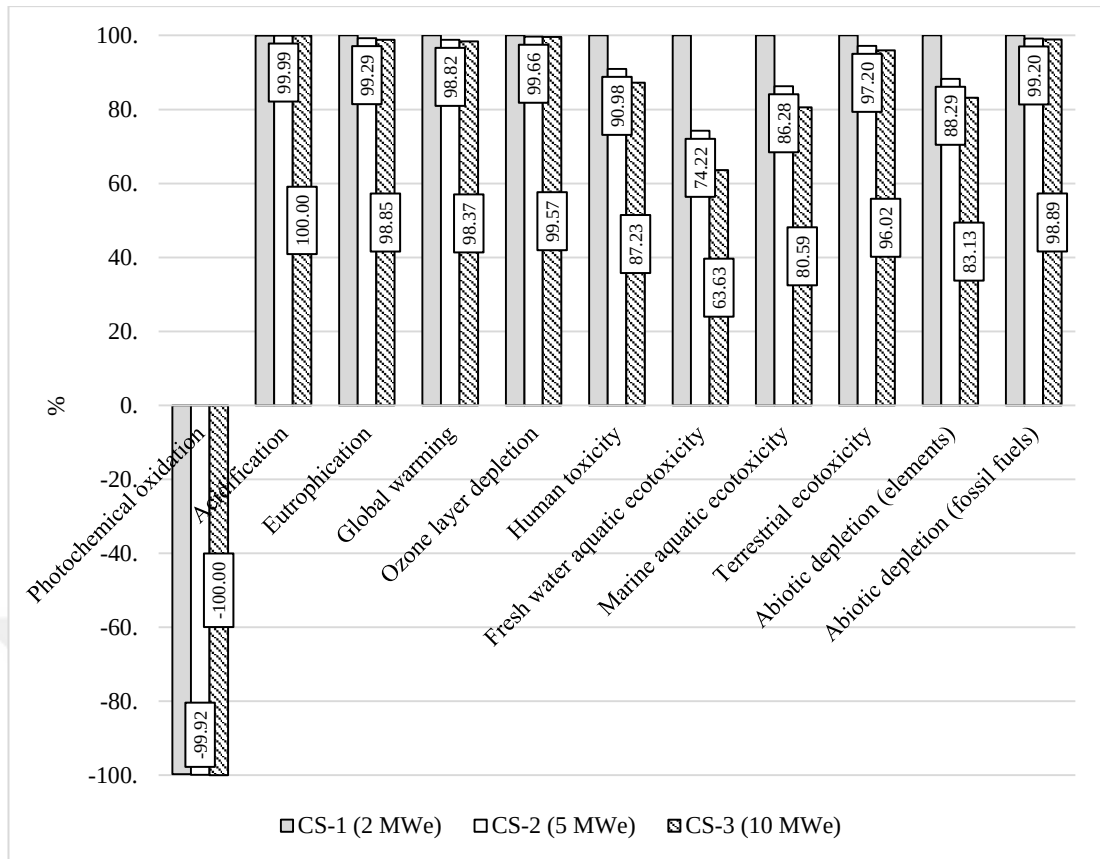


Figure 6.3 : Comparative midpoint characterization results of 1 kWh energy (biopower and bioheat) production for CS-1, -2, -3 (2 MWe, 5 MWe, and 10 MWe, respectively).

Table 6.3 : Characterization results of 1 kWh energy (biopower and bioheat) production for CS-1, -2, -3 (2 MWe, 5 MWe, 10 MWe, respectively).

Midpoint Impact Category	Unit	CS-1	CS-2	CS-3
Photochemical oxidation	kg C ₂ H ₄ eq	-1.2853E-04	-1.2882E-04	-1.2893E-04
Acidification	kg SO ₂ eq	9.0868E-04	9.0896E-04	9.0909E-04
Eutrophication	kg PO ₄ ³⁻ eq	9.0631E-05	8.9987E-05	8.9592E-05
Global warming	kg CO ₂ eq	1.7284E-02	1.7079E-02	1.7003E-02
Ozone layer depletion	kg CFC-11 eq	3.0802E-09	3.0698E-09	3.0671E-09
Human toxicity	kg 1,4-DB eq	4.3044E-03	3.9161E-03	3.7547E-03
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	4.1355E-03	3.0693E-03	2.6315E-03
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.2836	3.6957	3.4521
Terrestrial ecotoxicity	kg 1,4-DB eq	3.2776E-05	3.1857E-05	3.1471E-05
Abiotic depletion (elements)	kg Sb eq	2.4644E-08	2.1758E-08	2.0486E-08
Abiotic depletion (fossil fuels)	MJ	2.6318E-01	2.6107E-01	2.6025E-01

y-axis represents the percentage of each impact on the environment relative to other impacts. For each midpoint impact category, the CS having the highest environmental impact category indicator result was assigned a value of 100%. The other two cases were scaled to 100%. On the other hand, in the tables, the actual figures of the characterization results for midpoint impact categories are listed along with their units. It is important to note that the units of the characterization results are different, and hence impact categories cannot be compared with each other. In addition, the overall magnitude of the impacts cannot be determined (i.e., a low value does not always mean the impact is insignificant, or vice versa).

According to the comparative midpoint characterization results (Figure 6.1 to 6.3, Table 6.1 to 6.3), it is seen that CS-3 has the least environmental impact overall on all of the categories. The determination is valid for all functional units: 1 kWh biopower, 1 kWh bioheat, and 1 kWh energy productions. CS-2 follows CS-3. CS-1 causes the most impact in all of the categories. The results show that the smaller the CBHBP plant, the higher the impact it has. The main reason for this is that the CBHBP electrical efficiency gains increase with the capacity increase of the power plants. CS-3 has the highest electrical efficiency, which results in the lowest impacts on the environment per kWh energy production. In particular, the advantages of CS-3 are remarkable for the midpoint impact categories of HT, FWET, MET, TET, and ADE. Significant decreases in these impacts are due to infrastructural gains of CS-3, relative to CS-2 and CS-1. For other impact categories (PCO, ACD, ETR, GW, OD, and ADF), there were also decreases. Specific to 1 kWh energy production, looking at Figure 6.3 and Table 6.3, no significant differences were observed between the case studies for the PCO, ACD, ETR, GW, OD, and ADF categories. The negative values for PCO mean that there is an environmental benefit. This benefit is a result of NO emissions in the system boundary. However, it is important to mention that impact assessment methods use different approaches to calculate the impacts of NO emissions on PCO. For example, in terms of PCO, while the CML-IA baseline assumes that NO is good for air quality, ReCiPe does not split NO_x into NO and NO₂ and therefore assumes that NO has no effect on air quality.

Analyzing Table 6.1 and Table 6.2, it is seen that the characterization results for 1 kWh bioheat production are lower than those for 1 kWh biopower production. The reason is that exergy-based allocation was applied in the LCA study to fix the joint products

(biopower and bioheat). The exergy content of biopower production was '1', which is higher than that for the bioheat production (0.26), as explained in Chapter 4.

For the specific study, the characterization results for 1 kWh energy (Table 6.3) were found between the ones of 1 kWh biopower (Table 6.1) and 1 kWh bioheat (Table 6.2). This is because 1 kWh energy comprises 0.2233 kWh biopower and 0.7767 kWh bioheat for CS-1; 0.2534 kWh biopower and 0.7466 kWh bioheat for CS-2; and 0.2664 kWh biopower and 0.7336 kWh bioheat for CS-3. In addition, for 1 kWh energy production, impacts were associated with 1 kWh biomass energy production without differentiating biopower and bioheat.

To be able to compare impact categories with each other, and also to determine the relative magnitude of the impacts, normalization was applied in the LCA study, and the results are provided in the following sections.

6.1.1.1 Comparative characterization results for annual environmental impacts

The annual biopower production for each CS was selected to understand comparative midpoint characterization results for annual environmental impacts (depicted in Figure 6.4).

The impacts for CS-3 were represented as 100%, the highest impacts in magnitude corresponding to each impact category. The impacts for CS-1 and CS-2 were adjusted accordingly. Of course, the expected result was that CS-3 would have the highest annual environmental impacts because it has the highest capacity. However, the purpose of this section was to estimate the extent to which the increase in annual biopower production affects the results.

According to the results, the annual environmental impacts for CS-1 were 25–40 % of those for CS-3. Similarly, annual environmental impacts for CS-2 were 53–62 % of those for CS-3. Comparing CS-1 and CS-2, the annual environmental impacts for CS-1 were 48–65% of those for CS-2.

6.1.1.2 Comparison of the characterization results with the literature

To the best of our knowledge, there is no other LCA study on CBHBP generation in Turkey. However, there are academic studies done representing other countries. So, these results were compared with those studies.

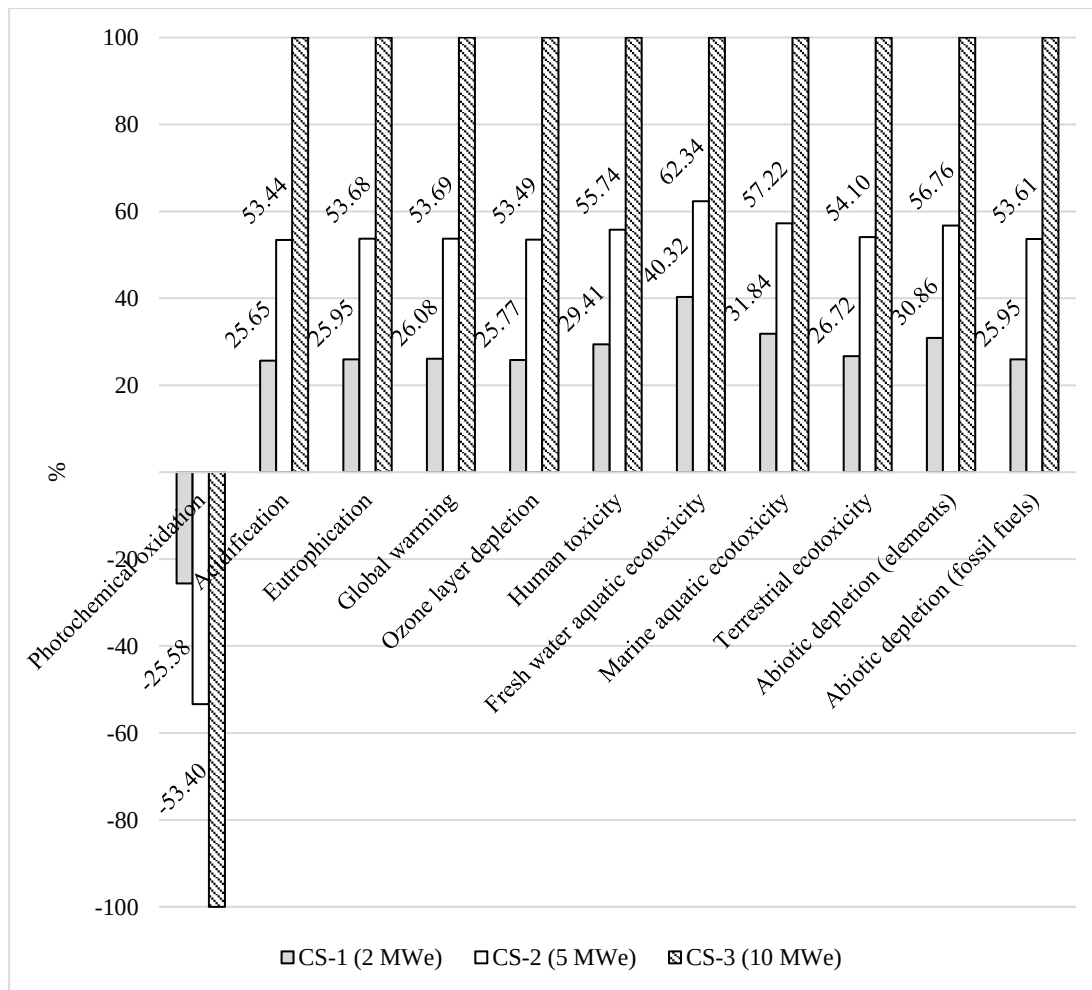


Figure 6.4 : Comparative midpoint characterization results for annual biopower production, CS-1, -2, -3 (2 MWe, 5 MWe, 10 MWe, respectively).

A review [222] covering 36 biopower, 18 bioheat, and 5 biopower and bioheat LCA studies (Table 2.9 in Chapter 2) was chosen to compare the results. Comparisons were done for the most used impact categories (ACD, ETR, and GW). Unfortunately, for the other impact categories there were not enough LCA studies for useful comparison.

Comparison results are provided in Figure 6.5 for ACD, in Figure 6.6 for ETR, and in Figure 6.7 for GW. In the figures, the results are given for 1 kWh biopower and/or bioheat production.

As seen from the figures, all the results in this study were within the ranges reported in the literature. Sometimes, wide ranges were observed in the literature values, which resulted from technological differences, local conditions, and methodological aspects of the LCA studies.

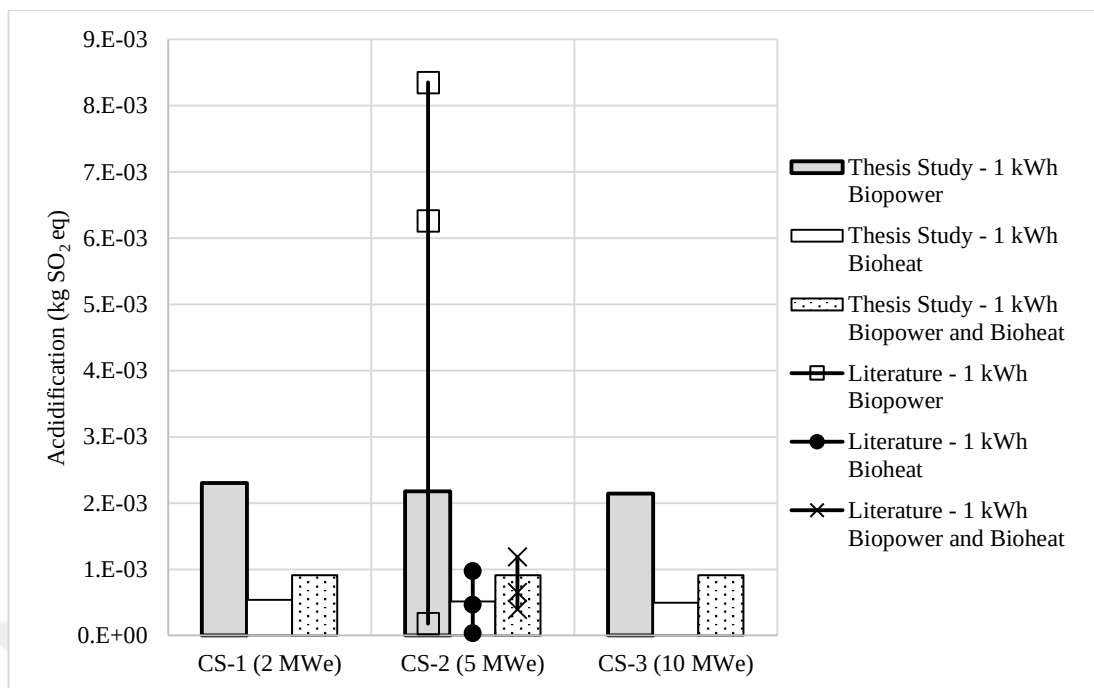


Figure 6.5 : Comparison of acidification results with the literature, 1 kWh biopower and/or bioheat, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively) [222].

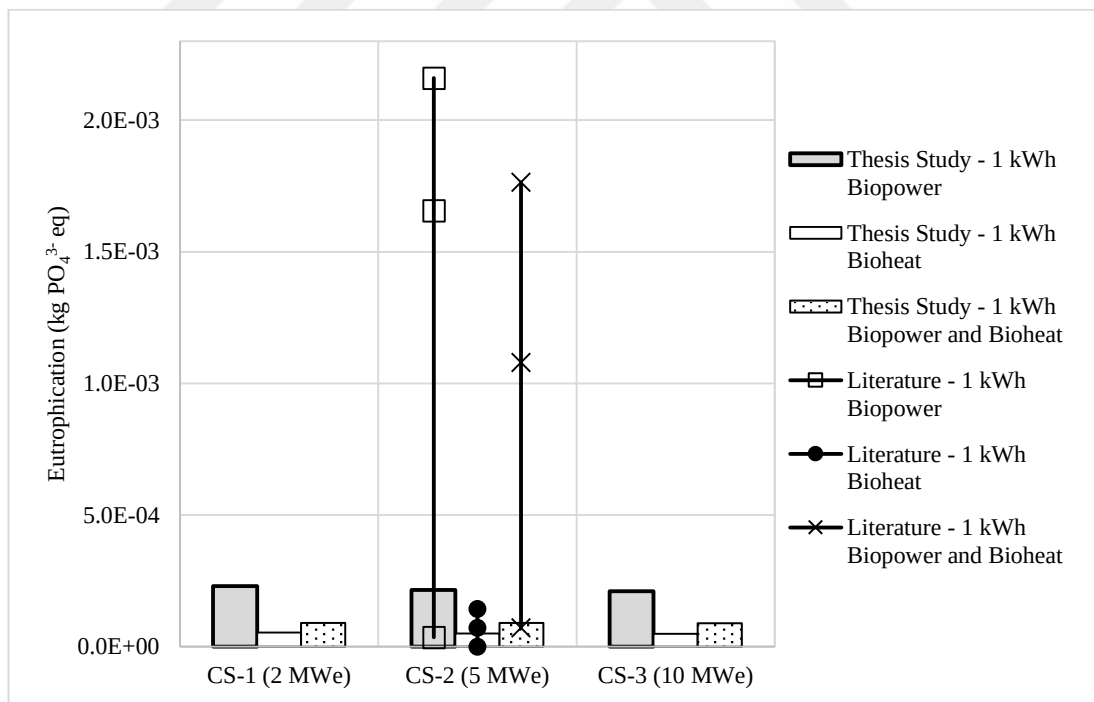


Figure 6.6 : Comparison of eutrophication results with the literature, 1 kWh biopower and/or bioheat, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively) [222].

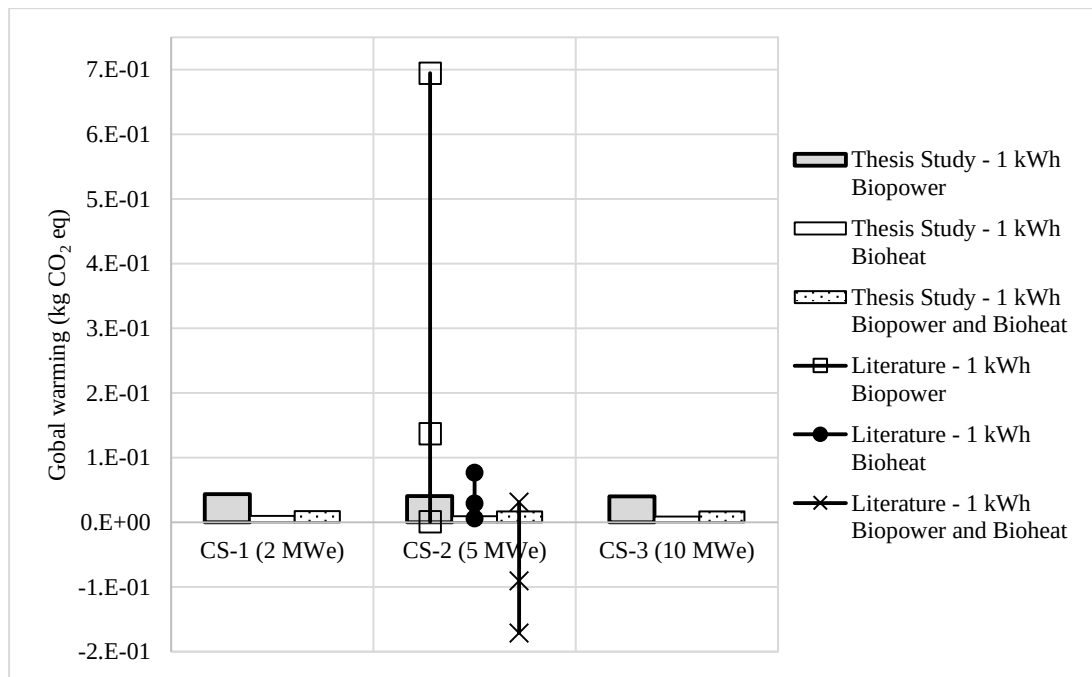


Figure 6.7 : Comparison of global warming results with the literature, 1 kWh biopower and/or bioheat, CS-1, -2, -3 (2 MWe, 5 MWe, 10 MWe, respectively) [222].

6.1.2 Comparative normalization results of midpoint impact categories

To better understand the relative magnitude of the characterization results, which have rather arbitrary units, normalization was applied in the LCA study. Normalization resolves the incompatibility of the units and shows to what extent an impact has a relatively high or low value compared to a reference. This makes it possible to compare the impact category indicator results with each other. For normalization in this research, World 2000, which is available in CML-IA baseline V3.3 and refers to the total emissions of each impact category in the world in the year 2000, was applied. The normalization factors for CML-IA baseline World 2000 are listed in Table 6.4. The normalized values were calculated by multiplying each impact category indicator result by its concomitant normalization factor in the table, which makes the normalized results dimensionless. The normalization figures and tables below were prepared accordingly.

The normalization results of every CS and their cross comparisons are provided in Figure 6.8 for 1 kWh biopower production, in Figure 6.9 for 1 kWh bioheat production, and in Figure 6.10 for 1 kWh energy (biopower and bioheat) production. In the figures, while x-axis represents the name of the midpoint impact categories, y-axis represents their normalized values.

The normalization figures (Figure 6.8 to 6.10) show that for every CS, MET is the impact category having the highest value related to the reference values listed in Table 6.4, followed by ACD, FWET, HT, ADF, ETR, and GW. Following these impact categories, ADE, TET, and OD, respectively, have lower values relative to the reference values. There is an environmental benefit for PCO. All cases have a positive effect against PCO. To understand why MET is remarkable among impact categories, the stages considered in the system boundary, and the substances emitted during operations in these stages having the highest contribution on MET were further examined. The results are provided in Section 6.1.4, along with those for the other impact categories.

Table 6.4 : Normalization factors used in the LCA study (CML-IA baseline V3.3 World 2000) [345].

Midpoint Impact Category	Unit	Normalization Factor
Photochemical oxidation	1/kg C ₂ H ₄ eq	2.72E-11
Acidification	1/kg SO ₂ eq	4.19E-12
Eutrophication	1/kg PO ₄ ³⁻ eq	6.32E-12
Global warming	1/kg CO ₂ eq	2.39E-14
Ozone layer depletion	1/kg CFC-11 eq	4.41E-09
Human toxicity	1/kg 1,4-DB eq	3.88E-13
Fresh water aquatic ecotoxicity	1/kg 1,4-DB eq	4.23E-13
Marine aquatic ecotoxicity	1/kg 1,4-DB eq	5.16E-15
Terrestrial ecotoxicity	1/kg 1,4-DB eq	9.15E-13
Abiotic depletion (elements)	1/kg Sb eq	4.78E-09
Abiotic depletion (fossil fuels)	1/MJ	2.63E-15

When comparing the case studies with each other, the normalization result for CS-1 was higher in all impact categories than for CS-2 and CS-3, which is in line with the characterization results. Especially, in terms of MET, CS-3 had more advantages than did CS-1 and CS-2. In addition, specific to 1 kWh energy production, looking at Figure 6.10, no significant differences are observed between the case studies for the PCO, ACD, ETR, GW, OD, and ADF categories.

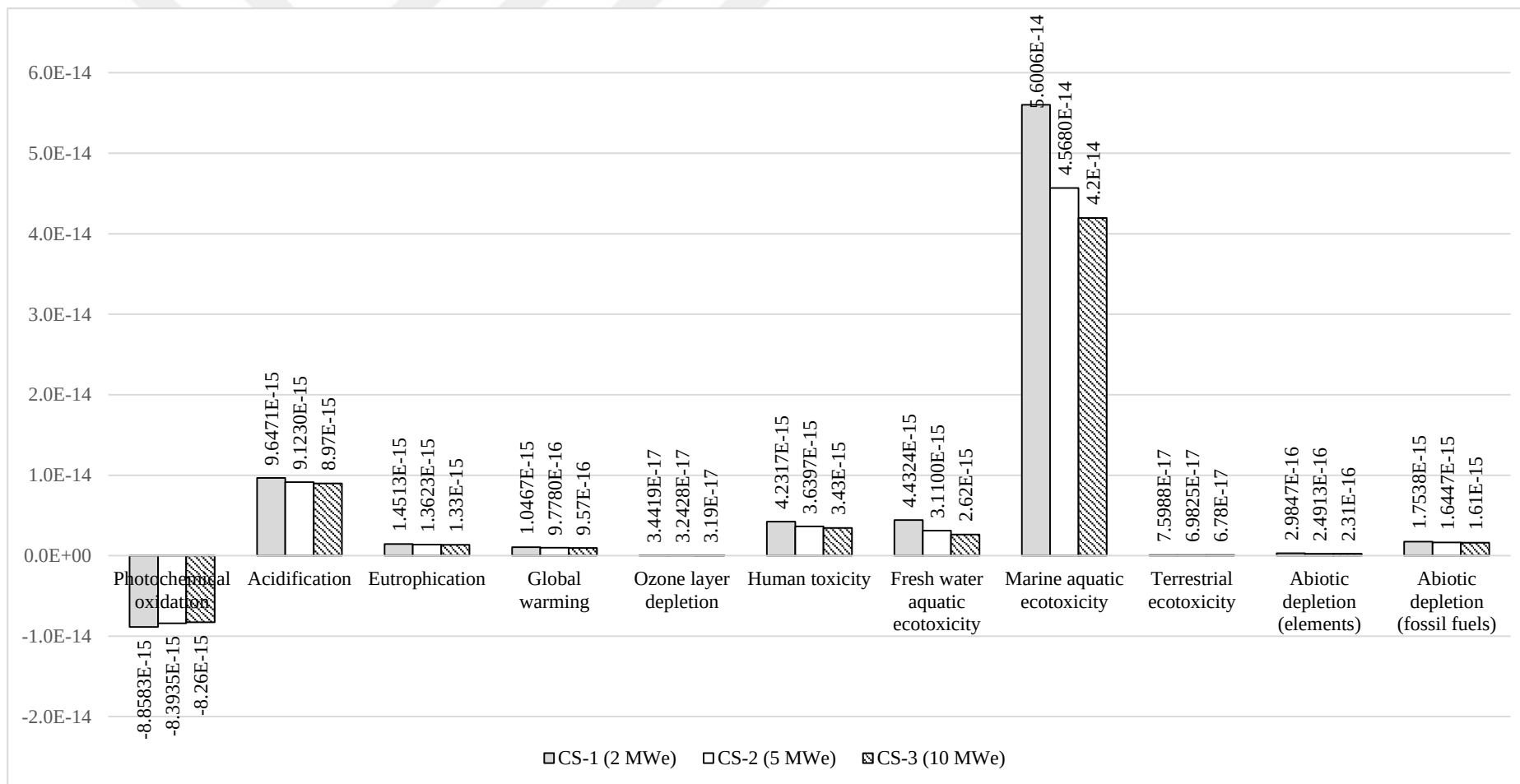


Figure 6.8 : Comparative normalization results (CML-IA baseline World 2000) of 1 kWh biopower production, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively).

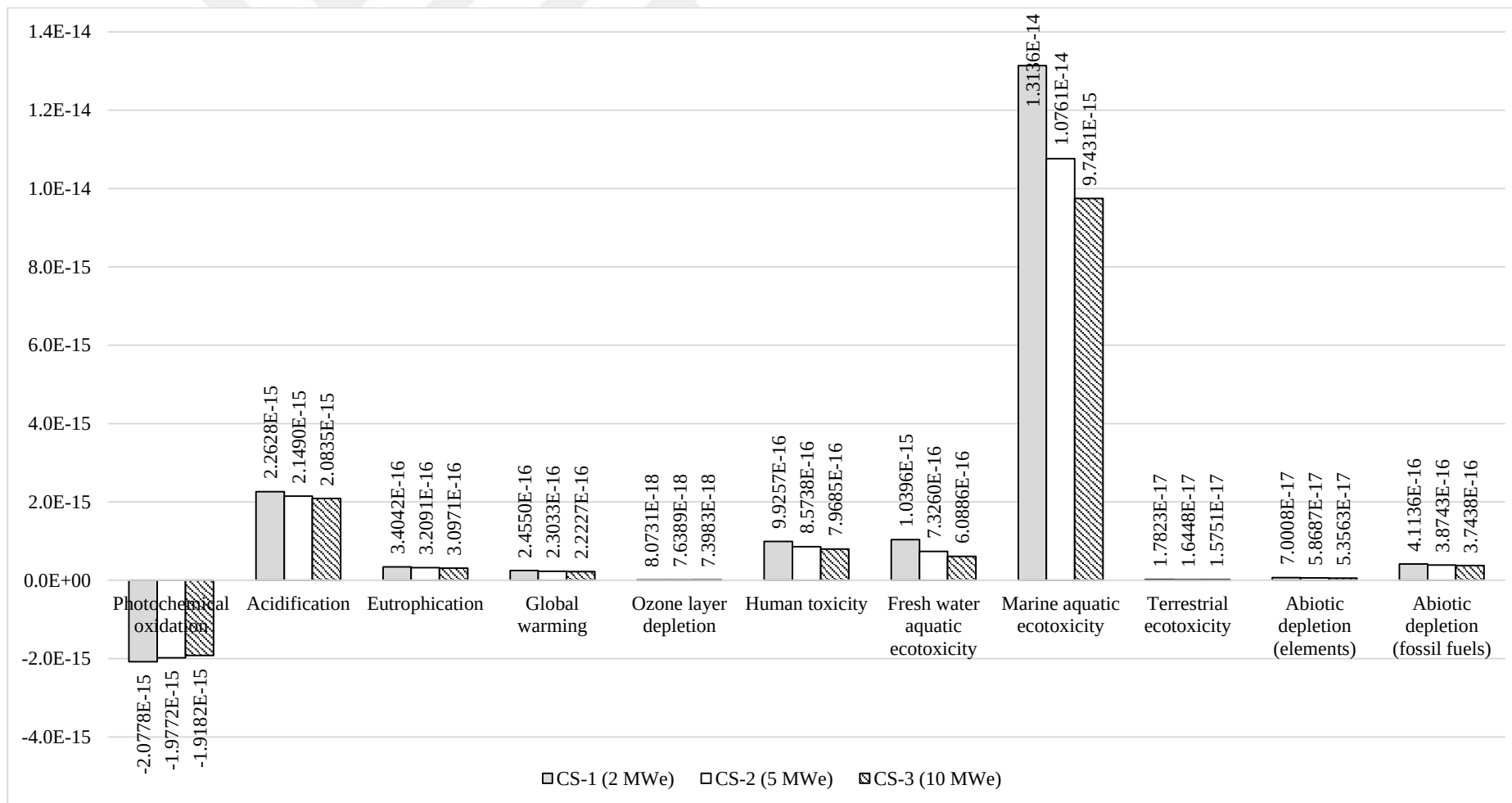


Figure 6.9 : Comparative normalization results (CML-IA baseline World 2000) of 1 kWh bioheat production, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively).

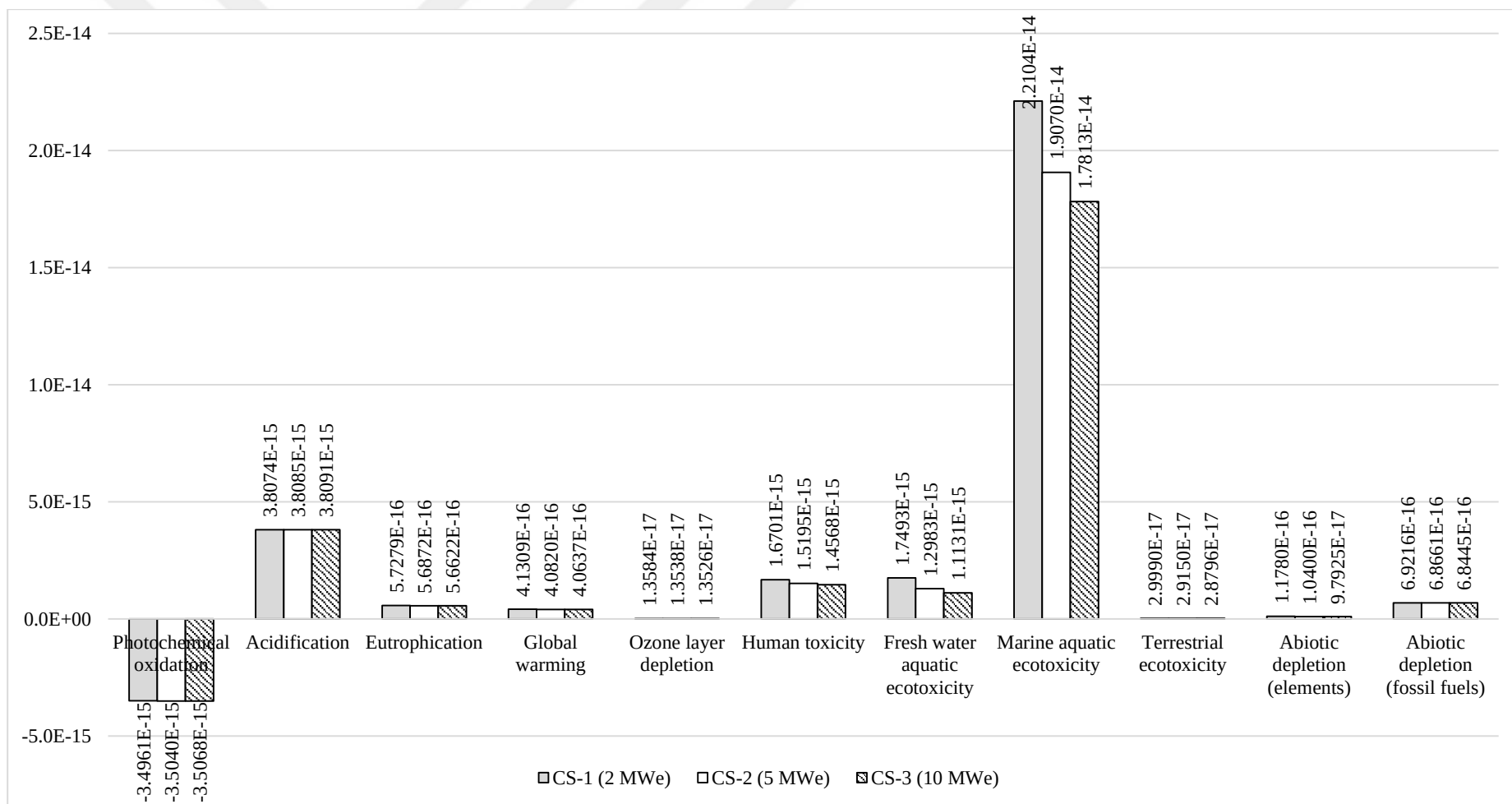


Figure 6.10 : Comparative normalization results (CML-IA baseline World 2000) of 1 kWh energy (biopower and bioheat) production, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively).

In the figures, a higher value means a higher impact on the environment. However, it is important to emphasize that among impact categories, a higher normalized value does not always mean more importance than others, or vice versa.

To understand the relative importance of the midpoint impacts on endpoint categories (i.e., human health, ecosystems, and resources), and to calculate endpoint scores, weighting was the next step taken in the LCA study.

6.1.3 Comparative weighting results of endpoint impact categories

To understand the importance of the environmental issues in terms of endpoint damage category levels (human health, ecosystems, and resources), weighting was applied in the LCA study. The environmental issues contributing to these damage category levels for ReCiPe Endpoint (H) method V1.12 were provided in Chapter 4. Climate change (human health), ionizing radiation, PM, HT, OD, and PCO are the environmental issues associated with human health (Table 4.2). While ecotoxicity, climate change (ecosystems), land use, ACD, and ETR are the environmental issues associated with ecosystems; depletion of abiotic resources is the environmental issue (ADE, ADF) associated with resources.

For weighting in this research, World ReCiPe H/H, which is available in ReCiPe Endpoint (H) and refers to a panel weighting set belonging to the hierarchist perspective, was applied. The hierarchist perspective is based on the most common policy principles with regard to time frames and other issues. Weighting factors for World ReCiPe H/H, which are the average panel assessment results, are listed in Table 6.5.

In the SimaPro software, the weighted results for the endpoint damage categories were calculated using the corresponding weighting factors in the table. In this study, weighting was applied to form a total score, which is expressed using the unit Pt. The point implies the total environmental load expressed as a single score, which means that the higher the score, the higher the environmental load. The purpose is also to facilitate interpretation although it is known that the scores are based on subjective and value-based weighting factors.

Weighting results of every CS and their cross comparisons are provided in Figure 6.11 for 1 kWh biopower production, in Figure 6.12 for 1 kWh bioheat production, and in Figure 6.13 for 1 kWh energy (biopower and bioheat) production.

Table 6.5 : Weighting factors used in the LCA study (World ReCiPe H/H) [346].

Endpoint Impact (Damage) Category	Factor (Pt)
Human health	300
Ecosystems	400
Resources	300

In the figures, the x-axis represents the name of the endpoint impact categories and the y-axis represents the scores in millipoints (mPt). To calculate the weighting results, because the ReCiPe Endpoint (H) does not differentiate NO and SO₃ emissions, NO is defined as NO_x and SO₃ is defined as SO_x. Looking at the figures overall, it is seen that human health has the highest importance relative to the weighting factors in Table 6.5, followed by resources. The importance of impacts on ecosystems is insignificant relative to those on human health and resources. Among the case studies, CS-3 had more advantages than did CS-1 and CS-2 overall (all categories). In particular, the positive aspects of CS-3 are remarkable for the damage categories of human health and resources.

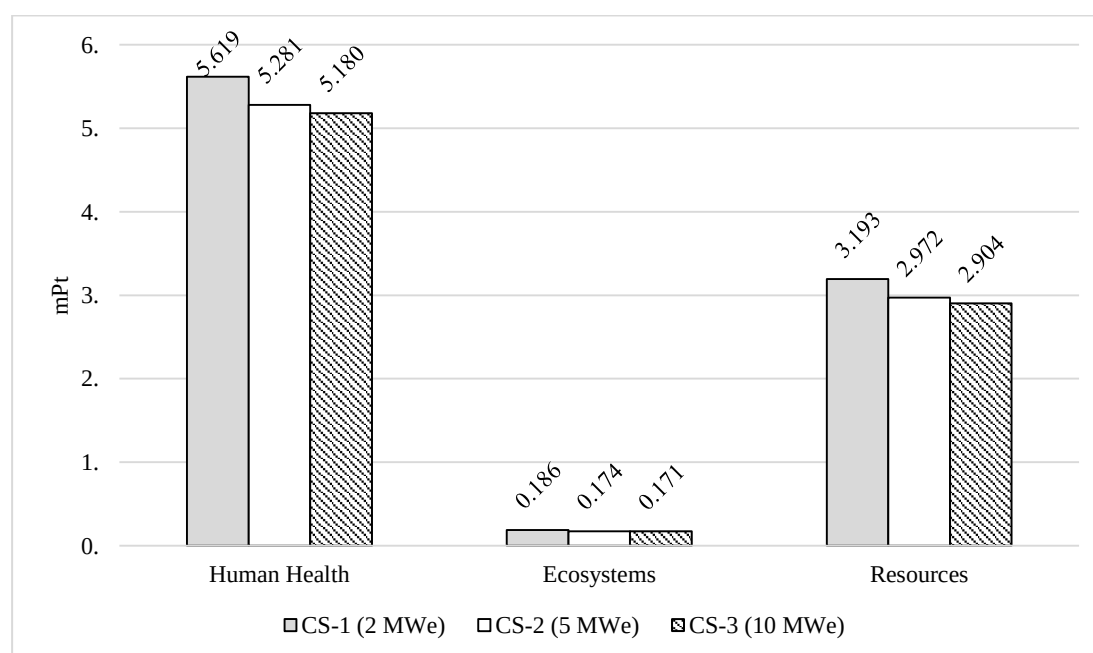


Figure 6.11 : Comparative weighting results of 1 kWh biopower production, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively).

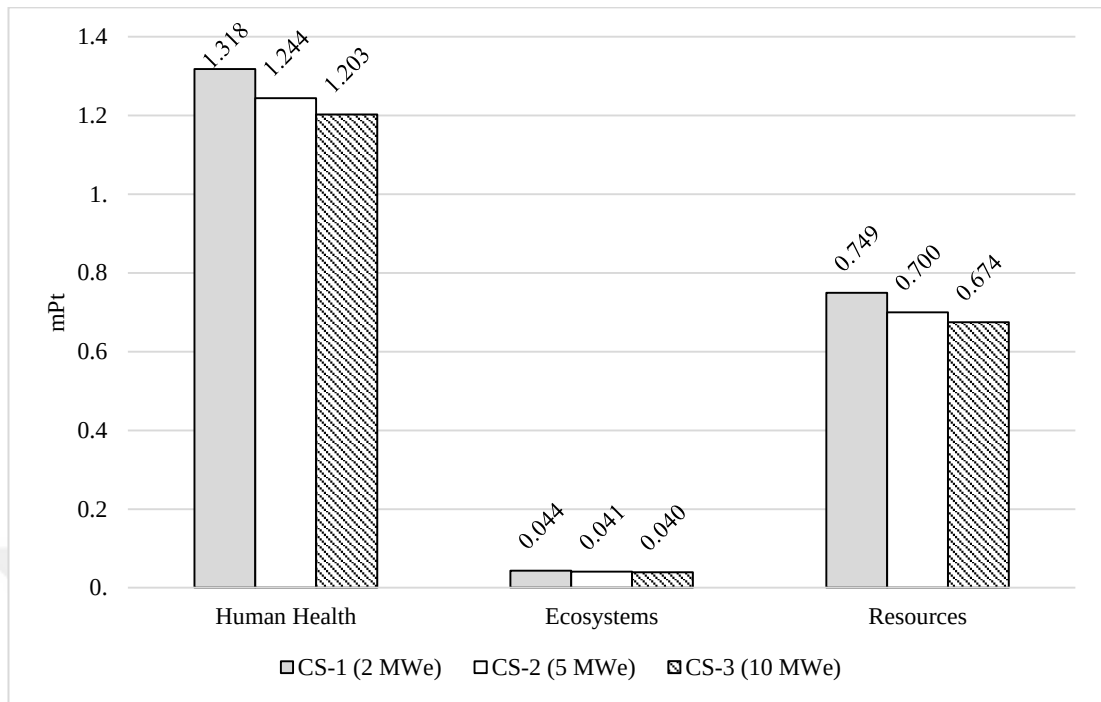


Figure 6.12 : Comparative weighting results of 1 kWh bioheat production, CS-1, -2, -3 (2 MWe, 5 MWe, 10 MWe, respectively).

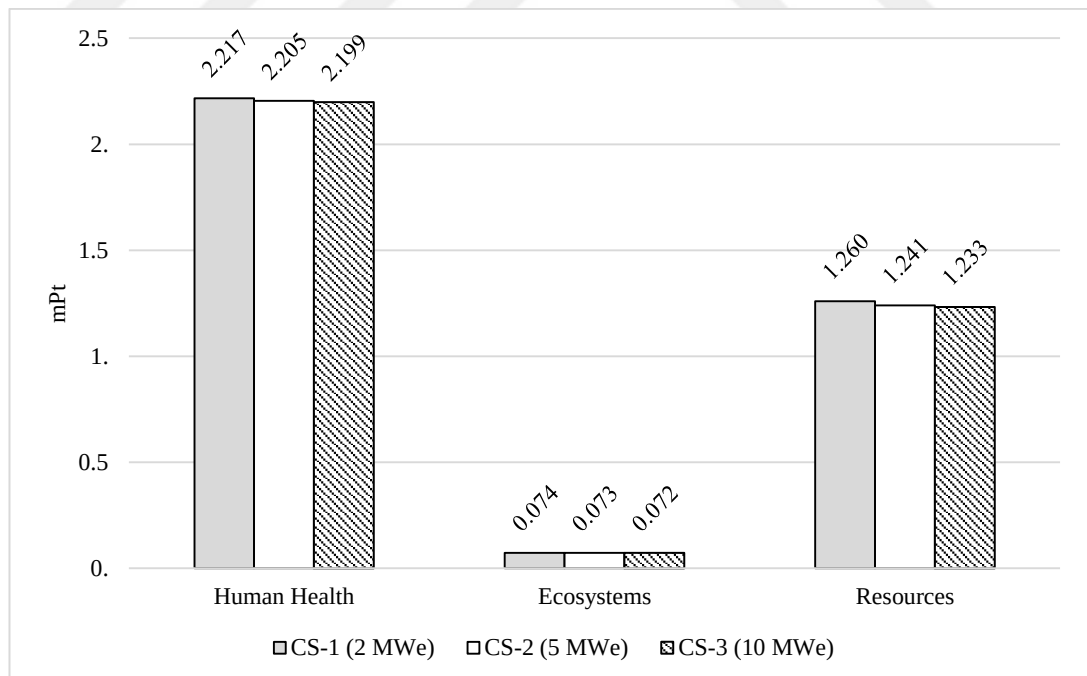


Figure 6.13 : Comparative weighting results of 1 kWh energy (biopower and bioheat) production, CS-1, -2, -3 (2 MWe, 5 MWe, 10 MWe, respectively).

With weighting based on endpoint damage categories, it became possible to calculate a single score for each CS. Table 6.6 depicts the total endpoint single scores for each CS corresponding to 1 kWh biopower, 1 kWh bioheat, and 1 kWh energy production. Accordingly, while the single score for CS-3 was 8.26% lower than for CS-1 (for 1 kWh biopower production), it was 9.19% lower for 1 kWh bioheat and 1.32% lower for 1 kWh energy production. When comparing CS-2 and CS-1, while the single score for CS-2 was 6.35% lower than for CS-1 for 1 kWh biopower production, it was 5.97% lower for 1 kWh bioheat and 0.93% lower for 1 kWh bioenergy production. When comparing CS-3 and CS-2, while the single score for CS-3 was 2.04% lower than for CS-1 for 1 kWh biopower production, it was 3.43% lower for 1 kWh bioheat and 0.40% lower for 1 kWh energy production. The reductions in scores were less significant for 1 kWh energy production, than for 1 kWh of biopower and bioheat production. The distribution of these endpoint single scores of damage categories is provided in the comparative weighting figures (Figure 6.11, Figure 6.12, Figure 6.13).

Table 6.6 : Endpoint single scores (World ReCiPe H/H), CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively).

Case Study	Endpoint Single Scores (mPt)		
	1 kWh biopower	1 kWh bioheat	1 kWh energy (biopower and bioheat)
CS-1	8.998	2.111	3.551
CS-2	8.427	1.985	3.518
CS-3	8.255	1.917	3.504

6.1.4 Contribution analysis for midpoint impact categories

This section provides contribution analyses based on the characterization results of the LCA study. It is important to note that negative contribution means an environmental benefit. First, to see the top stressors on the impacts for all cases, the top stressors (substances) and their contributions (%) to the midpoint impacts of 1 kWh energy production (biopower and/or bioheat) were examined.

Table 6.7 lists substances that are top stressors and their contributions for each midpoint impact category. Then, to understand the relative importance of the different stages, contribution analysis was done by arranging the LCA results into the stages

Table 6.7 : Top stressors and their contributions for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively), CML-IA baseline V3.03.

Midpoint Impact Categories	Top Stressors and Contributions (%)					Sum (%)
Photochemical oxidation (kg C₂H₄ eq)	NO	SO₂	CO			
CS-1	86.14 (benefit)	12.64	0.75			99.53
CS-2	86.18 (benefit)	12.63	0.72			99.53
CS-3	86.20 (benefit)	12.63	0.71			99.54
Acidification (kg SO₂ eq)	SO₂	NO	NO_x	SO₃		
CS-1	61.86	30.01	4.81	3.05		99.73
CS-2	61.85	30.04	4.79	3.05		99.73
CS-3	61.84	30.05	4.78	3.05		99.72
Eutrophication (kg PO₄³⁻ eq)	NO	NO_x	Phosphate	Nitrate	Chemical Oxygen Demand	
CS-1	79.17	12.53	3.32	2.40	1.51	98.93
CS-2	79.85	12.57	2.95	2.08	1.47	98.92
CS-3	80.25	12.61	2.76	1.86	1.46	98.94
Global warming (GWP100a) (kg CO₂ eq)	CO₂, fossil	CH₄	N₂O			
CS-1	96.15	2.00	1.23			99.38
CS-2	96.20	1.93	1.24			99.37
CS-3	96.21	1.91	1.24			99.36
Ozone layer depletion (ODP) (kg CFC-11 eq)	Bromotrifluoro-methane (Halon 1301)					
CS-1	97.83					97.83
CS-2	98.03					98.03
CS-3	98.06					98.06

Table 6.7 (continued) : Top stressors and their contributions for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively), CML-IA baseline V3.03.

Midpoint Impact Categories	Top Stressors and Contributions (%)					Sum (%)
Human toxicity (kg 1,4-DB eq)	Antimony	Chromium VI	Copper	Selenium	Nickel	
CS-1	26.53	20.65	9.53	6.51	4.51	67.73
CS-2	29.09	16.43	10.42	6.45	4.79	67.18
CS-3	30.30	14.52	10.84	6.36	4.93	66.95
Fresh water aquatic ecotoxicity (kg 1,4-DB eq)	Copper	Nickel	Vanadium	Beryllium		
CS-1	61.44	20.03	4.77	4.06		90.30
CS-2	58.12	19.76	5.24	4.88		88.00
CS-3	56.18	19.53	5.54	5.34		86.59
Marine aquatic ecotoxicity (kg 1,4-DB eq)	Hydrogen fluoride	Beryllium	Nickel	Copper	Barium	
CS-1	27.89	23.13	13.43	11.92	5.80	82.17
CS-2	29.97	23.94	11.40	9.70	6.51	81.52
CS-3	31.44	24.04	10.35	8.61	6.83	81.27
Terrestrial ecotoxicity (kg 1,4-DB eq)	Cypermethrin	Mercury	Zinc	Aldicarb	Chromium VI	
CS-1	50.25	19.87	5.50	4.42	4.29	84.33
CS-2	51.71	18.84	5.64	4.50	4.12	84.81
CS-3	52.33	18.41	5.70	4.52	4.05	85.01
Abiotic depletion (elements) (kg S eq)	Cadmium	Gold	Lead	Copper	Silver	
CS-1	24.28	22.86	17.38	13.34	7.19	85.05
CS-2	25.51	20.60	18.27	14.22	7.43	86.03
CS-3	26.05	19.62	18.65	14.60	7.54	86.46
Abiotic depletion (fossil fuels) (MJ)	Crude Oil	Natural Gas	Coal			
CS-1	90.10	5.85	3.98			99.93
CS-2	90.70	5.65	3.58			99.94
CS-3	90.93	5.56	3.45			99.93

given below, and therefore determining the contribution percentages of each stage to the midpoint impact categories.

- TR-Oak chip supply chain
 - TR-Oak chip supply, roadside
 - TR-Oak chip transport to CBHBP plant
- CBHBP plant operation
- TR-Oak ash transport and spreading
- Construction and decommissioning

Associating these stages with the system boundary of the LCA study, the TR-Oak chip supply chain included forest and roadside operations and TR-Oak chip transport to CBHBP plant. The CBHBP plant operation included TR-Oak chip feedstock preparation and CBHBP production. Construction and decommissioning included all infrastructure for the TR-Oak chip supply chain and CBHBP plant operation, except construction and decommissioning for lorries and road infrastructures which were included in the transport operations. By presenting analyses as percentage contributions of the stages above, it became possible to present a single figure and table for each CS and for all functional units (1 kWh biopower, 1 kWh bioheat, 1 kWh energy). The analyses for midpoint impact categories are provided in Figure 6.14 and Table 6.8 for CS-1, in Figure 6.15 and Table 6.9 for CS-2, and in Figure 6.16 and Table 6.10 for CS-3.

The tables include contribution representations placed in their rightmost column using a feature of excel software to make clear the percentage distributions of contributions to midpoint impact categories for each stage. By doing so, contributions were made schematic, clear, and easy to analyze. Looking at these contribution representations (Table 6.8, Table 6.9, Table 6.10), CBHBP operation is the main contributor for PCO, ACD, and ETR. For PCO there is an environmental benefit. For other impact categories, the adverse impact of CBHBP operation is insignificant. GW, OD, HT, MET, TET, ADE, and ADF are mainly due to TR-Oak chip supply-chain operations. In addition, construction and decommissioning is the main contributor to FWET. It also made a significant contribution to MET, HT, and ADE.

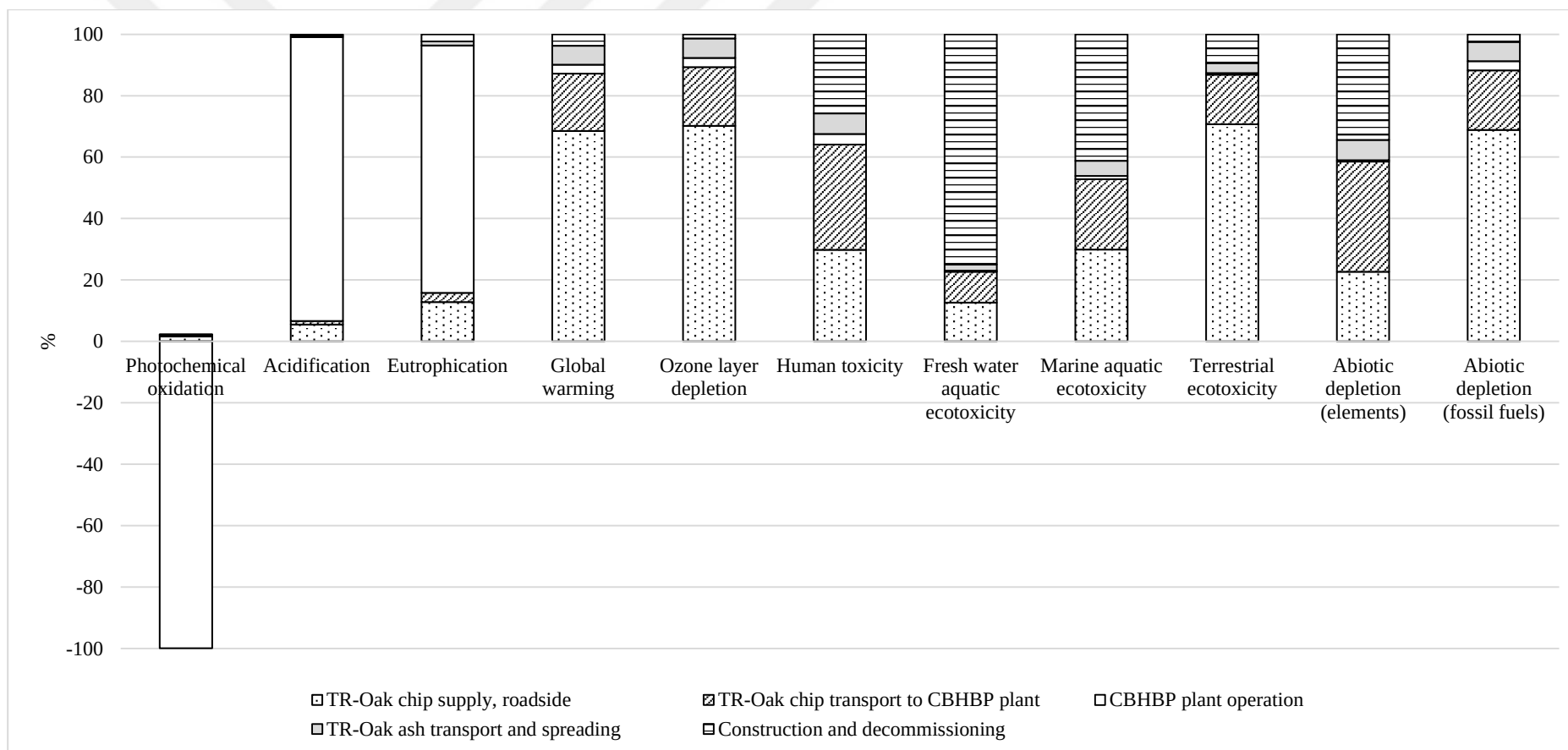


Figure 6.14 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-1 (2 MW_e), CML-IA baseline V3.03.

Table 6.8 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-1 (2 MW_e), CML-IA baseline V3.03.

Midpoint Impact Category	Contribution (%)					Contribution (%) Representation
	TR-Oak Chip Supply, Roadside	TR-Oak Chip Transport to CBHBP Plant	CBHBP Plant Operation	TR-Oak Ash Transport and Spreading	Construction and Decommissioning	
Photochemical oxidation	1.60	0.41	-99.95	0.14	0.20	
Acidification	5.46	1.20	92.44	0.54	0.36	
Eutrophication	12.84	2.91	80.63	1.28	2.33	
Global warming	68.53	18.68	2.92	6.15	3.72	
Ozone layer depletion	70.20	19.06	3.04	6.33	1.37	
Human toxicity	29.83	34.29	3.41	6.73	25.74	
Fresh water aquatic ecotoxicity	12.59	10.06	0.37	2.06	74.93	
Marine aquatic ecotoxicity	29.87	22.94	1.06	4.94	41.18	
Terrestrial ecotoxicity	70.74	16.12	0.50	3.29	9.35	
Abiotic depletion (elements)	22.63	35.91	0.45	6.58	34.42	
Abiotic depletion (fossil fuels)	68.87	19.38	2.97	6.31	2.47	

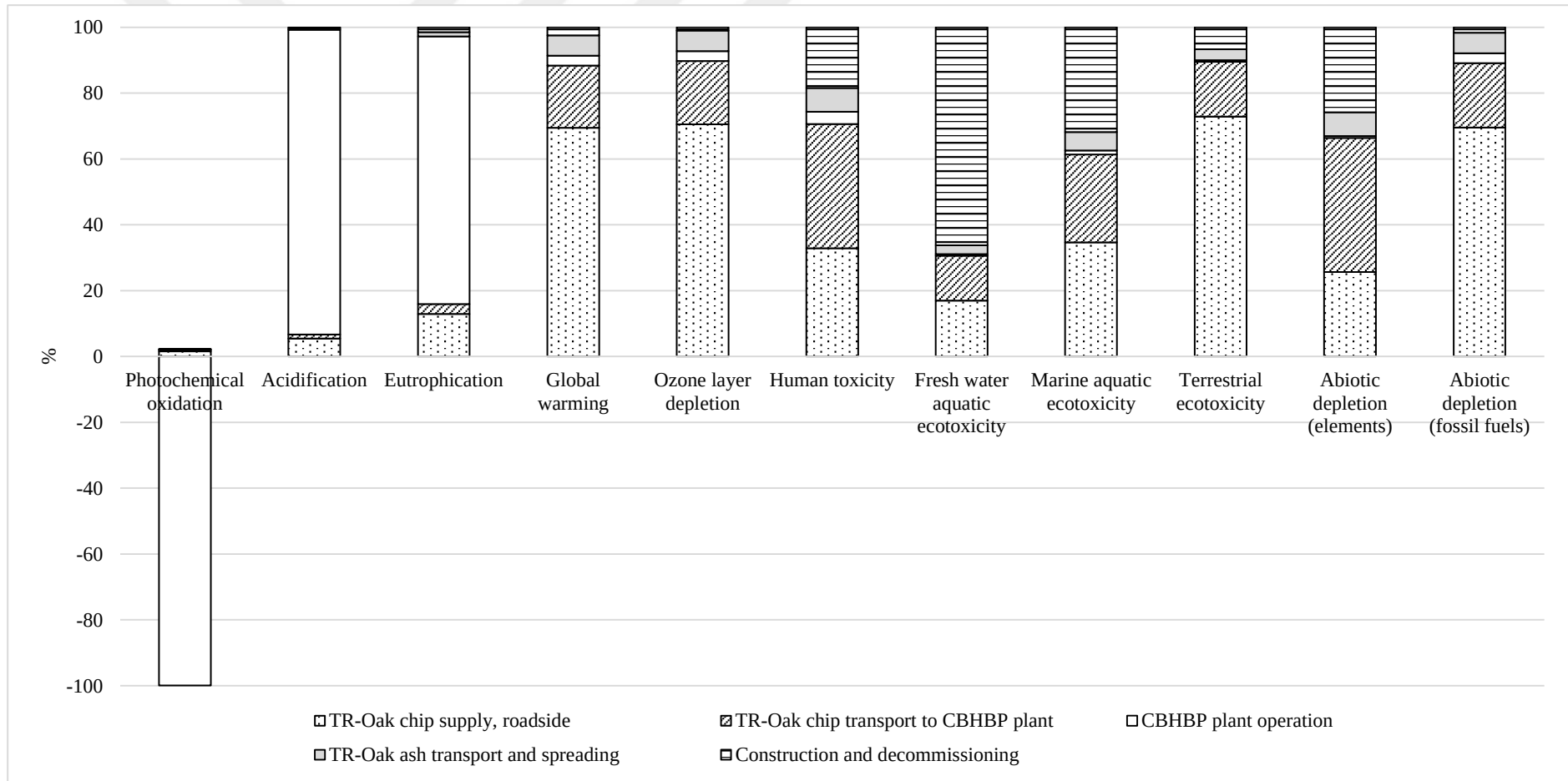


Figure 6.15 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-2 (5 MW_e), CML-IA baseline V3.03.

Table 6.9 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-2 (5 MW_e), CML-IA baseline V3.03.

Midpoint Impact Category	Contribution (%)					Contribution (%) Representation
	TR-Oak Chip Supply, Roadside	TR-Oak Chip Transport to CBHBP Plant	CBHBP Plant Operation	TR-Oak Ash Transport and Spreading	Construction and Decommissioning	
Photochemical oxidation	1.60	0.41	-99.95	0.14	0.13	
Acidification	5.47	1.21	92.55	0.54	0.24	
Eutrophication	12.96	2.94	81.33	1.28	1.50	
Global warming	69.46	18.93	2.96	6.14	2.51	
Ozone layer depletion	70.55	19.15	3.06	6.26	0.98	
Human toxicity	32.84	37.74	3.76	7.22	18.44	
Fresh water aquatic ecotoxicity	16.99	13.57	0.49	2.71	66.23	
Marine aquatic ecotoxicity	34.68	26.63	1.23	5.61	31.85	
Terrestrial ecotoxicity	72.88	16.61	0.52	3.31	6.68	
Abiotic depletion (elements)	25.67	40.73	0.51	7.27	25.81	
Abiotic depletion (fossil fuels)	69.53	19.56	3.00	6.27	1.63	

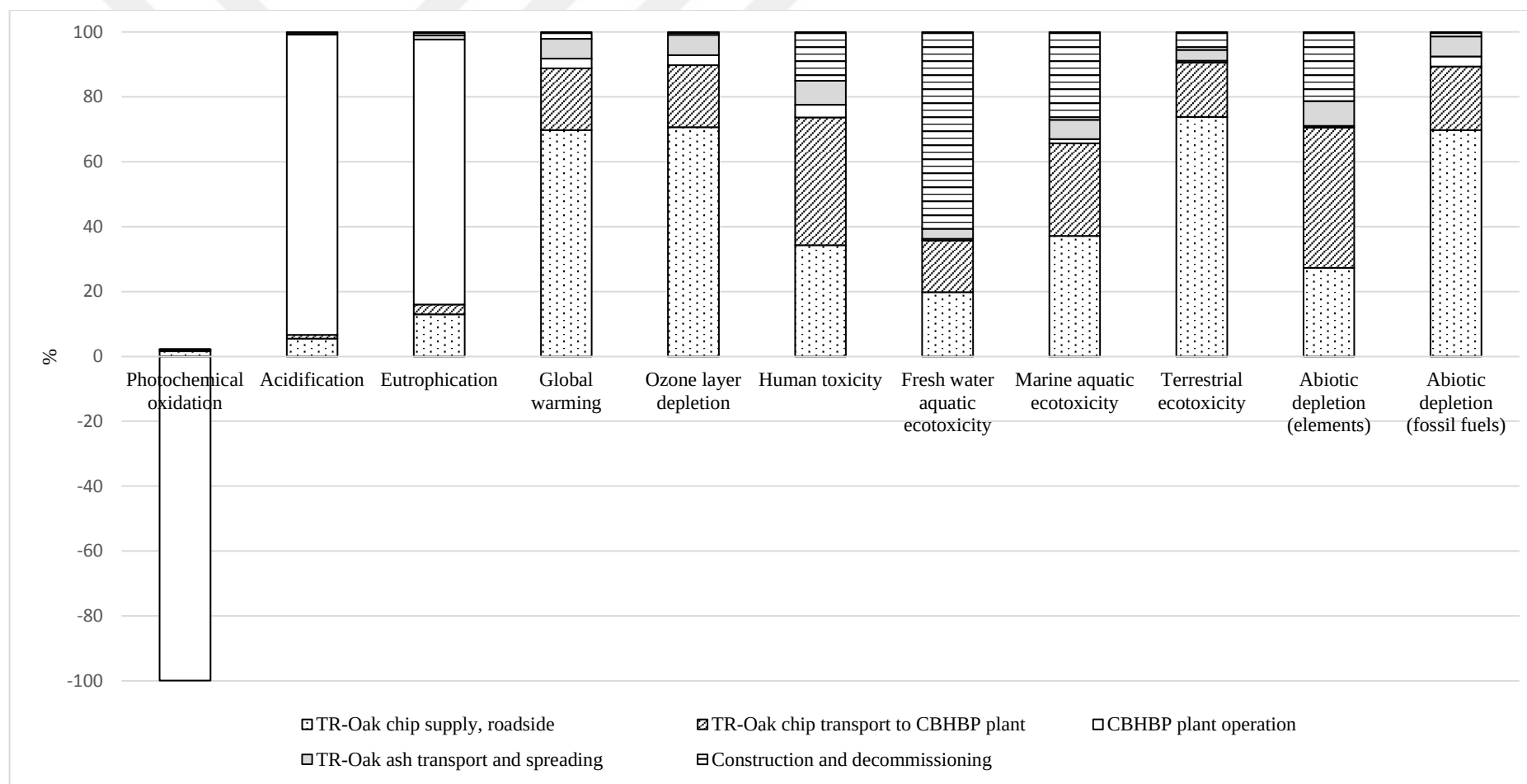


Figure 6.16 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-3 (10 MW_e), CML-IA baseline V3.03.

Table 6.10 : Contribution analysis for midpoint impacts of 1 kWh biopower and/or bioheat production, CS-3 (10 MW_e), CML-IA baseline V3.03.

Midpoint Impact Category	Contribution (%)					Contribution (%) Representation
	TR-Oak Chip Supply, Roadside	TR-Oak Chip Transport to CBHBP Plant	CBHBP Plant Operation	TR-Oak Ash Transport and Spreading	Construction and Decommissioning	
Photochemical oxidation	1.60	0.41	-99.95	0.14	0.10	
Acidification	5.47	1.21	92.58	0.53	0.21	
Eutrophication	13.02	2.95	81.73	1.28	1.02	
Global warming	69.81	19.02	2.98	6.13	2.07	
Ozone layer depletion	70.65	19.18	3.06	6.23	0.89	
Human toxicity	34.27	39.38	3.92	7.45	14.98	
Fresh water aquatic ecotoxicity	19.83	15.84	0.57	3.13	60.63	
Marine aquatic ecotoxicity	37.15	28.53	1.32	5.94	27.07	
Terrestrial ecotoxicity	73.82	16.82	0.53	3.31	5.53	
Abiotic depletion (elements)	27.28	43.28	0.55	7.62	21.27	
Abiotic depletion (fossil fuels)	69.79	19.63	3.01	6.25	1.31	

Beginning with PCO, the details of contribution analysis for each impact category are presented and discussed in the following lines.

PCO, which has an adverse effect on human health, derives from air emissions. According to the results, there is an environmental benefit for all cases because the CML method accepts that NO is good for air quality. While the positive impact (~86%) was mainly caused by NO emissions from the CBHBP operation, the negative impact was about 14%. The majority of negative impact was due to SO₂ emissions (~92%) followed by CO emissions (~5%). SO₂ emissions were mainly from CBHBP operation (~95%) followed by the TR-Oak chip supply chain (~4%), from the forest to the CBHBP plant. CO emissions were mainly from the TR-Oak chip supply chain (83% for CS-1, 87% for CS-2, 88% for CS-3), construction and decommissioning life cycle (10% for CS-1, 6% for CS-2, 5% for CS-3), and TR-Oak ash transport and spreading (~6% for all cases).

For all cases, the majority of ACD, which has a negative effect on ecosystems, was due to SO₂ (~62%), NO (~30%), NO_x (~5%), and SO₃ (~3%) emissions into the air. As for PCO, SO₂ emissions were mainly from the CBHBP operation (~95%), followed by the TR-Oak chip supply chain (~4%). While NO emissions were from the CBHBP operation, NO_x emissions were dominated by the TR-Oak chip supply chain (~86%), and TR-Oak ash transport and spreading (~7%). All the SO₃ emissions came from the CBHBP operation, and overall, the CBHBP operation was responsible for about 93% of ACD, for all three cases.

ETR, which has a negative ecosystem effect, was dominated by NO emissions (~80%), and NO_x (~13%) emissions into the air. Following were phosphate, nitrate, and chemical oxygen demand in the water. Like for ACD, NO emissions were due to CBHBP operation. In addition, the TR-Oak chip supply chain operations contributed the majority of NO_x emissions (~86%). Overall, while the CBHBP operation was responsible for about 81% of ETR, the TR-Oak chip supply chain was responsible for around 15% of ETR in all cases.

CO₂ from fossil sources throughout the system boundary was the major contributor (around 96%) to overall GW, which had an adverse effect on the ecosystems. CH₄ and N₂O followed CO₂. Most CO₂ arose from the TR-Oak chip supply chain operation (~90%), followed by TR-Oak ash transport and spreading (~6%). The rest arose from

CBHBP operation and infrastructure. About 71% of GW was a result of exhaust emissions due to the fossil fuel use in the foreground operations, harvesting, forwarding, chipping, and transportation. The rest was from background operations. The CBHBP operation contributed about 3% of GW due to front-end loader diesel emissions into the air. Overall, 93–95% of GW was due to TR-Oak chip supply chain operations, followed by TR-Oak ash transport and spreading.

Almost the entire OD impact (~98%) came from bromotrifluoro-methane (Halon 1301) which is a chemical mainly used as fire suppressants and coolants in petroleum and natural gas processes in the system boundary. OD damages human health. The TR-Oak chip supply chain operations, including transport, accounted for almost 90% of the total OD, followed by TR-Oak ash transport and spreading (~6%).

HT was largely (~ 90%) due to TR-Oak chip supply chain operations, and to the construction and decommissioning data used in the system boundary. Antimony, chromium IV, copper, and nickel to the air, and selenium into the water, accounted for ~67% of HT. The major emissions were due to brake-pad wear on the road transport vehicles (~45%), and to ferrochromium production (~13%). The treatment of spoil from coal mining in landfills accounted for almost 4% of HT. Air emissions from CBHBP production that contributed to HT were PM-10 and SO₂ (~ 3%).

Construction and decommissioning processes of the system boundary, were the largest contributors to FWET (75% for CS-1, 66% for CS-2, and 60% for CS-3). Treatment of scrap steel used in the construction accounted for 50% of FWET, while about 14% was from treatment of scrap copper. Almost 10% was from treatment of spoil from coal mining in landfills. The second largest contributor was the TR-Oak chip supply chain to the CBHBP plants (23% for CS-1, 30% for CS-2, and 35% for CS-3). The major emissions to fresh water were from metals (copper, nickel, vanadium, and beryllium: 90% for CS-1, 88% for CS-2, and 87% for CS-3).

TR-Oak chip supply chain operations contributed the largest impact to MET with 53% for CS-1, 61% for CS-2, and 66% for CS-3. Construction and decommissioning processes accounted for 41% for CS-1, 32% for CS-2, and 27% for CS-3 of the total MET. Hydrogen fluoride to the air, and beryllium, nickel, copper, and barium to the water were the major substances contributing to MET. Treatments of spoil from coal mining, sulfidic tailings, and scrap steel were the major background processes

contributing to MET (40–46 %). CBHBP operation was responsible for around 1% of MET, mainly due to diesel use by the front-end loader. CBHBP production alone had no effect on MET.

Mercury emissions to air, and Cypermethrin, zinc, Aldicarb, and chromium IV emissions to the soil were the main causes of TET. TR-Oak chip supply chain to the CBHBP plants had the largest impact (87% for CS-1, 90% for CS-2, and 91% for CS-3). Cypermethrin and Aldicarb emissions to the soil were mainly due to insecticides in the background processes used for the production of biolubrication oil. Chromium IV was used in electricity transmission and distribution networks in the background processes. Mercury emissions were due to cast iron and steel production processes. Zinc to soil was the result of tire-wear emissions.

ADE refers to the elements used as raw materials in the system boundary in various foreground and background processes, and hence depleted. ADE has an adverse effect on resources. The major elements responsible for ~ 85% of ADE were cadmium, gold, lead, copper, and silver. The main reason for ADE was the TR-Oak chip supply chain (59% for CS-1, 66% for CS-2, and 71% for CS-3); the rest was mainly from construction and decommissioning (34% for CS-1, 26% for CS-2, and 21% for CS-3). As mentioned, construction and decommissioning included all infrastructure for the TR-Oak chip supply chain and CBHBP plant operation, except construction and decommissioning for lorries and road infrastructures which were included in the transport operations.

Fossil resource depletion (ADF) associated with the system boundary was mainly due to oil consumption (around 90%), followed by natural gas (~6%), and coal (~4%). With almost 90% of the impact, the TR-Oak chip supply chain dominated the contribution to ADF, and was followed by TR-Oak ash transport and spreading with around 6%. CBHBP plant contributed ~3% to ADF, which was mainly due to fossil fuel use in the TR-Oak chip feedstock preparation yard.

6.1.5 Contribution analysis for endpoint impact categories

This section provides contribution analyses based on the weighting results of the LCA study. Contribution analysis was done by arranging the LCA results in the stages explained in the previous section, and then determining the contribution percentages of each stage to the endpoint impact categories (human health, ecosystems, and

resources). By presenting the analysis results as percentage contributions of the stages mentioned, it became possible to present a single figure and table for each CS and for all functional units (1 kWh biopower, 1 kWh bioheat, 1 kWh energy). The analysis results for human health, ecosystems, and resources are provided in Figure 6.17 and Table 6.11 for CS-1, CS-2, and CS-3. All the results belonged to the World ReCiPe H/H perspective of the ReCiPe Endpoint (H) V1.12 method.

Table 6.11 includes contribution representations placed in its rightmost column to make clear the percentage distributions of contributions to endpoint impact categories for each stage. Looking at these contribution representations, CBHBP operation was the main contributor for human health. The adverse impacts on ecosystems and resources were mainly due to the TR-Oak chip supply chain operations. The impacts of TR-Oak ash transport and spreading, and construction and decommissioning, were insignificant.

Analyzing Figure 6.17 and Table 6.11 in detail, the CBHBP plant operation was the largest contributor (~ 66%) to human health followed by the TR-Oak chip supply chain, which included the TR-Oak chip supply (roadside) and TR-Oak chip transport to CBHBP plant (~30%). The rest was due to TR-Oak ash transport to forest and spreading, as well as construction and decommissioning. However, it is important to note that because ReCiPe did not split NO_x into NO and NO₂ and assumed that NO had no effect on air quality; NO was defined as NO_x in the study. If we assume that NO has no effect on air quality, and get the results again, the general result was not changed anyway (i.e., CBHBP plant operation was the largest contributor (~ 57%) to human health, followed by the TR-Oak chip supply chain (~ 37%). On the other hand, the positive effect of NO on PCO was not considered in ReCiPe, which might also have decreased the adverse effects of CBHBP plant operation on human health. While the TR-Oak chip supply chain dominated damage to ecosystems (83–85 %), that for resources was 86–88 %. CBHBP plant operation has less adverse effect on ecosystems and resources relative to the TR-Oak chip supply chain. TR-Oak ash transport and spreading, and the construction and decommissioning stages, created lower environmental impacts in all the damage categories, if compared with other stages in the system boundary.

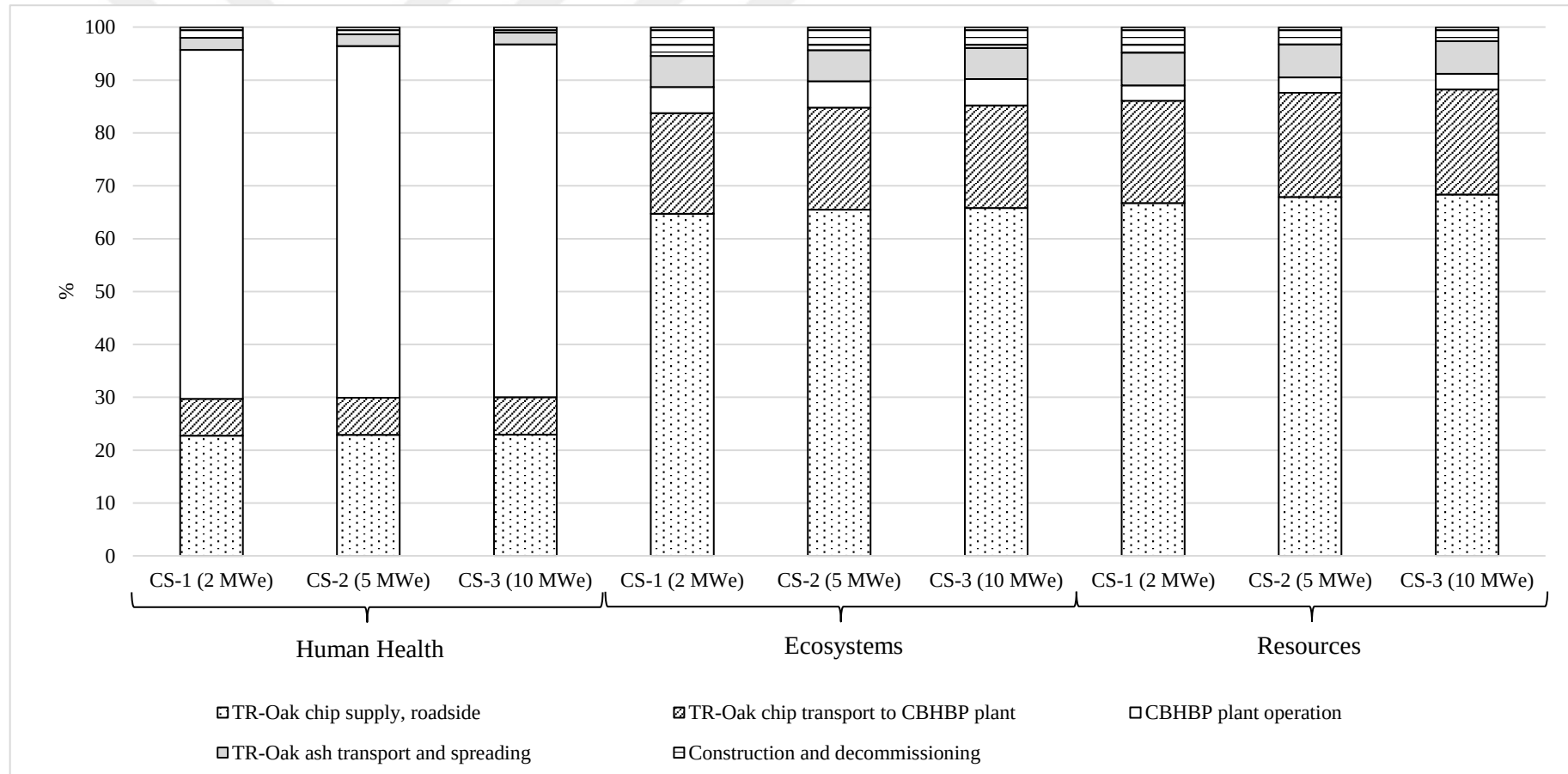


Figure 6.17 : Contribution analysis for endpoint impacts of 1 kWh biopower and/or bioheat production, CS-1, -2, -3 (2 MWe, 5 MWe, 10 MWe, respectively), ReCiPe Endpoint (H) V1.12 World ReCiPe H/H.

Table 6.11 : Contribution analysis for endpoint impacts of 1 kWh biopower and/or bioheat production, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively), ReCiPe Endpoint (H) V1.12 World ReCiPe H/H.

Case Study (CS)	Damage Category	Contribution (%)					Contribution (%) Representation
		TR-Oak Chip Supply, Roadside	TR-Oak Chip Transport to CBHBP Plant	CBHBP Plant Operation	TR-Oak Ash Transport and Spreading	Construction and Decommissioning	
CS-1	Human Health	22.72	6.99	66.01	2.27	2.01	
	Ecosystems	64.71	19.02	4.93	5.89	5.44	
	Resources	66.74	19.37	2.87	6.20	4.82	
CS-2	Human Health	22.89	7.04	66.49	2.25	1.33	
	Ecosystems	65.51	19.26	4.99	5.87	4.36	
	Resources	67.90	19.70	2.92	6.22	3.26	
CS-3	Human Health	22.96	7.06	66.71	2.24	1.03	
	Ecosystems	65.82	19.35	5.02	5.85	3.95	
	Resources	68.37	19.84	2.94	6.21	2.63	

Considering all cases, the total scores in mPt and their distributions for each stage were calculated for each functional unit (1 kWh biopower, 1 kWh bioheat, 1 kWh energy). They are shown in Table 6.12. The bottom of the table also includes contribution representations to make clear the percentage distributions of contributions to total scores for each stage.

As seen in the table, the TR-Oak chip supply chain is the stage with the highest score followed by CBHBP plant operation. According to the results, the TR-Oak chip supply chain has the highest environmental load for the system considered in the study, and hence the greatest care must be shown with this stage. The environmental load of the TR-Oak chip supply chain was about 17% higher than that of the CBHBP plant operation. While TR-Oak chip supply chain contributed ~ 51–52 % to the total score, the CBHBP plant operation contributed ~ 42–43 %.

Because it is known that the weighting factors on all methods were based on subjective evaluations, another perspective for the world available in the ReCiPe Endpoint (H) V1.12 method was used for comparison purposes. The perspective is World ReCiPe H/A, which includes average weighting sets. Similarly, considering all cases, the total scores in mPt and their distributions for each stage, were calculated for each functional unit (1 kWh biopower, 1 kWh bioheat, 1 kWh energy), and shown in Table 6.13.

As seen in the table, the CBHBP plant operation is the stage with the highest score, followed by the TR-Oak chip supply chain. According to the results for the perspective of World ReCiPe H/A, CBHBP plant operation had the highest environmental load for the system considered in the study. The environmental load of CBHBP plant operation was about 19% higher than if the TR-Oak chip supply chain. While the TR-Oak chip supply chain contributed ~ 43–44 % to the total score, CBHBP plant operation contributed ~ 51–52 %.

If we evaluate the results of both perspectives together, it is obvious that it is necessary to pay attention to both stages in the same sense, in terms of environmental loads.

Table 6.12 : Total score distribution of CBHBP plants: CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively), ReCiPe Endpoint (H) V1.12 World ReCiPe H/H.

Processes	CS-1 Scores (mPt)			CS-2 Scores (mPt)			CS-3 Scores (mPt)		
	1 kWh biopower	1 kWh bioheat	1 kWh energy	1 kWh biopower	1 kWh bioheat	1 kWh energy	1 kWh biopower	1 kWh bioheat	1 kWh energy
TR-Oak chip supply chain	4.575	1.073	1.806	4.332	1.020	1.808	4.263	0.990	1.809
TR-Oak chip supply, roadside	3.529	0.828	1.393	3.341	0.787	1.395	3.288	0.763	1.395
TR-Oak chip transport to CBHBP plant	1.047	0.245	0.413	0.991	0.233	0.414	0.975	0.226	0.414
CBHBP plant operation	3.810	0.894	1.504	3.607	0.850	1.506	3.550	0.824	1.507
TR-Oak ash transport and spreading	0.337	0.079	0.133	0.314	0.074	0.131	0.307	0.071	0.130
Construction and decommissioning	0.227	0.065	0.109	0.175	0.041	0.073	0.136	0.032	0.058
Contribution (%) Representation									
Total	8.998	2.111	3.551	8.427	1.985	3.518	8.255	1.917	3.504

Table 6.13 : Total score distribution of CBHBP plants: CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e, respectively), ReCiPe Endpoint (H) V1.12 World ReCiPe H/A.

Processes	CS-1 Scores (mPt)			CS-2 Scores (mPt)			CS-3 Scores (mPt)		
	1 kWh biopower	1 kWh bioheat	1 kWh energy	1 kWh biopower	1 kWh bioheat	1 kWh energy	1 kWh biopower	1 kWh bioheat	1 kWh energy
TR-Oak chip supply chain	4.215	0.989	1.664	3.991	0.940	1.666	3.927	0.912	1.667
TR-Oak chip supply, roadside	3.244	0.761	1.280	3.071	0.723	1.282	3.022	0.702	1.283
TR-Oak chip transport to CBHBP plant	0.971	0.228	0.383	0.920	0.217	0.384	0.905	0.210	0.384
CBHBP plant operation	5.015	1.176	1.979	4.749	1.119	1.982	4.673	1.085	1.983
TR-Oak ash transport and spreading	0.313	0.073	0.124	0.292	0.069	0.122	0.285	0.066	0.121
Construction and decommissioning	0.263	0.062	0.104	0.166	0.039	0.069	0.128	0.030	0.055
Contribution (%) Representation									
Total	9.807	2.300	3.870	9.197	2.167	3.840	9.014	2.093	3.826

6.2 Sensitivity Analysis on LCA results

The purpose of sensitivity analysis was to analyze the effects of variations in key assumptions and choices, and thus to study the influence of increases or decreases in the key assumptions and choices, on the LCA results. Following is an analysis and discussion of the most uncertain assumptions and choices: transport distance between roadside and CBHBP plant, equipment productivity, CBHBP plant lifetime, and allocation procedure.

6.2.1 Effect of transport distance between roadside and CBHBP plant on LCA results

To analyze the effect of transport distance between the roadside landing and the CBHBP plant, it was changed from 20 to 100 km and the outcomes for characterization results were compared.

Table 6.14 shows the effect of transport distance on midpoint impacts to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 impact assessment method in the SimaPro software.

For the base case of CS-1, which assumes a transport distance of 50 km, the corresponding impact was fixed at 100%. Then, relative increases or decreases for higher or lower transport distances were calculated and provided in the table. The highest increases or decreases were seen for the impacts most affected by TR-Oak chip transport to the CBHBP plant, as explained in the contribution analysis section of this chapter. These impacts were ADE, HT, MET, ADF; followed by GW, OD, TET, and FWET. The variations in PCO, ACD, and ETR were negligible because these impacts were mostly affected by CBHBP plant operation. An increase in transport distance from 50 to 100 km increased ADE and HT ~ 40%; MET 26%; and ADF, GW, and OD around 21%. These were followed by TET with ~19% and FWET with ~12%.

6.2.2 Effect of equipment productivity on LCA results

To see the effect of productivity of the main pieces of equipment on the LCA results, 20% increases or decreases were defined for the base case productivities reported in Table 6.15.

Table 6.14 : Effect of transport distance on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

Impact (%)	Transport Distance (km)					
	20	40	50	60	80	100
Photochemical oxidation	-100.293	-100.098	-100	-99.902	-99.707	-99.512
Acidification	99.169	99.723	100	100.277	100.831	101.385
Eutrophication	97.992	99.331	100	100.669	102.008	103.347
Global warming	87.115	95.705	100	104.295	112.885	121.475
Ozone layer depletion	86.852	95.617	100	104.383	113.148	121.913
Human toxicity	76.348	92.116	100	107.884	123.652	139.420
Fresh water aquatic ecotoxicity	93.062	97.687	100	102.313	106.938	111.563
Marine aquatic ecotoxicity	84.173	94.724	100	105.276	115.827	126.379
Terrestrial ecotoxicity	88.881	96.294	100	103.706	111.119	118.531
Abiotic depletion (elements)	75.228	91.743	100	108.257	124.772	141.286
Abiotic depletion (fossil fuels)	86.633	95.544	100	104.456	113.367	122.278

Table 6.15 : Productivities of the major pieces of equipment used in the LCA study.

Equipment	Equipment Productivities (t/h)		
	-20%	Base Case	+20%
Harvester	4.8	6	7.2
Forwarder	7.2	9	10.8
Mobile Chipper	17.6	22	26.4
Front-end Loader	8	10	12

The outcomes for the characterization results were compared in Table 6.16, which shows the effect of productivity on the midpoint impacts to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 impact assessment method in SimaPro software. For the base case of CS-1, the corresponding impact was fixed at 100%. Then, relative increases or decreases for 20% higher or lower productivity were calculated and the results provided in the table. Table 6.16 shows that for all impacts, there were always increases in impacts for decreases in productivity, and decreases in impacts for increases in productivity. The highest increases or decreases were seen for impacts most affected by TR-Oak chip supply (roadside), as explained in the contribution analysis section of this chapter.

Table 6.16 : Effect of equipment productivities on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

Impact (%)	Equipment Productivity Changes (%)		
	-20%	Base Case	+20%
Photochemical oxidation	-99.58	-100	-100.28
Acidification	101.45	100	99.03
Eutrophication	103.41	100	97.73
Global warming	117.78	100	88.15
Ozone layer depletion	118.22	100	87.85
Human toxicity	107.62	100	94.92
Fresh water aquatic ecotoxicity	103.21	100	97.86
Marine aquatic ecotoxicity	107.66	100	94.89
Terrestrial ecotoxicity	117.79	100	88.14
Abiotic depletion (elements)	105.71	100	96.19
Abiotic depletion (fossil fuels)	117.87	100	88.09

These impacts were GW, OD, TET, and ADF, followed by HT and MET. Then came ADE, FWET, and ETR. The variations in PCO, and ACD were negligible because these impacts were mostly affected by CBHBP plant operation. A 20% change (increase or decrease) in productivity changed GW, OD, TET, and ADF around 12%. HT and MET increased 8% for a 20% decrease in productivity, and decreased 5% for a 20% increase in productivity. A 20% change (increase or decrease) in productivity changed ADE around 6%, and changed FWET and ETR around 3%.

6.2.3 Effect of CBHBP plant lifetime on LCA results

To see the effect of CBHBP plant lifetime on LCA results, it was changed from 20 to 30 years and the outcomes of the characterization results were compared. Lifetime includes construction for TR-Oak chip supply (to roadside) and CBHBP plant operations.

Table 6.17 shows the effect of lifetime on midpoint impacts to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 impact assessment method in SimaPro software.

For the base case of CS-1, which assumes a lifetime of 20 years, the corresponding impact was fixed at 100%. Then, relative increases or decreases of 30 years were calculated and provided in the table. The highest decreases were seen for the impacts most affected by construction and decommissioning stage, as explained in the contribution analysis section of this chapter. These impacts were FWET, MET, ADE, HT, and TET. The variations in PCO, ACD, ETR, GW, OD, and ADF were negligible because these impacts were less affected by the construction and decommissioning stage. An increase in lifetime from 20 years to 30 years decreased FWET ~25%, MET ~ 14%, and ADE ~ 12%; followed by decreased in HT of ~10%, and TET of ~5%.

6.2.4 Effect of allocation procedure on LCA results

Although, exergy is the most used and suggested allocation procedure for CBHBP plants in the literature [194,220,222,223,262,380], it is intended to examine the effect of allocation procedure choice on midpoint environmental impacts because LCA standards do not suggest a specific approach for allocation in CBHBP plants. Therefore, the impacts from exergy allocation was compared with the impacts of energy allocation for CS-1, -2, and -3.

Table 6.17 : Effect of CBHBP plant lifetime on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

Impact	Plant Lifetime (years)	
	20	30
Photochemical oxidation	-100	-100.
Acidification	100	99.8807
Eutrophication	100	99.2234
Global warming	100	98.7602
Ozone layer depletion	100	99.5424
Human toxicity	100	91.4197
Fresh water aquatic ecotoxicity	100	75.0247
Marine aquatic ecotoxicity	100	86.2742
Terrestrial ecotoxicity	100	96.8819
Abiotic depletion (elements)	100	88.5256
Abiotic depletion (fossil fuels)	100	99.1764

Figure 6.18 shows the effect of the allocation procedure on midpoint impacts to produce 1 kWh biopower for all cases using the CML-IA baseline V3.03 impact assessment method in SimaPro software. As it can be seen in the figure, when energy allocation was applied for all impact categories, the impacts were (~58, 56, and 55) % lower than those for CS-1, -2, and -3, respectively. The impact for CS-1 was the lowest because the biopower share of CS-1 was the lowest (compared with CS-2 and -3).

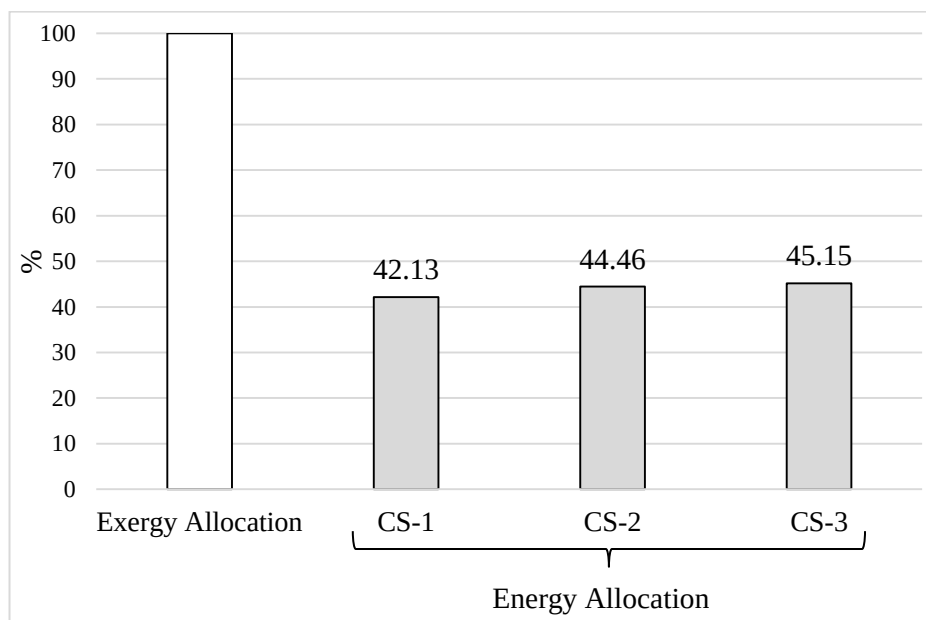


Figure 6.18 : Effect of allocation procedure on midpoint impacts to produce 1 kWh biopower, CS-1, -2, -3 (2 MW_e, 5 MW_e, 10 MW_e respectively), CML-IA baseline V3.03.

6.3 Effect of Eco-design Parameters on LCA Results

The following subsections provide the effect of feedstock properties and process conditions on LCA results to introduce an eco-design approach.

6.3.1 Effect of feedstock properties on LCA results

As mentioned in Chapter 4, biomass feedstock was specified (TR-Oak) in the thesis, and hence its properties are specific. However, its most changeable property is the biomass moisture content. That is why, the effect of moisture content on the LCA results is detailed in the following section.

6.3.1.1 Moisture content

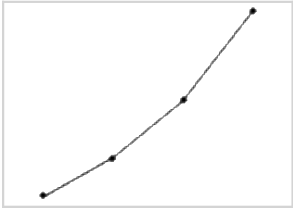
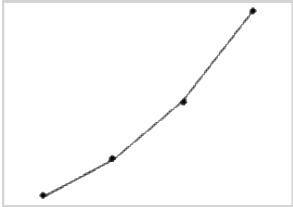
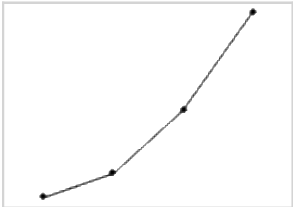
The purpose of this section is to understand the effect of moisture content on emissions, and to reveal its importance for producing CBHBP. In this case, ACD, ETR, and GW are the midpoint impacts, and CS-1 is the CBHBP production chosen for analysis.

Based on the total score distributions in Table 6.12 and Table 6.13, ACD, ETR, and GW were chosen among the impact categories because they are representative of the most important two stages of the system boundary: CBHBP operation and TR-Oak chip supply chain. ACD and ETR were chosen because they represent the adverse effect of CBHBP plant operation, as explained in the contribution analysis studies. Similarly, GW was chosen because it represents the adverse effect of TR-Oak chip supply chain. CS-1 was chosen for analysis because it has higher environmental impacts per kWh biopower production, as provided in the characterization results. Aspen Plus process simulation of CS-1, which is explained in Chapter 3, was run with different moisture content values (20, 30, 40, and 50) %.

Table 6.18 reveals the effect of TR-Oak chip feedstock moisture content on midpoint impacts to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 impact assessment method in SimaPro software. The table also includes the change trends in ACD, ETR, and GW with different moisture content values.

According to the results, increases in ACD, ETR, and GW show the same trends. Increase in moisture content from 20% to 30% increased ACD, ETR and GW at the same rate, which was around 3%; while 10% increment from 30% to 40% increased

Table 6.18 : Effect of TR-Oak chip feedstock moisture content on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

Impact	Moisture Content of TR-Oak Chip Feedstock (weight %)				Change Trend
	20	30	40	50	
Acidification (kg SO ₂ eq)	2.2349E-03	2.3024E-03	2.4039E-03	2.5613E-03	
Eutrophication (kg PO ₄ ³⁻ eq)	2.2307E-04	2.2964E-04	2.4021E-04	2.5661E-04	
Global warming (kg CO ₂ eq)	4.2587E-02	4.3794E-02	4.6944E-02	5.1829E-02	
TR-Oak chip mass flow to CBHBP production (kg/h) ^a	2779	3273	3980	5076	

^a Aspen Plus process simulation output.

ACD and ETR about 5%, and GW ~7%. Increase in moisture content from 40% to 50% increased ACD and ETR about 7%. In this case, the increase in GW was almost 11%. Increasing the moisture content from 30 to 50% caused about 11% increase in ACD and ETR, and 18% increase in GW. The higher increases for 40 and 50% moisture content values are because the TR-Oak chips were transported with 40 and 50% moisture content.

For all impacts considered here, the higher the moisture content, the higher the impact. This is due to increasing feedstock requirements in parallel to moisture content increases. TR-Oak chip mass flow to CS-1 (kg/h) for each moisture content determined using Aspen Plus process simulation is also provided in the table. More feedstock and higher moisture content require more transportation needs. In fact, increases in transportation needs are the main reason for increases in impacts, especially in GW. The highest increases are shown for GW. This is because the TR-Oak chip supply chain (TR-Oak chip supply from forest to roadside and TR-Oak chip transport to CBHBP plant) is the main contributor to GW.

Figure 6.19 shows the effect of moisture content on contribution analysis for GW to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 method. Because the contribution analysis reported in the previous section revealed the importance of the TR-Oak chip supply chain and CBHBP plant operation in terms of environmental issues, this figure was prepared for these operations. As mentioned above, TR-Oak chip supply chain (TR-Oak chip supply from forest to roadside and TR-Oak chip transport to CBHBP plant) is the stage most affected by the increases in moisture content. Overall, the 18% increase in GW caused by increasing the moisture content from 30 to 50% was due to TR-Oak chip transport to CBHBP plant (~10.3%) and TR-Oak chip supply from forest to roadside (~7.4%).

6.3.2 Effect of Process Conditions on LCA results

This section provides the effect of process conditions, excess air ratio, and furnace temperature, on LCA results.

6.3.2.1 Excess air ratio

Optimum excess air is essential for biomass combustion systems to achieve complete combustion, and to reduce pollutants. The purpose of this section is to understand the

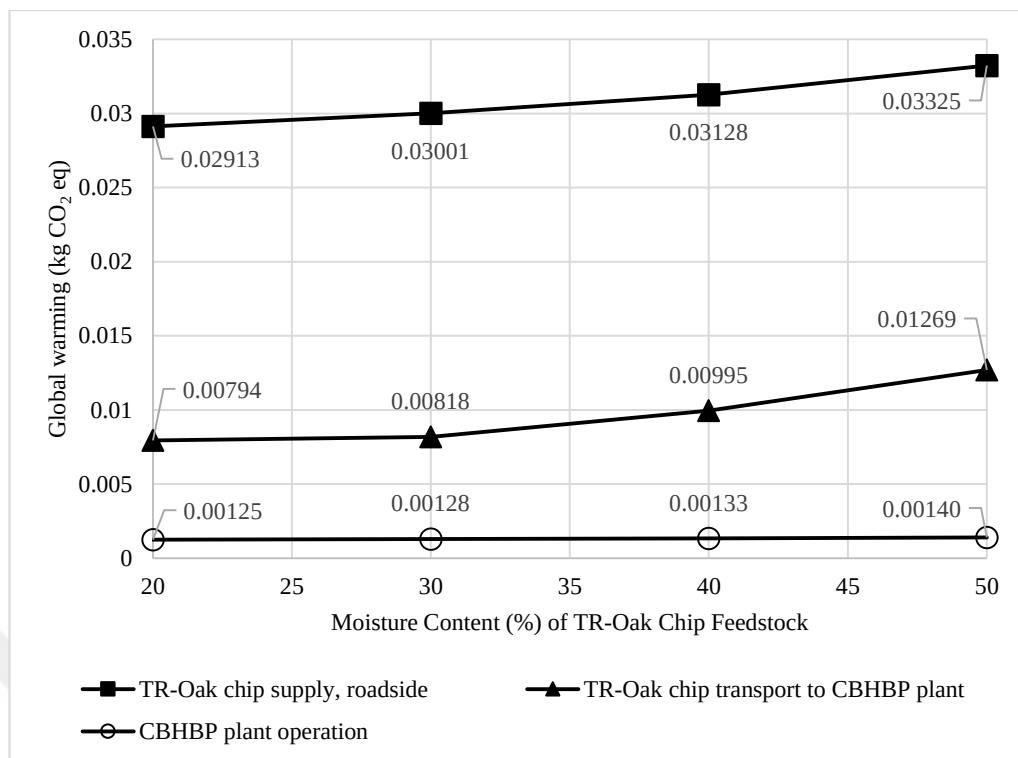


Figure 6.19 : Effect of moisture content on contribution analysis for global warming to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

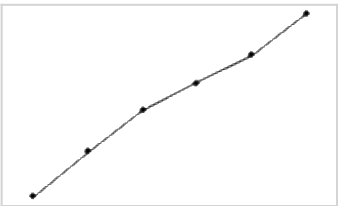
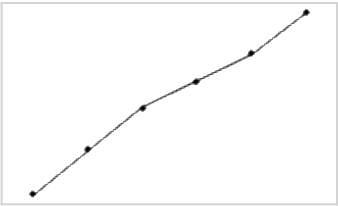
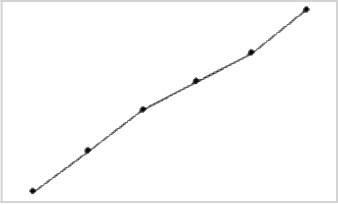
effect of excess air ratio on emissions, and to reveal its importance for producing CBHBP. ACD, ETR, and GW are the midpoint impacts, and CS-1 is the CBHBP production chosen for analysis. Aspen Plus process simulation of CS-1, which is explained in Chapter 3, was run for different excess air ratios (1.2, 1.5, 1.8, 2.0, 2.2 and 2.5).

Table 6.19 reveals the effect of excess air on midpoint impacts to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 impact assessment method in SimaPro software. The table also includes the trends of change in ACD, ETR, and GW with different excess air ratios.

According to the results, when comparing an excess air ratio of 1.2 and 2.5, there was an increase for all impacts, but the increase in GW was much less (~6%) than ETR (224%) and ACD (68%). The increase in GW was parallel to the TR-Oak chip mass flow increase between the excess-air ratios of 1.2 and 2.5.

The high increase in ETR and ACD was a result of the increase in NO_x emissions. As the excess air ratio went up, the conversion rate of fuel bound nitrogen to NO_x and

Table 6.19 : Effect of excess air on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

Impact	Excess Air Ratio						Change Trend
	1.2	1.5	1.8	2.0	2.2	2.5	
Acidification (kg SO ₂ eq)	1.9718E-03	2.3024E-03	2.6077E-03	2.8091E-03	3.0112E-03	3.3180E-03	
Eutrophication (kg PO ₄ ³⁻ eq)	1.4772E-04	2.2964E-04	3.0478E-04	3.5421E-04	4.0377E-04	4.7895E-04	
Global warming (kg CO ₂ eq)	4.3237E-02	4.3794E-02	4.4365E-02	4.4754E-02	4.5150E-02	4.5759E-02	
TR-Oak chip mass flow to CBHBP production (kg/h) ^c	3229	3273	3318	3349	3380	3428	

^c Aspen Plus process simulation output.

N₂O increased. With an excess air ratio of 1.2, 93% of the fuel-bound nitrogen was in the combustion products, but only 74% was in the combustion products with an excess air ratio of 2.5. Hence, increase in NO_x formation was the main reason for increased impacts, especially for ETR and ACD. This is because > 90% of ETR was due to NO_x emissions, as provided in Table 6.7. Because the contribution of NO_x to ACD is around 30% and SO_x emissions do not change much with different excess air ratios, the increase in ACD was lower than the increase in ETR. While 95% of S was converted into SO₂ and the rest was converted into SO₃ for an excess air ratio of 1.2, 93% of S was converted into SO₂ and the rest was converted into SO₃ for an excess air ratio of 2.5. Considering all stages together, the higher increases in ETR (~56%) and ACD (~17%) were observed with the excess air ratios of 1.2 and 1.5. The increases in ETR and ACD were ~33% and ~13%, respectively, with the excess air ratios of 1.5 and 1.8. While Figure 6.20 shows the effect of the excess air ratio on the contribution analysis for ETR to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 method, Figure 6.21 shows the effect of the excess air ratio on the contribution analysis for ACD. Because the contribution analysis reported in the previous section revealed the importance of TR-Oak chip supply chain and CBHBP plant operation in terms of environmental issues, the figures were prepared for these operations.

As mentioned above, CBHBP plant operation was the stage most affected by increases in the excess air ratio. For CBHBP plant operation, a 25% increase in the excess air ratio (from 1.2 to 1.5) increased the amount of ETR about 78%, and ACD about 18%. In addition, an increase in the excess air ratio from 1.5 to 1.8 increased ETR and ACD about 40% and 14%, respectively. The figures depict that considering all stages together, the higher increases observed in ETR (~56%) and ACD (~17%) with the excess air ratios of 1.2 and 1.5 were mainly due to CBHBP plant operation. On the other hand, the increase in the TR-Oak chip-supply chain for both ETR and ACD was negligible.

6.3.2.2 Furnace temperature

The purpose of this section is to determine the effect of furnace temperature on emissions, and to reveal its importance for producing CBHBP. ACD, ETR, and GW were the midpoint impacts and CS-1 was the CBHBP production chosen for analysis.

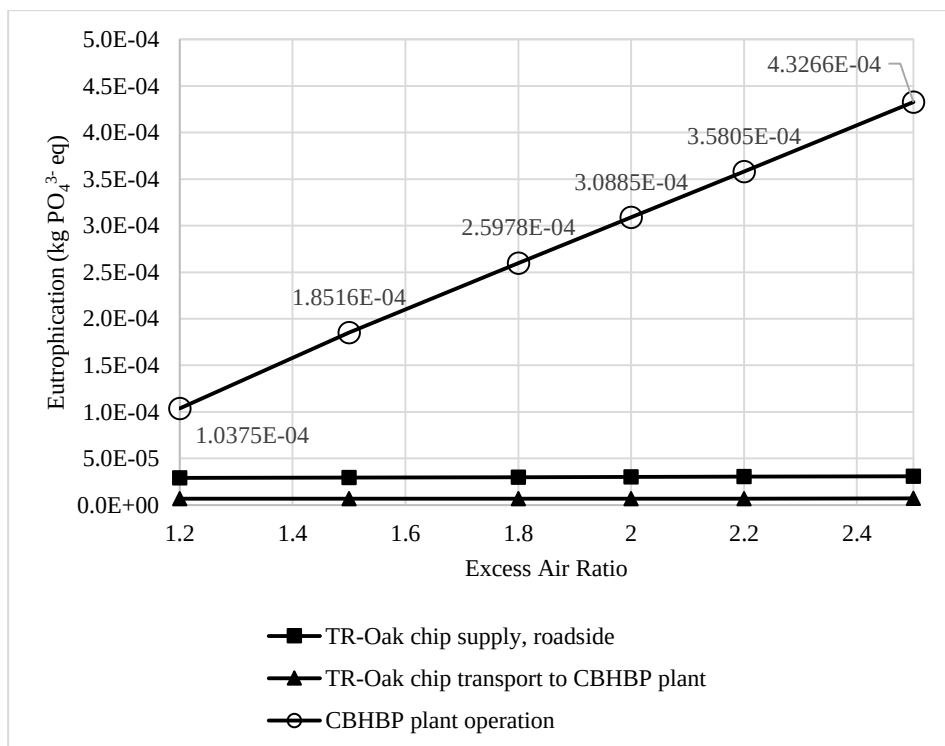


Figure 6.20 : Effect of excess air ratio on contribution analysis for eutrophication to produce 1 kWh biopower, CS-1 (2 MWe), CML-IA baseline V3.03.

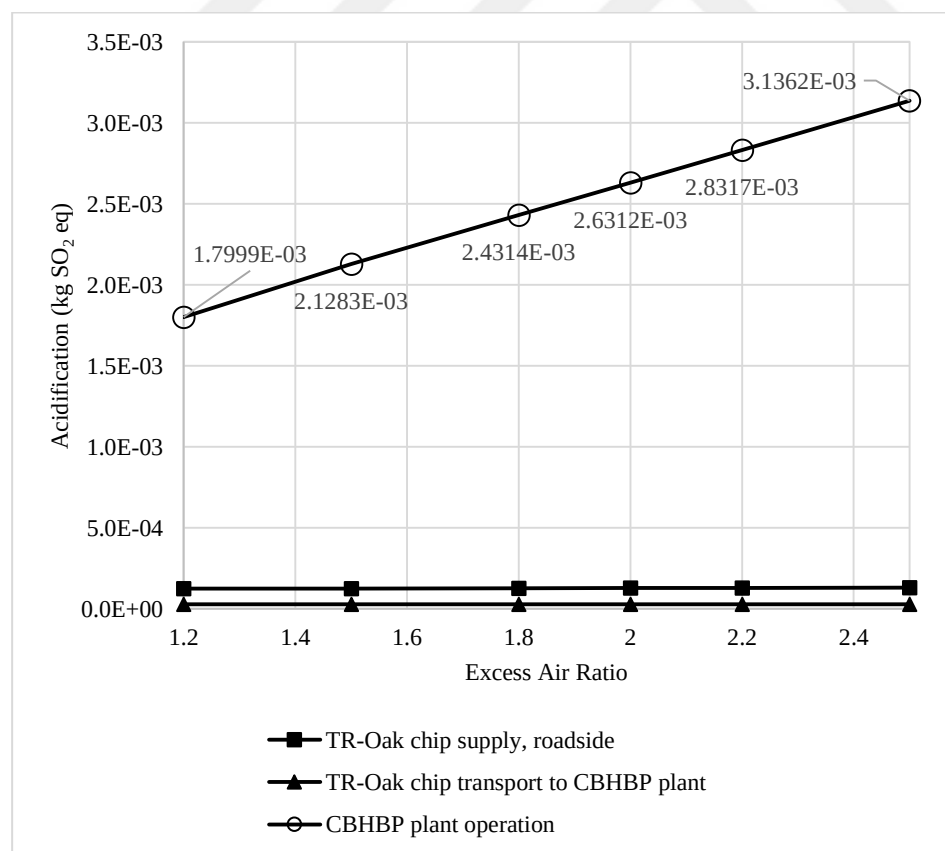


Figure 6.21 : Effect of excess air ratio on contribution analysis for acidification to produce 1 kWh biopower, CS-1 (2 MWe), CML-IA baseline V3.03.

An Aspen Plus process simulation of CS-1 (explained in Chapter 3) was run for different furnace operation temperatures (850, 900, 950, 1000, 1100 and 1200 °C).

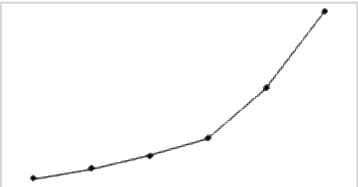
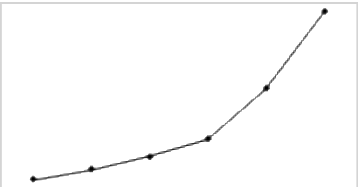
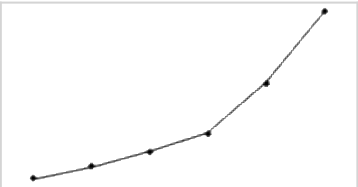
Table 6.20 reveals the effect of furnace temperature on midpoint impacts to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 impact assessment method in SimaPro software. The table also shows the trends in change of ACD, ETR, and GW with different furnace temperatures.

According to the results, while there was an increase for all impacts, the increase in GW was negligible. The high increases in ETR and ACD were due to the increase in NO_x emissions with increasing furnace temperature. As the furnace temperature went up, the conversion rate of fuel bound nitrogen to NO_x and N₂O increased. While ~95% of the fuel bound nitrogen was in the combustion products for a furnace temperature of 850 °C, only ~48% was in the combustion products for a furnace temperature of 1200 °C. Hence, increases in NO_x formation was the main reason for increases in ETR and ACD. This is because > 90% of ETR was due to NO_x emissions as provided in Table 6.7.

The increase in ACD was lower than the increase in ETR. While ~90% of S was converted into SO₂ and the rest was converted into SO₃ for a furnace temperature of 850 °C, ~99% of S was converted into SO₂ and the rest converted into SO₃ for a furnace temperature of 1200 °C. Considering all stages together, the higher increases in ETR (~77% and ~78%) were observed for the increases in furnace temperature from 850 to 950 °C and from 900 to 1000 °C, respectively. An increase in furnace temperature from 1000 to 1100 °C increased ETR by around 73%. On the other hand, for ACD, while the first significant increase was seen between 900 and 1000 °C (~25%), the higher increases (~33% and ~38%) were observed for increases in furnace temperature from 1000 to 1100 °C and from 1100 to 1200 °C, respectively.

While Figure 6.22 shows the effect of furnace temperature on contribution analysis for ETR to produce 1 kWh biopower for CS-1 (2 MW_e) using the CML-IA baseline V3.03 method, Figure 6.23 shows the effect of furnace temperature on contribution analysis for ACD. As mentioned above, because CBHBP plant operation was the stage affected by increased furnace temperature, the figures were prepared for CBHBP plant operation.

Table 6.20 : Effect of furnace temperature on midpoint impacts to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

Impact	Furnace Temperature (°C)						Change Trend
	850	900	950	1000	1100	1200	
Acidification (kg SO ₂ eq)	1.9227E-03	2.0835E-03	2.3024E-03	2.5922E-03	3.4399E-03	4.7414E-03	
Eutrophication (kg PO ₄ ³⁻ eq)	1.2983E-04	1.7210E-04	2.2964E-04	3.0584E-04	5.2873E-04	8.7100E-04	
Global warming (kg CO ₂ eq)	4.3770E-02	4.3781E-02	4.3794E-02	4.3811E-02	4.3855E-02	4.3919E-02	
TR-Oak chip mass flow to CBHBP production (kg/h) ^c	3272	3272	3273	3274	3275	3277	

^c Aspen Plus process simulation output.

For CBHBP plant operation, increases in furnace temperature from 850 to 950 °C and from 900 to 1000 °C increased the amount of ETR by around 117% and 105%, and ACD by around 22% and 27%, respectively. An increase in furnace temperature from 1000 to 1100 °C increased the amount of ETR by around 85%, and ACD by around 35%. ACD increased by almost 40% for an increase in furnace temperature from 1100 to 1200 °C. On the other hand, the increase in the TR-Oak chip supply chain for both ETR and ACD was negligible.

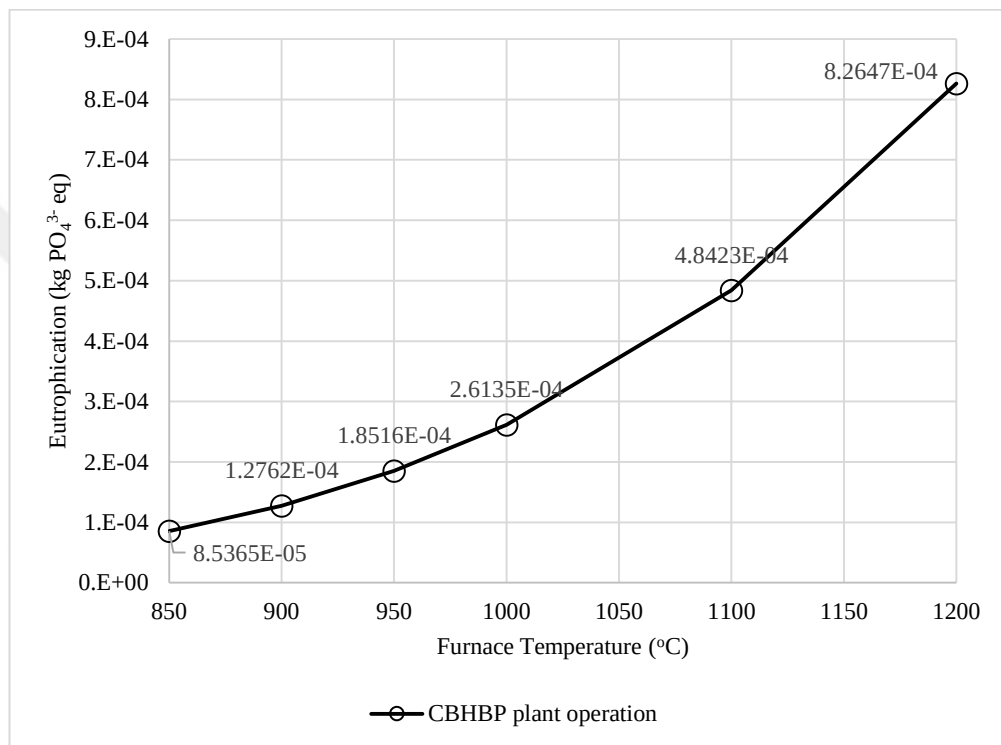


Figure 6.22 : Effect of furnace temperature on contribution analysis for eutrophication to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

6.4 Comparison of LCA Results for TR-Oak Chip-fueled CBHBP Production and Turkish Lignite-fueled Power Production

The purpose of this section is to compare 1 kWh biopower production with 1 kWh Turkish lignite power production, in terms of air emissions from combustion.

Air emissions from biopower production occurred in CS-1. Air emissions from Turkish lignite power production were taken from an LCA research study in the literature [381], which considered thirteen lignite power plants in Turkey and calculated their air emissions. These emissions are shown in Table 6.21.

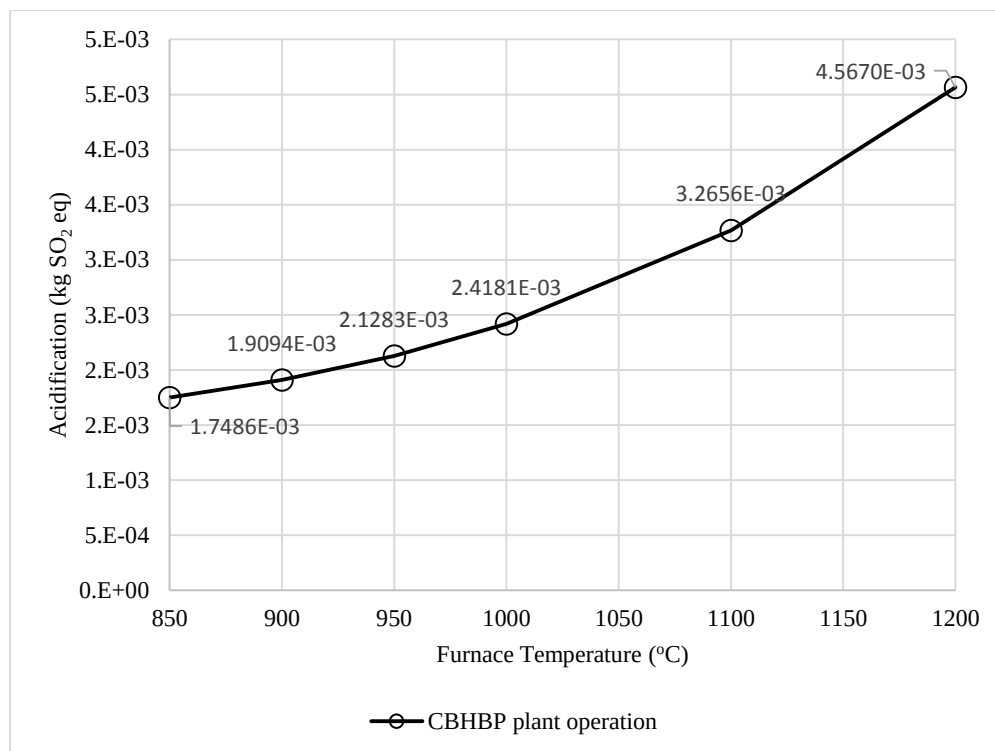


Figure 6.23 : Effect of furnace temperature on contribution analysis for acidification to produce 1 kWh biopower, CS-1 (2 MW_e), CML-IA baseline V3.03.

ACD, ETR, and GW were the midpoint impacts compared. Comparison for endpoint impacts included human health and ecosystems because only air emissions were taken into account. Regarding the impact assessment methods, the CML-IA baseline V3.03 provided in SimaPro software was used to compare midpoint impacts, and ReCiPe Endpoint (H) V1.12 was used to compare endpoint impacts. This is consistent with usage in the previous sections.

Table 6.21 : Air emissions from Turkish lignite power production [381].

Air Emissions	kg/kWh
CO	0.00067
CO ₂	1.02
NO _x	0.00211
N ₂ O	0.00003
SO ₂	0.00784
CH ₄	0.00002
Particulate matter (>PM-10)	0.00011
Particulate matter (PM-2.5-PM-10)	0.00011
Particulate matter (PM-2.5)	0.00094

While comparison of midpoint impacts is shown in Figure 6.24, that for endpoint impacts is shown in Figure 6.25. As can be seen in both figures, TR-Oak chip-fueled biopower production is much more advantageous than Turkish lignite-fueled power production for both midpoint and endpoint impacts. Figure 6.24 depicts that biopower production had almost no GW impact because biomass combustion is a carbon neutral process. While ACD of biopower production was ~17% of lignite power production, ETR was ~39% of lignite power production. The scores for the endpoint damage categories and total scores are shown in Figure 6.25. For human health, the adverse effect of lignite power production was remarkable. While the single score for biopower was 3.3, that for lignite power was 49.3 (15 times higher). For both human health and ecosystems in total, the environmental load from 1 kWh Turkish lignite-fueled power production was 16 times higher than that from 1 kWh TR-Oak chip-fueled biopower production in terms of air emissions from combustion.

In terms of top stressors attributed to lignite power production, CO₂ was the major emission, resulting in an adverse effect on ecosystems (~99). CO₂ also dominated the negative impacts on human health (~64). SO_x followed CO₂ with ~18%. Particulates contributed ~12% to human health, followed by NO_x with ~5%.

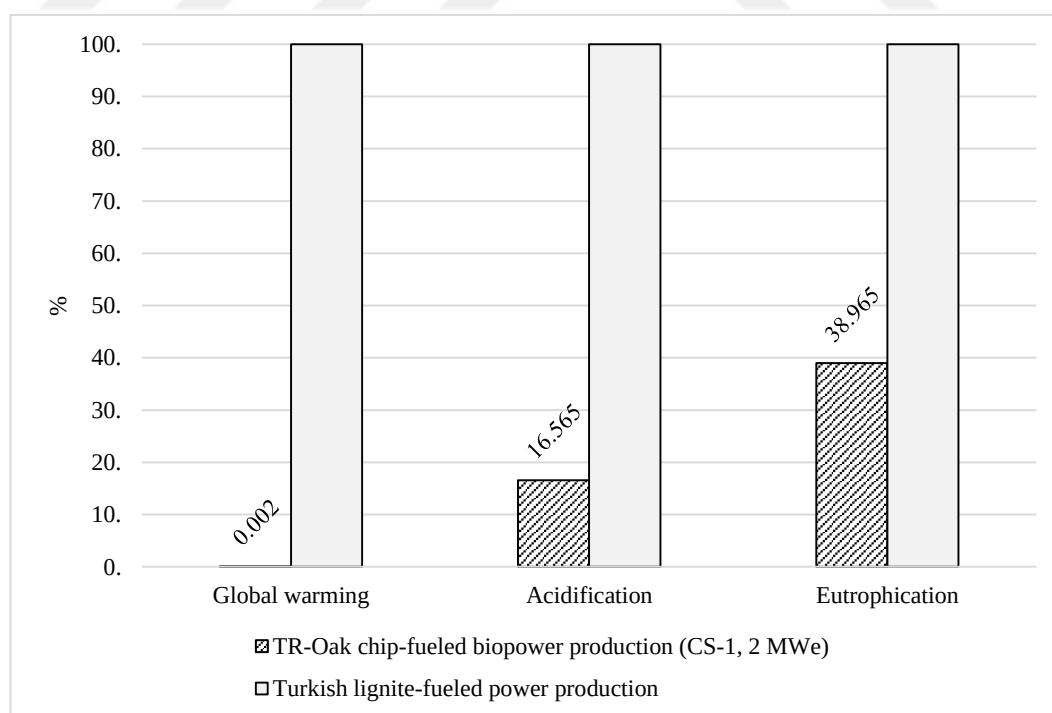


Figure 6.24 : Comparison of TR-Oak chip-fueled biopower production and Turkish lignite-fueled power production for midpoint impacts, 1 kWh, CML-IA baseline V3.03.

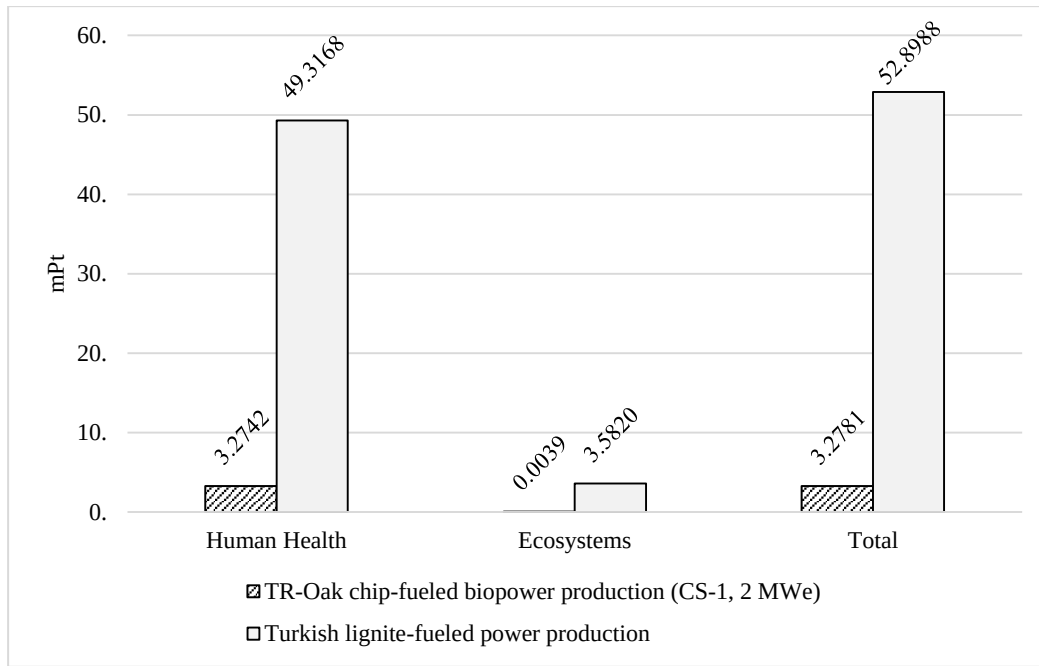


Figure 6.25 : Comparison of TR-Oak chip-fueled biopower production and Turkish lignite-fueled power production for endpoint impacts, 1 kWh, ReCiPe Endpoint (H) V1.12 3 World ReCiPe H/H.

6.5 Cost Results and Discussion for Case Study-1, -2, and -3

This section presents cost estimates of TR-Oak chip-fueled CBHBP plants, incorporating the data previously presented for each of the three case studies. In addition, the results from a sensitivity analysis are provided that was performed for the most important influencing factors on cost estimates.

6.5.1 Cost estimates for Case Study-1, -2, and -3

Table 6.22 presents the cost estimates of TR-Oak chip-fueled CBHBP plants. Cost estimates included total investment cost (USD), investment cost per installed biopower (USD/kW), annual costs, revenues and profit (USD/a), cost performance indicators with simple payback period (a), and biopower unit cost (USD/kWh and cent/kWh). The investment cost consisted of direct, indirect, and contingency costs. Direct costs were for boiler, turbine, and generator, feedstock handling equipment, other equipment, and balance of plant. Indirect costs consisted of engineering, procurement, and construction costs associated with the design and construction of the plants; project, land, and miscellaneous costs associated with the preparation of land; and other indirect costs. Engineering, procurement, and construction costs were set as 20% of direct costs. Project, land, and miscellaneous costs were set as 5% of direct costs.

Table 6.22 : Cost estimates of TR-Oak chip-fueled CBHBP plants.

	Case Study-1	Case Study-2	Case Study-3
Investment Cost (USD)			
Direct Costs			
Boiler	1,500,000	3,750,000	7,500,000
Turbine and generator	1,020,000	2,550,000	5,100,000
Feedstock handling equipment	660,000	1,650,000	3,300,000
Other equipments	540,000	1,350,000	2,700,000
Balance of plant	960,000	2,400,000	4,800,000
Indirect Costs			
Engineering, procurement, construction ^a	1,216,800	3,042,000	6,084,000
Project, land, miscellaneous ^b	304,200	760,500	1,521,000
Contingency Cost^c	1,404,000	3,510,000	7,020,000
Total Investment Cost (USD)	7,605,000	19,012,500	38,025,000
Investment Cost per kW (USD/kW)	3803	3803	3803
Annual Costs (USD/a)			
O&M Costs			
Fixed O&M costs	240,000	600,000	1,200,000
Variable O&M costs	544,000	1,360,000	2,720,000
TR-Oak Chip Cost	778,974	1,714,790	3,260,362
Capital Recovery Cost	775,710	1,939,275	3,878,550
Annual Revenues (USD/a)			
Biopower sale ^d	2,127,040	5,317,600	10,635,200
Bioheat sale ^e	1,159,862	2,456,837	4,592,409
Annual Profit (USD/a)			
Including capital recovery cost	948,218	2,160,372	4,168,697
Excluding capital recovery cost	1,723,928	4,099,647	8,047,247
Cost Performance Indicators			
Payback period (a)	4.4	4.6	4.7
Biopower production cost per year (USD/a)	1,178,822	3,157,228	6,466,503
Biopower unit cost (USD/kWh)	0.087	0.093	0.095
Biopower unit cost (cent/kWh)	8.7	9.3	9.5

^a Engineering, procurement, construction costs are 20% of direct costs [378].

^b Project, land, miscellaneous costs are 5% of direct costs [378].

^c Contingency cost is 30% of direct costs [378].

^d Biopower sold to grid takes into account own consumption of the plants which is 8% [35,214,343,359,373].

^e Bioheat sold to district takes into account internal distribution losses which is 3% [35].

In addition, to account for expected uncertainties, there was a contingency cost defined, which was 30% of direct costs [378]. Fixed and variable O&M costs, TR-Oak chip cost, and capital recovery cost made up the annual costs. As previously provided in the cost inventory data, when conducting a cost estimate, the impact of economies of scale for the CBHBP plants considered was not taken into account. CBHBP plants are used on-site and annual revenues come from biopower sold to the grid and bioheat sold to a district heating network. Within the calculation of revenue from biopower sale, 8% on-site power consumption at the plants was taken into account [35,214,343,359,373]. On the other hand, bioheat sales takes into account 3% internal distribution losses [35]. Annual profit of the plants was calculated including and excluding capital recovery cost. The cost performance indicators show the payback period, biopower production cost per year, and biopower unit cost for all cases.

For all CBHBP plants, investment cost per installed biopower was 3803 USD/kW, which corresponds to the lower values reported in Table 2.8. Results from analysis of the influence of investment costs on biopower unit cost are presented in the next section.

TR-Oak chip feedstock cost covered about 30–33 % of annual costs including capital recovery cost and about 45–50 % of annual costs excluding capital recovery cost. The influence of feedstock price on biopower unit cost was also included in the analysis in the next section.

The payback period was found to be about 5 years (4.4 years for CS-1, 4.6 years for CS-2, 4.7 years for CS-3), which is acceptable. Biopower unit costs were calculated to be (8.7, 9.3, and 9.5) cent/kWh for CS-1, -2, and -3, respectively, which compromise with the values in Table 2.8. Payback period and biopower unit cost show that CBHBP cost estimates considered in this study are all economically possible. Moreover, if the impact of economies of scale for CBHBP plants were taken into account, biopower unit costs for CS-2 and -3 would be lower than they are now. On the other hand, bioheat sale is what makes CBHBP plants attractive and competitive. Without bioheat sale in this study, biopower unit cost would be about 17 cent/kWh for all plants, which would make CBHBP implementation impossible. To repeat, the cost estimates in this study are realistic, but they do not represent actual costs for any specific project.

6.5.2 Sensitivity analyses on investment cost and TR-Oak chip cost

Investment and biofuel feedstock costs are important factors influencing biopower production cost. Thus, sensitivity analysis was performed to determine their effects on biopower unit cost. CS-2 was the CBHBP production case used for this analysis.

While Figure 6.26 shows the effect of investment cost on biopower unit cost, Figure 6.27 shows the effect of TR-Oak chip cost on biopower unit cost. Both figures include a comparison to the respective feed-in tariffs: 13.3 cent/kWh for minimum and 17 cent/kWh with premiums.

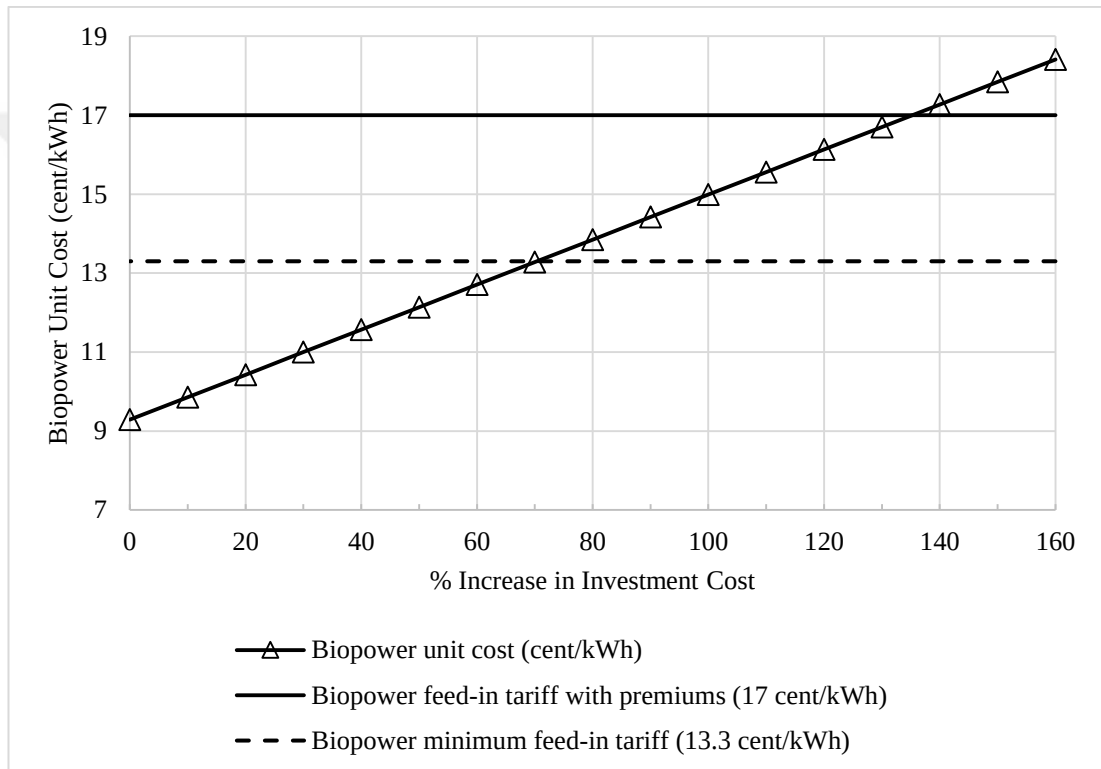


Figure 6.26 : Effect of investment cost on biopower unit cost.

Figure 6.26 shows that variation of the investment cost by $\pm 10\%$ leads to a variation of the biopower unit cost of $\pm 5.7\%$. Therefore, it can be concluded that possible investment subsidies for biopower production could improve the economic results of CBHBP plants. For the cost estimates in this study, about 70% increase in the investment cost corresponded to biopower unit cost that equaled the minimum biopower feed-in tariffs. On the other hand, a 70% increase in the investment cost (i.e., 6464 USD/kWh) is much higher than the cost figures in Table 2.8.

Figure 6.27 shows that variation of TR-Oak chip cost by ± 10 USD/t led to variation of the biopower unit cost by ± 1.441 cent/kWh. For the cost estimate in this study, about 65 USD/t for TR-Oak chip cost corresponded to the biopower unit cost, which was equal to the minimum biopower feed-in tariffs. About 90 USD/t is the limit required not to exceed the feed-in tariffs with premium.

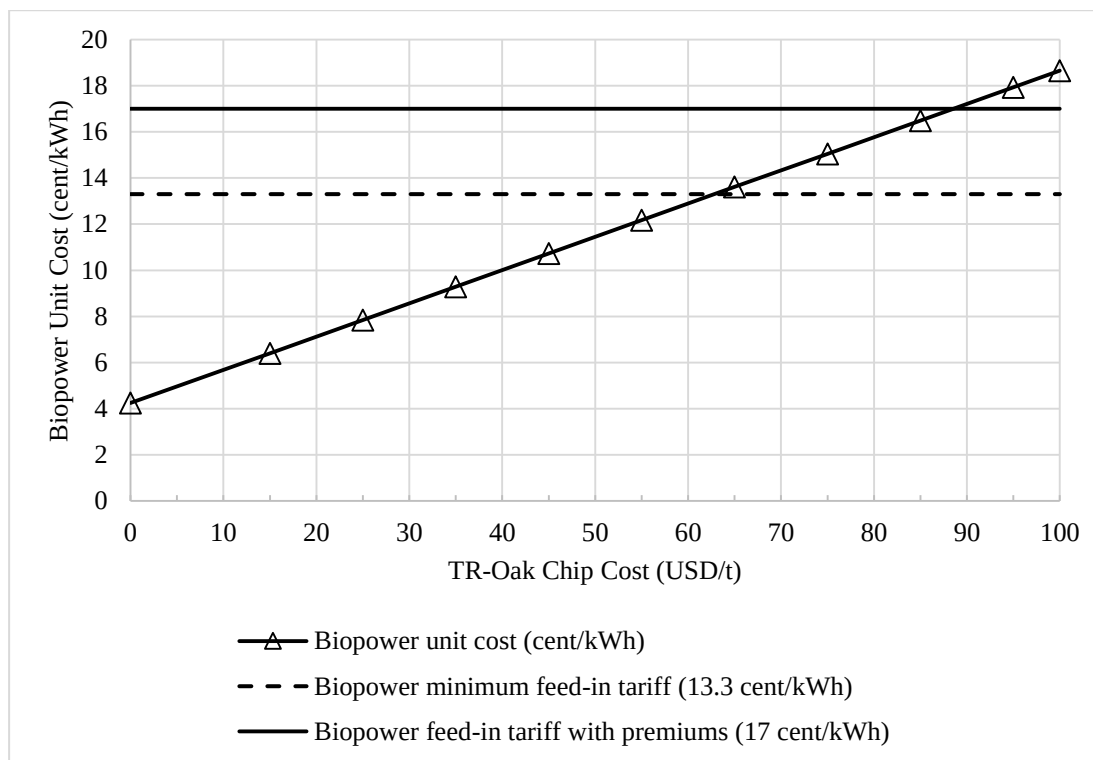


Figure 6.27 : Effect of TR-Oak chip cost on biopower unit cost.

7. CONCLUSIONS AND RECOMMENDATIONS

In this thesis research, an LCA for three simulated cases of TR-Oak chip-fueled, combustion-based in situ CBHBP production was presented using an eco-design approach. The system boundary, which considers sustainable feedstock supply chain activities, started with harvesting of TR-Oak coppices and ended with delivering biopower and bioheat to a grid and a district heating network, respectively. In addition, representative cost estimates for CBHBP production have been provided. It is anticipated that these could facilitate decision making for investors interested in CBHBP technologies in Turkey. In the study, Aspen Plus V8.4 process simulation software and SimaPro V8.1.1.16 LCA software were used together. This thesis research is the first attempt, to our knowledge, to conduct an LCA in coordination with a process simulation, and to introduce an eco-design (green design) approach for sustainable CBHBP production. Ultimately, the CBHBP plants proposed in the thesis are unique, ready, applicable, and investable. They incorporate a biorefinery concept intended to advance the building of a bio-based (low carbon) economy.

The conclusions reached in the study are summarized as follows.

1. According to the comparative midpoint characterization and normalization, and endpoint weighting results, of CS-1, CS-2, and CS-3 (with biopower outputs of 2, 5, and 10 MW_e, respectively), CS-3 has the least environmental impact overall on all of the impact categories valid for all functional units (i.e., 1 kWh biopower, 1 kWh bioheat, and 1 kWh energy production). This is because CS-3 has the highest electrical efficiency, and therefore has the lowest impacts on the environment per kWh energy production. Of course, this conclusion does not apply to annual environmental impacts. Comparative characterization results for the annual biopower production in CS-1, -2, and -3 show that CS-3 has the highest annual environmental impacts because it has the highest scale. Therefore, when deciding on a scale for CBHBP production, there will always be a trade-off between scale and annual environmental impacts (i.e., the higher the scale, the higher electrical efficiency and lower

environmental impacts per kWh energy production, but higher annual environmental impacts and vice versa). Moreover, reducing feedstock demand and strain on the biomass supply chain of the CBHBP plants is another issue to consider.

2. The comparison of characterization results for ACD, ETR, and GW with the literature has shown that they are within the ranges reported. However, it is remarkable that there is such a wide range in the literature values. This is basically due to methodological and subjective choices used in LCA studies, apart from technological and regional differences.
3. With normalization, it has become possible to analyze the relative magnitude of the characterization results obtained. For the case studies considered and among all impact categories, MET had the highest value relative to the normalization factors reported for the world in the year 2000. In terms of MET, the contribution analysis made in this study reveals the importance of background waste treatment processes of the TR-Oak chip supply chain, and of the construction and decommissioning operations.
4. With weighting, based on the relative value-based weighting factors, it has become possible to see the importance of environmental issues in terms of endpoint damage categories, and to express the total environmental load as a single score in Pt. For all cases, relative to the weighting factors considered, human health has the highest importance, followed by resources. The importance of impacts on ecosystems is insignificant relative to those on human health and resources. In terms of single scores, CS-3 has the lowest, and hence shows the lowest environmental load for 1 kWh biopower, 1 kWh bioheat, and 1 kWh energy production, which is not valid for the annual impacts mentioned above in item 1.
5. The relative importance of the different stages in the system boundary has been made understandable via contribution analysis by arranging the LCA results into the stages of the TR-Oak chip supply chain, CBHBP plant operation, TR-Oak ash transport and spreading, and construction and decommissioning. Contribution percentages of each stage to midpoint impact categories have shown that CBHBP operation is the main contributor for PCO (benefit), ACD

and ETR. For PCO, there is an environmental benefit that is mainly a result of NO emissions into air because the CML-IA baseline impact assessment method assumes that NO is good for air quality. The impacts of ACD and ETR are mainly due to SO_x and NO_x emissions into air. This reveals the importance of biomass characterization, furnace design, and operating conditions, which are critical to overcome difficulties in biomass combustion, and to reduce air emissions. In addition, PM-10 emissions into air from CBHBP operation contribute to HT with a minor percentage, 1.4–1.7 %. About 90% of HT is due to the TR-Oak chip supply chain, and construction and decommissioning operations in the system boundary. Among other stages in the system boundary, TR-Oak chip supply chain operations are the major contributors for GW, OD, HT, MET, TET, ADE, and ADF. Construction and decommissioning is the main contributor to FWET. It also makes a significant contribution to MET, HT, and ADE. Exhaust emissions due to fossil fuel use in foreground operations (harvesting, forwarding, chipping, transportation), non-exhaust emissions during transportation (brake wear, tire wear, etc.), emissions from background fossil fuel processes (mining, refining, etc.), emissions during raw materials acquisition for construction (mining and production of elements), and emissions from waste treatment processes for decommissioning, cause the main stressors attributed to the TR-Oak chip supply chain and construction and decommissioning operations.

6. Contribution analysis for endpoint impacts has shown that CBHBP operation is the main factor for human health (about 66%). The adverse impacts on ecosystems (~85%) and resources (~88%) are mainly due to TR-Oak chip supply chain operations. According to the total scores calculated for two weighting perspectives in ReCiPe (World ReCiPe H/H and World ReCiPe H/A), both the CBHBP operation and the TR-Oak chip supply chain are stages that need to be designed with the highest care. One is not more or less important than the other. Evaluating both perspectives together, it is obvious that it is crucial to pay attention to both stages, TR-Oak chip supply chain and CBHBP operation, in the same sense in terms of environmental loads. It is crucial to emphasize that being a renewable source to produce energy does not necessarily mean that its products are sustainable. In the case of CBHBP

implementations, it is very important to design the system in a way to minimize the total environmental load. This research shows that both feedstock supply chain and CBHBP operation have critical importance for minimizing the environmental load and achieving sustainable CBHBP production.

7. The effect of moisture content (for TR-Oak chip feedstock) on GW has shown the significance of transportation, and hence the TR-Oak chip supply chain as the stage most affected by increases in moisture content. Increasing moisture content from 30% to 50% causes about an 18% increase in GW. It is known that moisture content is a feedstock property that can be changed easily by allowing biomass to dry naturally. Therefore, it is essential that uncomminuted TR-Oak logs and residues be stored at roadside in a way to promote rapid drying. This ensures lower transportation cost and more efficient operation at the CBHBP plant.
8. The effect of the excess air ratio and furnace temperature as process conditions on environmental impacts has shown the importance of CBHBP plant operation due to increases in NO_x emissions. Excess air ratio is one of the key parameters for improving biomass combustion, mainly in terms of ETR; then of ACD. The higher increases in ETR (~56%) and ACD (~17%) are observed between the excess air ratios of 1.2 and 1.5. It is crucial that furnace design should ensure biomass combustion at optimum excess air ratio (i.e., not higher than the optimal amount needed). In addition, with increasing furnace temperature, high increases occur in mainly ETR and then ACD. An increase from 900 to 1000 °C increases ETR ~78%; an increase from 1100 to 1200 °C increases ACD ~38%. It is essential to guarantee optimized management of heat distribution in biomass boiler furnace designs.
9. Sensitivity analysis of the LCA results was done for the transport distance between the roadside landing and the CBHBP plant, equipment productivities, CBHBP plant lifetime, and allocation procedure. Significant increases are seen of environmental impacts as the transport distance increases. Therefore, before a supply chain decision is made, it is essential to evaluate specific transport distance alternatives in terms of environmental impacts. Equipment productivity is variable as a result of different field conditions, operators, etc. Equipment productivity should be determined specifically, because decreases

in productivity result in increased impacts, and vice versa. In addition, increasing CBHBP plant lifetime leads to lower impacts overall. However, this conclusion does not consider increased maintenance requirements with increased lifetime of a CBHBP plant. The comparison between the impacts of exergy allocation with the impacts of energy allocation, highlights the importance of transparency in the allocation procedure applied to LCA studies.

10. CBHBP cost estimates presented in this study are all economically meaningful and possible. Cost estimates for all CS show that investment cost per installed biopower is 3803 USD/kW, and that the payback period is about 5 years. Biopower unit costs are (8.7, 9.3, and 9.5) cent/kWh for CS-1, -2, and -3, respectively, without the influence of economies of scale for CBHBP plants. It is important that biopower unit cost calculation considers revenue for the bioheat produced. Without the bioheat sales, the biopower unit cost would be about 17 cent/kWh for all plants, which makes CBHBP implementation impossible under the current framework conditions in Turkey. Sensitivity analyses show that variation of investment cost by $\pm 10\%$ leads to variation of the biopower unit cost by $\pm 5.7\%$, and a variation of TR-Oak chip cost of ± 10 USD/t leads to variation of biopower unit cost by ± 1.441 cent/kWh.
11. Comparison of 1 kWh TR-Oak chip-fueled biopower production with 1 kWh Turkish lignite-fueled power production, in terms of air emissions from combustion shows that TR-Oak chip-fueled biopower production is much more advantageous than Turkish lignite-fueled power production. Compared with lignite power production, biopower production has almost no GW impact because biomass combustion is a carbon neutral process. For human health, the adverse effects of lignite power production are remarkable. The single score for 1 kWh Turkish lignite-fueled power production is 15 times higher than that for 1 kWh TR-Oak chip-fueled biopower production. CO₂, SO_x, and particulate emissions from lignite power production are the predominant factors in the negative impacts on human health.

The recommendations from this thesis study are summarized as follows.

1. LCA is an established approach to evaluate environmental impacts, and hence LCA principles are well known and standardized. However, standards provide

guidelines but still allow freedom to LCA practitioners. Therefore, it should not be forgotten that LCA studies provide results specific to the system considered, and for the particular methodological choices and assumptions made. In this context, LCA studies should be as clear, detailed and transparent as possible, as was done in this thesis research. In this research, methodological choices, assumptions, and inputs were defined using a systematic approach so that other LCA practitioners, regardless of the LCA study they will conduct, can also take the approach provided in this LCA study as a reference.

2. Normalization and weighting were performed in the LCA study to simplify the interpretation of the characterization results; although it is known that they are optional elements to use. In this research, world average values provided in the impact assessment methods were used as references for the normalization and weighting factors because Turkey does not currently have its own factors. Because the references can be chosen freely, normalization and weighting factors can be customized to reflect Turkish conditions. Therefore, for future LCA studies, workers in Turkey should determine Turkish normalization and weighting factors, and use them in future LCA studies to reflect Turkish conditions.
3. The methods presented in this research for TR-Oak chip supply chain and CBHBP plant operations are believed to be the most applied methods in the biomass energy sector in experienced countries, and the most suitable methods to initiate a biomass energy sector in Turkey. Still, it is essential to evaluate specific conditions on site prior to the decision to implement CBHBP. Of course, the capabilities of suppliers always have an effect on decisions. However, in practice, the lowest cost method that meets the needs is not the only criteria for a successful and sustainable CBHBP implementation. Environmental impacts of both TR-Oak chip supply chain and CBHBP operations should be evaluated carefully. In addition, maximum attention should be paid to gaining the assistance of people living nearby.
4. In order to implement the eco-design approach in the study, the parameters considered to have the most important effects on the LCA results were chosen. However, for the eco-design approach in the system boundary, parameters

other than moisture content, excess air ratio, and furnace temperature could also be applied.

5. The inventory for the TR-oak chip supply chain is based on the collection of representative average values from literature, biomass energy companies, previous practices, lessons learned, and the ecoinvent database. These take into account the methods most applied in experienced countries. Future work could involve design of unit processes and preparation of inventories based on Turkish-specific scenarios. The scenarios could also include coppice forest activities, and therefore cultivation processes and wood growth could be taken into consideration.
6. Life cycle optimization (LCO), which combines LCA methodology and optimization tools, is other work that could be applied to this thesis study in the future. With LCO, in consideration of increasing concern about sustainable development; economic, environmental, and social impacts can be considered as equal objectives, and optimal solutions can be identified by revealing the tradeoffs in solutions considering multiple objectives.
7. Cost estimates in the thesis should be regarded as representative costs. They have been calculated based on current commercial CBHBP applications, and therefore they are realistic and can facilitate decision making for investors interested in CBHBP technologies in Turkey. However, they of course, do not represent actual costs for any specific project. Naturally, the costs should be calculated specifically for each project. In addition, the impact of economies of scale for the CBHBP plants considered is an issue to be taken into consideration during a real cost estimate study.
8. For CBHBP implementations, bioheat sale is what makes the CBHBP plants competitive. Therefore, for CBHBP plants, it is necessary that CBHBP investors must be able to sell all available bioheat and get revenue.
9. To estimate costs for CBHBP plants, unfortunately it has not been possible to reach real market prices via leading local and international biomass energy sector suppliers. Instead, SAM [377] was taken as a base, which is a performance and financial model of the “National Renewable Energy Laboratory” in the USA, which is used to facilitate decision making based on

current commercial renewable-based power and/or heat applications. If a national free software similar to the SAM model were available in Turkey, it would have been used in this thesis. It is thought that the development of this kind of model in Turkey would help not only to develop biomass energy but also develop all renewable energy applications in the country, by providing quick information to decision makers.

10. In Turkey, since 2007, studies have been carried out on the utilization of forest biomass sources for energy production. For example, the GDF set up the “Bioenergy Working Group” in 2008. Working group reports were published in 2009 [73,354], and a forest biomass and bioenergy workshop was held in 2010 [382]. With respect to forest biomass sources, the forests in Turkey have quite high residue potential that could be utilized for biopower purposes [73,354]. The first thing is to utilize this potential sustainably to contribute to the national economy. The Turkish government also encourages production and use of energy derived from forest residues, in particular, by establishing power generation plants in rural areas [383]. It is known that forest residues, if not removed, cause serious problems such as wildfires. To prevent these fires, forest maintenance is essential. However, the cost of forest maintenance by removing residues from forests, is quite high. In addition, these residues, even if removed, are not suitable for industrial purposes. Utilization of forest residues for biopower production enhances forest maintenance by reducing wildfire behavior and improving forest health.
11. There is still not a market in Turkey for commercial utilization of forest biomass sources for energy production. The private sector is cautious, basically due to issues regarding continuity and prices of biomass supply. This clearly presents a need for national policy for energy production from forest biomass sources. YEGM under MENR, and GDF under MoFWA, should cooperate to determine the most appropriate ways of using forest biomass in energy production in Turkey. TÜBİTAK, universities, and research institutions should cooperate as well. It is also important to mention that biomass energy is in one of the priority areas of TÜBİTAK [384].
12. Starting from the year 2006, forest management policy in Turkey has been the conversion of all coppice forests to high forests thinking that high forest

management is the most suitable choice for nature [67,68]. However, it is crucial that modern energy forestry should enter into the forest management policy of Turkey as soon as possible, in line with:

- a. GDF Strategic Plan (2017–2021), and GDF Action Plan for Industrial Afforestation (2013–2053) [383]
- b. Turkey National Forestry Program (2004–2023) [385]
- c. The Ministry of Development (MoD) Tenth Development Plan (2014–2018) [386]
- d. Sustainable Forest Management Specialization Commission Report of the Tenth Development Plan [387]
- e. Law on Utilization of Renewable Energy Sources for the Purpose of Generating Electrical Energy (law no. 5346) also known as the Renewable Energy Law (the YEK Law) [25]
- f. MENR 2015–2019 Strategic Plan [91]
- g. NREAP of MENR [92]
- h. MoEU National Climate Change Adaptation Strategy and Action Plan [87]
- i. INDC submitted to the UNFCCC [88] secretariat.

In this context, oak coppice forests, which constitute the vast majority of coppice forests in the country, should be utilized for energy purposes instead of all being transformed to high forests. Modern energy forestry applications, which require methods using modern machinery with intensive management to get the highest wood production per unit area per time, should be initiated in these forests. There is extensive knowledge of this subject in the government, only mobilization is needed to organize and manage modern energy forestry in Turkey.

13. Indeed, for Turkey, oak coppice forests are biomass treasures and readily available sources of biomass for production of biomass energy. Distributed CBHBP plants with technological, social, economic, and environmental contributions should be implemented in areas that are near both these biomass

treasures and the settlements with heat and power demands as soon as possible. Such plants should become widespread in the country. In this regard, forest villages offer the best opportunities for distributed CBHBP deployment in Turkey. In forest villages, wood is often used inefficiently as an energy source for heating and cooking, resulting in a serious threat to forest sustainability. CBHBP deployment near forest villages could avoid excessively heavy utilization of forests and the current serious threat to forest sustainability in the countryside. In addition, distributed CBHBP plants near forest villages would incorporate forest villagers into sustainable forest management practices as among the most important stakeholders for sustainable biopower and bioheat production in Turkey. This approach, uniquely provides on-site environmental, economic, and social benefits to the people living nearby. Also, on-site CBHBP plants would be able to eliminate the risk of fire from high voltage lines passing through the forests. The “Bioenergy Working Group” of GDF has proposed that the Mediterranean and Marmara regions that have the capacity to produce woody biomass in considerable quantities from coppice forest management are the most suitable regions for establishment of distributed CBHBP plants in Turkey [73]. In rural areas, if electricity consumption of a dwelling is assumed to be 200–250 kWh/m, an on-site CBHBP plant with 2000 kW_e installed power would meet the electricity needs of about 5300–6600 dwellings, along with heating and hot water requirements.

14. Industries already using wood as a raw material in Turkey are thinking that modern energy forestry applications to be implemented in Turkey will challenge their wood supply. However, modern energy forestry applications are executed under the roof of an integrated biorefinery concept and forest product supply chain framework, simultaneously providing services to forest products industries (timber, fiberboard, packaging, etc.), pulp and paper industry, and biopower and/or bioheat plants.
15. Co-combustion of TR-Oak chips, primarily with Turkish lignite, by simply mixing and feeding the wood chips into the existing lignite power station boilers offer another option to be considered. In general, biomass can be blended in different proportions ranging from 2 to 25% or more. For co-combustion applications no modifications are typically needed when up to 10%

(proportion) of biomass is used. It is important to emphasize that co-combustion would reduce the amount of lignite used in the plant, thereby providing carbon savings and more favorable environmental impacts compared to plants using lignite only.





REFERENCES

- [1] **IEA** (International Energy Agency). *Statistics search*. Retrieved 04 June 2017, from <http://www.iea.org/statistics/statisticssearch/>
- [2] **IEA** (International Energy Agency). (2016). *Key world energy statistics 2016*. Retrieved 19 May 2017, from <https://www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf>.
- [3] **BP**. (2017). *BP Energy outlook 2035*. Retrieved 19 May 2017, from <http://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2017/bp-energy-outlook-2017.pdf>.
- [4] **UNWCED** (The United Nations World Commission on Environment and Development). (1987). *Report of the World Commission on Environment and Development: Our common future*. Geneva, Switzerland. Retrieved 04 June 2017, from <http://www.un-documents.net/our-common-future.pdf>.
- [5] **IEA** (International Energy Agency). (2016). *Energy, climate change and environment: 2016 insights*. Retrieved 03 June 2017, from <https://www.iea.org/publications/freepublications/publication/ECCE2016.pdf>.
- [6] **IPCC** (Intergovernmental Panel on Climate Change). (2013). *Climate change 2013: The physical science basis, working group I contribution to the fifth assessment report*. Switzerland. Retrieved 04 June 2017, from http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf.
- [7] **REN21** (Renewable Energy Policy Network for the 21st Century). (2016). *Renewables 2016 global status report*. Paris. Retrieved 04 June 2017, from http://www.ren21.net/wp-content/uploads/2016/06/GSR_2016_Full_Report_REN21.pdf.
- [8] **Isler, A., & Karaosmanoglu, F.** (2010). Biofuels in Turkey. In B. Karaman, F. Adaman, & G. Ozertan (Eds.), *Rethinking structural reform in Turkish agriculture: beyond the world bank's strategy* (pp. 319-340). New York: Nova Science Publishers, Inc.
- [9] **Seveda, M. S., Rathore, N. S., & Kumar, V.** (2011). Biomass as a source of energy. In A. F. Zobaa & R. C. Bansal (Eds.), *Handbook of renewable energy technology* (pp. 323-344). Singapore: World Scientific.
- [10] **Strezov, V.** (2014). Properties of biomass fuels. In V. Strezov & T. J. Evans (Eds.), *Biomass processing technologies*. USA: CRC Press.
- [11] **McKendry, P.** (2002). Energy production from biomass (part 1): overview of biomass. *BioresourceTechnology*, 83, 37-46.

- [12] **Saracoglu, N.** (2010). The biomass potential of Turkey for energy production: Part I. *Energy Sources, Part B: Economics, Planning, and Policy*, 5(3), 272-278. doi: 10.1080/15567240802532981
- [13] **Saracoglu, N.** (2009). Fuel wood as a source of energy in Turkey. *Energy Sources, Part B: Economics, Planning, and Policy*, 4(4), 396-406. doi: 10.1080/15567240701758893
- [14] **Abbasi, T., & Abbasi, S. A.** (2010). Biomass energy and the environmental impacts associated with its production and utilization. *Renewable and Sustainable Energy Reviews*, 14(3), 919-937. doi: 10.1016/j.rser.2009.11.006
- [15] **WBA** (World Bioenergy Association). (2016). *WBA global bioenergy statistics 2016*. Retrieved 04 June 2017, from <http://www.indiaenvironmentportal.org.in/files/file/WBA%20GBS%202016.pdf>.
- [16] **WEC** (World Energy Council). (2016). *World energy resources 2016*. Retrieved 04 June 2017, from <https://www.worldenergy.org/publications/2016/world-energy-resources-2016/>.
- [17] **IEA** (International Energy Agency). (2009). *Biorefineries: adding value to the sustainable utilisation of biomass*. Retrieved 03 June 2017, from <http://www.ieabioenergy.com/wp-content/uploads/2013/10/Task-42-Booklet.pdf>.
- [18] **IEA** (International Energy Agency). (2014). *IEA Bioenergy Task 42 biorefining: Sustainable and synergetic processing of biomass into marketable food & feed ingredients, products (chemicals, materials) and energy (fuels, power, heat)*. Retrieved 04 June 2017, from http://www.iea-bioenergy.task42-biorefineries.com/upload_mm/2/2/f/594a4711-8520-4a74-badf-798b7b87bd55_11901%20IEA%20Bioenergy%20Task42_LR.pdf.
- [19] **ETKB** (T.C. Enerji ve Tabii Kaynaklar Bakanlığı). *Denge tablosu 2015*. Retrieved 24 November 2016, from <http://www.eigm.gov.tr/tr-TR/Denge-Tablolari/Denge-Tablolari>.
- [20] **Saracoglu, N.** (2010). The biomass potential of Turkey for energy production: Part II. *Energy Sources, Part B: Economics, Planning, and Policy*, 5(4), 384-389. doi: 10.1080/15567240903384340
- [21] **YEGM** (Yenilenebilir Enerji Genel Müdürlüğü). *Türkiye biyokütle enerjisi potansiyeli atlası (BEPA): T.C. Enerji ve Tabii Kaynaklar Bakanlığı*. Retrieved 27 November 2016, from <http://bepa.yegm.gov.tr/>.
- [22] **Gokcol, C., Dursun, B., Alboyaci, B., & Sunan, E.** (2009). Importance of biomass energy as alternative to other sources in Turkey. *Energy Policy*, 37(2), 424-431. doi: 10.1016/j.enpol.2008.09.057
- [23] **Benli, H.** (2013). Potential of renewable energy in electrical energy production and sustainable energy development of Turkey: Performance and policies. *Renewable Energy*, 50, 33-46. doi: 10.1016/j.renene.2012.06.051

- [24] **Baris, K., & Kucukali, S.** (2012). Availability of renewable energy sources in Turkey: Current situation, potential, government policies and the EU perspective. *Energy Policy*, 42, 377-391. doi: 10.1016/j.enpol.2011.12.002
- [25] **Yenilenebilir enerji kaynaklarının elektrik enerjisi üretimi amaçlı kullanımına ilişkin kanun (no. 5346).** (2005): *Türkiye Cumhuriyeti Resmi Gazete*, 25819, 18 May 2005. Retrieved 22 May 2017, from http://www.eie.gov.tr/yenilenebilir/y_mevzuat.aspx
- [26] **REN21** (Renewable Energy Policy Network for the 21st Century). (2015). *Renewables 2015 global status report*. Paris. Retrieved 04 June 2017, from http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf.
- [27] **Eksi, G., & Karaosmanoglu, F.** (2017). Combined bioheat and biopower: A technology review and an assessment for Turkey. *Renewable and Sustainable Energy Reviews*, 73, 1313-1332. doi: 10.1016/j.rser.2017.01.093
- [28] **Eksi, G., & Karaosmanoglu, F.** (2016). Combined bioheat and biopower production and forest biomass *In Proceedings of the 10th International Clean Energy Symposium* (pp. 120-131). Istanbul, Turkey, 24-26 October.
- [29] **IEA** (International Energy Agency). (2007). *Biomass for power generation and CHP*. Retrieved 01 December 2016, from <https://www.iea.org/publications/freepublications/publication/essentials3.pdf>.
- [30] **González, A., Riba, J.-R., Puig, R., & Navarro, P.** (2015). Review of micro- and small-scale technologies to produce electricity and heat from Mediterranean forests' wood chips. *Renewable and Sustainable Energy Reviews*, 43, 143-155. doi: 10.1016/j.rser.2014.11.013
- [31] **Sayigh, A., & Roddy, D. J.** (Eds.). (2012). *Comprehensive renewable energy - Volume 5: Biomass and biofuel production*. USA: Elsevier.
- [32] **Salomón, M., Savola, T., Martin, A., Fogelholm, C.-J., & Fransson, T.** (2011). Small-scale biomass CHP plants in Sweden and Finland. *Renewable and Sustainable Energy Reviews*, 15(9), 4451-4465. doi: 10.1016/j.rser.2011.07.106
- [33] **Kirjavainen M, S. K., Savola T, Salomón M, Alakangas E.** (2004). *Small-scale biomass CHP technologies: situation in Finland, Denmark and Sweden - OPET report 12*: European Commission, Directorate-General for Energy and Transport. Retrieved 04 December 2016, from http://www.opet-chp.net/download/wp2/small_scale_biomass_chp_technologies.pdf.
- [34] **Jenssen, T., König, A., & Eltrop, L.** (2014). Bioenergy villages in Germany: Bringing a low carbon energy supply for rural areas into practice. *Renewable Energy*, 61, 74-80. doi: 10.1016/j.renene.2012.08.014
- [35] **Obernberger, I., Hammerschmid, A., & Forstinger, M.** (2015). *IEA Bioenergy Task 32 project: Techno-economic evaluation of selected decentralised CHP applications based on biomass combustion with steam turbine and ORC processes*. Austria: BIOS BIOENERGIESYSTEME GmbH

Research, Development and Design of Plants for Heat and Power Production from Biomass. Retrieved 04 December 2016, from https://nachhaltigwirtschaften.at/resources/iea_pdf/reports/iea_bioenergy_task32_tea_chp_applications_2015.pdf.

- [36] **Salomón, M., Savola, T., Kirjavainen, M., Martin, A. R., & Fogelholm, C.-J.** (2002). Distributed combined heat and power generation with small-scale biomass plants: State of the art review *In Proceedings of the Second International Symposium on Distributed Generation: Power System and Market Aspects*. Stockholm, Sweden, 2-4 October.
- [37] **ISO** (International Organization for Standardization). (2006). *Environmental management - Life Cycle Assessment - Principles and framework (BS EN ISO 14040)*. London, UK: ISO, British Standards Institute.
- [38] **ISO** (International Organization for Standardization). (2006). *Environmental management - Life Cycle Assessment - Requirements and guidelines (BS EN ISO 14044)*. London, UK: ISO, British Standards Institute.
- [39] **TSE** (Turkish Standards Institution). (2007). *Environmental management - Life Cycle Assessment - Principles and framework (TS EN ISO 14040)*. Ankara: TSE.
- [40] **TSE** (Turkish Standards Institution). (2007). *Environmental management - Life Cycle Assessment - Requirements and guidelines (TS EN ISO 14044)*. Ankara: TSE.
- [41] **Ar, F. F., Karaosmanoglu, F., Koc, A. A., Acaroglu, M., Mutlu, S. F., Sarsu, F., . . . Aygun, O. F.** (2010). *Biyoyakıtlar*. Ankara: WECTNC (World Energy Council Turkish National Committee).
- [42] **Ed de Jong, G. J.** (2015). Biorefinery Concepts in Comparison to Petrochemical Refineries. In R. H. Ashok Pandey, Mohammad Taherzadeh, K. Madhavan Nampoothiri, Christian Larroche (Ed.), *Industrial Biorefineries and White Biotechnology*. USA: Elsevier
- [43] **R. Van Ree, J. S., R. Bakker, R. Blaauw, R. Zwart, B. Van Der Drift.** (2011). Biofuel-driven biorefineries for the co-production of transportation fuels and added-value products. In J. C. Rafael Luque, James Clark (Ed.), *Handbook of biofuels production - processes and technologies*. UK: Woodhead Publishing Limited.
- [44] **Rafael Luque, J. C., James Clark.** (2011). Introduction: an overview of biofuels and production technologies. In J. C. Rafael Luque, James Clark (Ed.), *Handbook of biofuels production - processes and technologies*. UK: Woodhead Publishing Limited.
- [45] **Donald L. Van Dyne, M. G. B., and L. Davis Clements.** (1999). A Strategy for Returning Agriculture and Rural America to Long-Term Full Employment Using Biomass Refineries. In J. Janick (Ed.), *Perspectives on new crops and new uses*. Alexandria, VA.: ASHS Press.
- [46] **James H. Clark, F. E. I. D.** (2008). The Biorefinery Concept – An Integrated Approach. In J. H. Clark & F. E. I. Deswarte (Eds.), *Introduction to chemicals from biomass*. Chichester, UK: Wiley.

- [47] **BMELV.** (2012). *Biorefineries roadmap*. Berlin: Federal Ministry of Food, Agriculture and Consumer Protection (BMELV). Retrieved 24 November 2016, from https://www.bmbf.de/pub/BMBF_Roadmap-Bioraffinerien_en_bf.pdf.
- [48] **IEA** (International Energy Agency). *Bioenergy Task 42 Biorefining*. Retrieved 04 June 2017, from <http://www.iea-bioenergy.task42-biorefineries.com/en/ieabiorefinery.htm>
- [49] **USDA** (U.S. Department of Agriculture - The National Institute of Food and Agriculture). (2012). *Introduction to bioenergy-Bioenergy and sustainability course series*. Retrieved 30 July 2015, from <http://fyi.uwex.edu/biotrainingcenter/>.
- [50] **Karaosmanoğlu, F.** (2006). Biyok yakıt teknolojisi ve İTÜ araştırmaları *In Proceedings of ENKÜS 2006 İTÜ Enerji Çalıştayı ve Sergisi* (pp. 110-125). Istanbul, Turkey, 22-23 June.
- [51] **Forest Research** (Biomass Energy Centre, UK). *Biomass energy resources*. Retrieved 04 June 2017, from http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,15174&_dad=portal&_schema=PORTAL
- [52] **Rosillo-Calle, F., Groot, P., Hemstock, L. S., & Woods, J.** (2007). *Biomass assessment handbook, bioenergy for a sustainable environment*. London: Earthscan.
- [53] **Sowlati, T.** (2016). Modeling of forest and wood residues supply chains for bioenergy and biofuel production. In J. B. Holm-Nielsen & E. A. Ehimen (Eds.), *Biomass supply chains for bioenergy and biorefining* (pp. 167–190): Woodhead Publishing, Elsevier.
- [54] **Dominik Röser, A. A., Inge Stupak, Karri Pasanen.** (2008). Forest energy resources and potentials. In A. A. Dominik Röser, Karsten Raulund-Rasmussen, Inge Stupak (Ed.), *Sustainable use of forest biomass for energy : a synthesis with focus on the Baltic and Nordic region* (pp. 9-28). Dordrecht, The Netherlands: Springer.
- [55] **Ecoprog.** (2011). *Biomass to Energy, The World Market for Biomass Power Plants 2011/2012*. Retrieved 04 June 2017, from <http://www.ecoprog.com/> and http://neec.no/wp-content/uploads/studie_biomass_power_plants.pdf.
- [56] **EPA** (U.S. Environmental Protection Agency). (2007). *Biomass combined heat and power catalog of technologies*. USA: Combined Heat and Power Partnership. Retrieved 04 June 2017, from https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_v.1.1.pdf.
- [57] **Leinonen, A.** (2004). *Harvesting technology of forest residues for fuel in the USA and Finland* (Vol. VTT research notes 2229): VTT Technical Research Centre of Finland. Retrieved 04 June 2017, from <http://www.vtt.fi/inf/pdf/tiedotteet/2004/T2229.pdf>.
- [58] **OGM** (Orman Genel Müdürlüğü). (2015). *Türkiye orman varlığı: T. C. Orman ve Su İşleri Bakanlığı*. Retrieved 10 May 2017, from <https://www.ogm.gov.tr/ekutuphane/Yayinlar/T%C3%BCrkiye%20Orman%20Varl%C4%B1%C4%9F%C4%B1-2016-2017.pdf>.

- [59] **OGM** (Orman Genel Müdürlüğü). (2015). *Ormancılık istatistikleri*: T. C. Orman ve Su İşleri Bakanlığı. Retrieved 10 May 2017, from <https://www.ogm.gov.tr/ekutuphane/Istatistikler/Forms/AllItems.aspx>.
- [60] **Kayacan, B., Zengin, H., & Kadiogullari, A. I.** (2016). Turkey. In C. Vidal, I. Alberdi, L. Hernández, & J. Redmond (Eds.), *National forest inventories: Assessment of wood availability and use* (pp. 807-828). Switzerland: Springer.
- [61] **OGM** (Orman Genel Müdürlüğü). (2013). *Orman atlası*. Ankara: Orman ve Su İşleri Bakanlığı. Retrieved 10 May 2017, from <https://www.ogm.gov.tr/ekutuphane/Yayinlar/Orman%20Atlasi.pdf>.
- [62] **OGM** (Orman Genel Müdürlüğü). (2016). *Oduna dayalı orman ürünlerinin üretim ve pazarlama faaliyetleri*. Ankara: İşletme ve Pazarlama Dairesi Başkanlığı. Retrieved 10 May 2017, from <https://www.ogm.gov.tr/ekutuphane/EgitimDokumanlari/Forms/AllItems.aspx>.
- [63] **Atmiş, E., & Çil, A.** (2013). Sustainable forestry in Turkey. *Journal of Sustainable Forestry*, 32(4), 354-364. doi: 10.1080/10549811.2013.767210
- [64] **Taşkıran, I.** (2009). Orman Artıklarının Enerji Dönüşümünde Kullanılması ve Gazlaştırıcılar *In Proceedings of the International Waste to Energy Symposium (IWES 2)* (pp. 107-112). Istanbul, Turkey, 12-13 November.
- [65] **Öztürk, S.** (2013). *Türkiye meşeleri teşhis ve tanı kılavuzu*: T. C. Orman ve Su İşleri Bakanlığı, Orman Genel Müdürlüğü, Orman Zararlılarıyla Mücadele Dairesi Başkanlığı.
- [66] **Yaltırık, F.** (1984). *Türkiye meşeleri teşhis kılavuzu*. İstanbul: Yenilik Basımevi.
- [67] **OGM** (Orman Genel Müdürlüğü). (2014). *Baltalık ormanlarının koruya dönüştürülmesi eylem planı (2006-2015)*. Retrieved 10 May 2017, from <https://www.ogm.gov.tr/ekutuphane/Yayinlar/>.
- [68] **OGM** (Orman Genel Müdürlüğü). (2006). *Meşe ormanlarının rehabilitasyonu eylem planı (2006-2015)*. Retrieved 10 May 2017, from <https://www.ogm.gov.tr/ekutuphane/Yayinlar/>.
- [69] **Şahin, A.** (2014). Marmara Bölgesi'ndeki meşe ormanları ve koruya tahvil (dönüştürme) uygulamaları-2. *Orman ve Av, September/October*(5), 8-23.
- [70] **Şahin, A.** (2014). *Orman Genel Müdürlüğü'nün 23.12.2013 Tarih ve 612436 Sayılı Olur'ları ile Oluşturulan Komisyonun Çalışması Sonucunda Hazırlanan Marmara Bölgesi Koruya Dönüştürme Raporu*: Orman Genel Müdürlüğü, Marmara Ormancılık Araştırma Enstitüsü Müdürlüğü, Orman Amenajmanı ve Hasılat Araştırmaları Başmühendisliği.
- [71] **Meeting minutes**: 23 May 2014, 04 July 2014, 16 December 2015, 21 January 2016, 07 June 2016. Marmara Ormancılık Araştırma Enstitüsü, Orman Genel Müdürlüğü, İstanbul.

- [72] **Bekiroğlu, S., Atıcı, E., Özer, G. Ö., Yadigar, S., & Uslu, B.** (2013). Baltalıkların oluşumu ve baltalıkların koruya dönüştürülmesinin sosyoekonomik boyutu (İstanbul örneği). *Journal of the Faculty of Forestry, Istanbul University*, 63(2), 61-70.
- [73] **OGM** (Orman Genel Müdürlüğü). (2009). *Yenilenebilir enerjide orman biyokütlesinin durumu - Biyoenerji çalışma grubu raporu*. Ankara, Dumat Ofset. Retrieved 30 November 2016, from <http://www.ogm.gov.tr/ekutuphane/Yayinlar/Yenilenebilir%20Enerjide%20Orman%20Biyok%C3%BCtlesinin%20Durumu.pdf>.
- [74] **Karayilmazlar, S., Saracoglu, N., Cabuk, Y., & Kurt, R.** (2011). Biyokütlenin Türkiye'de enerji üretiminde değerlendirilmesi. *Journal of Bartın Faculty of Forestry*, 13(19), 63-75.
- [75] **Turker, M. F., & Ayaz, H.** (1997). Energy forestry and fuel briquettes as an alternative to illegal fuel wood consumption as an obstacle to sustainable forestry *In Proceedings of the XI. World Forestry Congress* (Vol. 3, pp. 313). Antalya, Turkey, 13-22 October.
- [76] **Saracoglu, N.** (1998). Turkish energy forestry *In Proceedings of UN-ECE Timber Committee Workshop on Recycling, Energy and Market Interactions* (pp. 90-95). Istanbul, Turkey, 3-6 November
- [77] **ENAT** (Endüstriyel Ağaç Tarımı Sanayi ve Ticaret A.Ş.). Retrieved 18 May 2017, from <http://enat.com.tr/>
- [78] **TEMA** (Türkiye Erozyonla Mücadele, Ağaçlandırma ve Doğal Varlıkları Koruma Vakfı). Retrieved 18 May 2017, from http://www.tema.org.tr/web_14966-2_1/index.aspx
- [79] **TÜİK** (Türkiye İstatistik Kurumu). (2016). *İstatistiklerle Türkiye - Turkey in statistics 2015*. Ankara. Retrieved 30 November 2016, from <http://www.tuik.gov.tr>.
- [80] **ISPAT** (Investment Support and Promotion Agency of Turkey). Retrieved 28 November 2016, from <http://www.invest.gov.tr/en-US/sectors/Pages/Energy.aspx>
- [81] **ETKB** (T. C. Enerji ve Tabii Kaynaklar Bakanlığı). (2016). *Dünya ve ülkemiz enerji ve tabii kaynaklar görünümü: Strateji Geliştirme Başkanlığı*. Retrieved 25 November 2016, from <http://www.enerji.gov.tr/tr-TR/Enerji-ve-Tabii-Kaynaklar-Gorunumleri>.
- [82] **Bölük, G., & Koç, A. A.** (2013). The implications of biofuel policy in Turkey. *International Journal of Energy Economics and Policy*, 3(Special Issue, 2013), 14-22.
- [83] **Keleş, S., & Bilgen, S.** (2012). Renewable energy sources in Turkey for climate change mitigation and energy sustainability. *Renewable and Sustainable Energy Reviews*, 16(7), 5199-5206. doi: 10.1016/j.rser.2012.05.026
- [84] **Toklu, E.** (2013). Overview of potential and utilization of renewable energy sources in Turkey. *Renewable Energy*, 50, 456-463. doi: 10.1016/j.renene.2012.06.035

- [85] **Yuksel, I., & Kaygusuz, K.** (2011). Renewable energy sources for clean and sustainable energy policies in Turkey. *Renewable and Sustainable Energy Reviews*, 15(8), 4132-4144. doi: 10.1016/j.rser.2011.07.007
- [86] **TÜİK** (Türkiye İstatistik Kurumu). (2016). *Seragazi Emisyon Envanteri 2014*. Retrieved 28 November 2016, from <http://www.tuik.gov.tr/PreHaberBultenleri.do?id=21582#>.
- [87] **ÇSB** (T. C. Çevre ve Şehircilik Bakanlığı). (2012). *Türkiye'nin iklim değişikliği uyum stratejisi ve eylem planı (2011-2023)*. Ankara. Retrieved 04 December 2016, from [http://www.csb.gov.tr/db/iklim/editordosya/uyum_stratejisi_eylem_plani_EN\(2\).pdf](http://www.csb.gov.tr/db/iklim/editordosya/uyum_stratejisi_eylem_plani_EN(2).pdf).
- [88] **The Republic of Turkey intended nationally determined contribution (INDC)**. Retrieved 01 May 2016, from http://www4.unfccc.int/submissions/INDC/Published%20Documents/Turkey/1/The_INDC_of_TURKEY_v.15.19.30.pdf
- [89] **Şekercioğlu, S., & Yılmaz, M.** (2012). Renewable energy perspectives in the frame of Turkey's and the EU's energy policies. *Energy Conversion and Management*, 63, 233-238. doi: 10.1016/j.enconman.2012.01.039
- [90] **ETKB** (T. C. Enerji ve Tabii Kaynaklar Bakanlığı). (2010). *2010-2014 Stratejik plan*.
- [91] **ETKB** (T. C. Enerji ve Tabii Kaynaklar Bakanlığı). (2014). *2015-2019 Stratejik plan*. Retrieved 29 May 2017, from http://sp.enerji.gov.tr/ETKB_2015_2019_Stratejik_Planı.pdf.
- [92] **ETKB** (T. C. Enerji ve Tabii Kaynaklar Bakanlığı). (2014). *Türkiye ulusal yenilenebilir enerji eylem planı 2013-2023*. Retrieved 04 December 2016, from http://www.eie.gov.tr/duyurular_haberler/document/National_Renewable_Energy_Action_For_Turkey.PDF.
- [93] **EPDK** (Enerji Piyasası Düzenleme Kurumu). Retrieved 30 November 2016, from <http://epdk.org.tr/TR/Dokumanlar/Elektrik/Lisanslar>
- [94] **TEİAŞ** (Türkiye Elektrik İletim A.Ş.). *Kurulu güç*. Retrieved 28 November 2016, from <http://www.teias.gov.tr/YukTevziRaporlari.aspx>
- [95] **TEİAŞ** (Türkiye Elektrik İletim A.Ş.). *Annual development of Turkey's installed capacity by primary energy resources (1984-2005) and (2006-2015)*. Retrieved 30 November 2016, from <http://www.teias.gov.tr/T%C3%BCrkiyeElektrik%C4%B0statistikleri/istatistik2015/istatistik2015.htm>
- [96] **TEDAŞ** (Türkiye Elektrik Dağıtım A.Ş.). *Lisanssız Elektrik Üretimi*. Retrieved 30 November 2016, from http://www.tedas.gov.tr/#!/tedas_lisanssizelektrikuretimi
- [97] **Horlock, J. H.** (1997). *Cogeneration - Combined heat and power (CHP), thermodynamics and economics*. Florida, USA: Krieger Publishing Company.
- [98] **Raj, N. T., Iniyar, S., & Goic, R.** (2011). A review of renewable energy based cogeneration technologies. *Renewable and Sustainable Energy Reviews*, 15(8), 3640-3648. doi: 10.1016/j.rser.2011.06.003

- [99] **Kucinskas, V., Jasinskas, A., & Jotautiene, E.** (2014). Analysis and environmental assessment of biomass and biofuels usage possibilities. *Journal of Biomass to Biofuel*. doi: 10.11159/jbb.2014.004
- [100] **Wong, J. B., & Kovacic, J. M.** (2009). Cogeneration and distributed generation. In S. Doty & W. C. Turner (Eds.), *Energy management handbook*. Lilburn, GA: Fairmont Press.
- [101] **Al-Shemmeri, T. T.** (2011). Thermodynamics, performance analysis and computational modelling of small and micro combined heat and power (CHP) systems. In R. Beith (Ed.), *Small and micro combined heat and power (CHP) systems*. UK: Woodhead Publishing.
- [102] **Patel, M., Zhang, X., & Kumar, A.** (2016). Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. *Renewable and Sustainable Energy Reviews*, 53, 1486-1499. doi: 10.1016/j.rser.2015.09.070
- [103] **Kolanowski, B. F.** (2008). *Small-scale cogeneration handbook* (Third ed.). USA: CRC Press.
- [104] **BIOCOGEN** (Biomass Cogeneration Network). Retrieved 26 November 2016, from <http://www.cres.gr/biocogen/>
- [105] **Tillman, D. A., & Jamison, R. L.** (1982). Cogeneration with wood fuels: A review. *Fuel Processing Technology*, 5, 169-181.
- [106] **Bianchi, M., Branchini, L., De Pascale, A., & Peretto, A.** (2014). Application of environmental performance assessment of CHP systems with local and global approaches. *Applied Energy*, 130, 774-782. doi: 10.1016/j.apenergy.2014.04.017
- [107] **Ackermann, T., Andersson, G., & Soder, L.** (2001). Distributed generation: a definition. *Electric Power Systems Research*, 57, 195-204.
- [108] **Lopes, J. A. P., Hatziaargyriou, N., Mutale, J., Djapic, P., & Jenkins, N.** (2007). Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. *Electric Power Systems Research*, 77(9), 1189-1203. doi: 10.1016/j.epsr.2006.08.016
- [109] **Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R., & D'haeseleer, W.** (2005). Distributed generation: definition, benefits and issues. *Energy Policy*, 33(6), 787-798. doi: 10.1016/j.enpol.2003.10.004
- [110] **IEA** (International Energy Agency). (2002). *Distributed generation in liberalised electricity markets*. Retrieved 04 December 2016, from <http://library.umac.mo/ebooks/b13623175.pdf>.
- [111] **Shustrova, T., Karpman, E., Ndereba, J., & Stoyanov, S.** (2013). *Biomass combined heat and power in the United Kingdom*: Technische Hochschule Nürnberg Georg Simon Ohm. Retrieved 01 December 2016, from https://www.th-nuernberg.de/fileadmin/Fachbereiche/bw/studienschwerpunkte/international_business/Master/CAIFD/SeminarPapers/Biomass_UK_Seminar_Paper.pdf.

- [112] **Bazmi, A. A., Zahedi, G., & Hashim, H.** (2015). Design of decentralized biopower generation and distribution system for developing countries. *Journal of Cleaner Production*, 86, 209-220. doi: 10.1016/j.jclepro.2014.08.084
- [113] **C2ES** (The Center for Climate and Energy Solutions). *Cogeneration/Combined Heat and Power (CHP)*. Retrieved 26 November 2016, from <http://www.c2es.org/technology/factsheet/CogenerationCHP>
- [114] **EPA** (US Environmental Protection Agency). *Combined Heat and Power (CHP) Partnership*. Retrieved 26 November 2016, from <https://www.epa.gov/chp>
- [115] **IEA** (International Energy Agency). *Combined Heat and Power (CHP)*. Retrieved 26 November 2016, from <https://www.iea.org/chp/>
- [116] **EU** (European Union). (2004). *Directive 2004/8/EC of the European Parliament and of the Council on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC*. Official Journal of the European Union. Retrieved 04 December 2016, from <http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32004L0008&qid=1480165097966&from=en>.
- [117] **EU** (European Union). *Climate Action*. Retrieved 26 November 2016, from http://ec.europa.eu/clima/policies/strategies/index_en.htm
- [118] **TÜRKOTED** (Türkiye Kojenerasyon ve Temiz Enerji Teknolojileri Derneği). (2016). *2014 Türkiye Kojenerasyon Tesisleri Envanteri*. Istanbul.
- [119] **AEBIOM** (The European Biomass Association). (2016). *Statistical report 2016 European bioenergy outlook: Key findings*. Retrieved 05 November 2016, from <http://www.aebiom.org/statistical-report-2016/>.
- [120] **AEBIOM** (The European Biomass Association). (2015). *Statistical report 2015 European bioenergy outlook: Key findings*. Retrieved 05 November 2015, from http://www.aebiom.org/wp-content/uploads/2015/10/AEBIOM-Statistical-Report-2015_Key-Findings1.pdf.
- [121] **TÜRKOTED** (Türkiye Kojenerasyon ve Temiz Enerji Teknolojileri Derneği). Retrieved 26 November 2016, from <http://turkoted.org/>
- [122] **Dong, L., Liu, H., & Riffat, S.** (2009). Development of small-scale and micro-scale biomass-fuelled CHP systems - A literature review. *Applied Thermal Engineering*, 29(11-12), 2119-2126. doi: 10.1016/j.applthermaleng.2008.12.004
- [123] **IEA** (International Energy Agency). (2012). *Technology roadmap, bioenergy for heat and power*. France. Retrieved 01 December 2016, from <http://www.iea.org/publications/freepublications/publication/technology-roadmap-bioenergy-for-heat-and-power-.html>.
- [124] **Erol, M., Haykiri-Acma, H., & Küçükbayrak, S.** (2010). Calorific value estimation of biomass from their proximate analyses data. *Renewable Energy*, 35(1), 170-173. doi: 10.1016/j.renene.2009.05.008
- [125] **Guo, M., Song, W., & Buhain, J.** (2015). Bioenergy and biofuels: History, status, and perspective. *Renewable and Sustainable Energy Reviews*, 42, 712-725. doi: 10.1016/j.rser.2014.10.013

- [126] **CRES** (Centre for Renewable Energy Sources). (2003). *Solid biomass cogeneration.: Biomass cogeneration network (BIOCOGEN)*. Retrieved 04 December 2016, from <http://www.cres.gr/biocogen/pdf/solid%20biomass.pdf>.
- [127] **Steubing, B., Zah, R., & Ludwig, C.** (2012). Heat, electricity, or transportation? The optimal use of residual and waste biomass in Europe from an environmental perspective. *Environ Sci Technol*, 46(1), 164-171. doi: 10.1021/es202154k
- [128] **Becher, S., & Kaltschmitt, M.** (1994). Logistic chains of solid biomass- Classification and chain analysis *In Proceedings of the 8th European Biomass Conference, Biomass for energy, environment, agriculture and industry* (1st ed., Vol. 1, pp. 401–408). Vienna, Austria, 3-5 October.
- [129] **Larkin, S., Ramage, J., & Scurlock, J.** (2004). Bioenergy. In G. Boyle (Ed.), *Renewable Energy*. Oxford ; New York: Oxford University Press.
- [130] **Sokhansanj, S., & Hess, J. R.** (2009). *Biofuels - Methods and protocols* (J. R. Mielenz Ed.). USA: Humana Press.
- [131] **Holm-Nielsen, J. B., & Ehimen, E. A.** (Eds.). (2016). *Biomass supply chains for bioenergy and biorefining*: Woodhead Publishing.
- [132] **Wolfsmayr, U. J., & Rauch, P.** (2014). The primary forest fuel supply chain: A literature review. *Biomass and Bioenergy*, 60, 203-221. doi: 10.1016/j.biombioe.2013.10.025
- [133] **Murphy, F., Devlin, G., & McDonnell, K.** (2014). Forest biomass supply chains in Ireland: A life cycle assessment of GHG emissions and primary energy balances. *Applied Energy*, 116, 1-8. doi: 10.1016/j.apenergy.2013.11.041
- [134] **Thakur, A., Canter, C. E., & Kumar, A.** (2014). Life-cycle energy and emission analysis of power generation from forest biomass. *Applied Energy*, 128, 246-253. doi: 10.1016/j.apenergy.2014.04.085
- [135] **Lindholm, E. L., Berg, S., & Hansson, P. A.** (2010). Energy efficiency and the environmental impact of harvesting stumps and logging residues. *European Journal of Forest Research*, 129(6), 1223-1235. doi: 10.1007/s10342-010-0412-1
- [136] **Whittaker, C., Mortimer, N., Murphy, R., & Matthews, R.** (2011). Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. *Biomass and Bioenergy*, 35(11), 4581-4594. doi: 10.1016/j.biombioe.2011.07.001
- [137] **Jäppinen, E., Korpinen, O.-J., Laitila, J., & Ranta, T.** (2014). Greenhouse gas emissions of forest bioenergy supply and utilization in Finland. *Renewable and Sustainable Energy Reviews*, 29, 369-382. doi: 10.1016/j.rser.2013.08.101
- [138] **Eriksson, L., & Gustavsson, L.** (2010). Comparative analysis of wood chips and bundles – Costs, carbon dioxide emissions, dry-matter losses and allergic reactions. *Biomass and Bioenergy*, 34(1), 82-90. doi: 10.1016/j.biombioe.2009.10.002

- [139] **Eriksson, L., & Gustavsson, L.** (2010). Costs, CO₂- and primary energy balances of forest-fuel recovery systems at different forest productivity. *Biomass and Bioenergy*, 34(5), 610-619. doi: 10.1016/j.biombioe.2010.01.003
- [140] **Gómez, A., Rodrigues, M., Montañés, C., Dopazo, C., & Fueyo, N.** (2010). The potential for electricity generation from crop and forestry residues in Spain. *Biomass and Bioenergy*, 34(5), 703-719. doi: 10.1016/j.biombioe.2010.01.013
- [141] **Tabata, T., & Okuda, T.** (2012). Life cycle assessment of woody biomass energy utilization: Case study in Gifu Prefecture, Japan. *Energy*, 45(1), 944-951. doi: 10.1016/j.energy.2012.06.064
- [142] **Camero, C., & Sowlati, T.** (2014). Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – A review of literature. *Renewable and Sustainable Energy Reviews*, 36, 62-73. doi: 10.1016/j.rser.2014.04.041
- [143] **EUBIA** (European Biomass Industry Association). Retrieved 08 July 2016, from <http://www.eubia.org/>
- [144] **Kärhä, K.** (2011). Industrial supply chains and production machinery of forest chips in Finland. *Biomass and Bioenergy*, 35(8), 3404-3413. doi: 10.1016/j.biombioe.2010.11.016
- [145] **Karl Stampfer, C. K.** (2006). Current state and development possibilities of wood chip supply chains in Austria. *Croatian Journal of Forest Engineering*, 27(2), 135-145.
- [146] **Eker, M., Coban, O., H., & Alkan, H.** (2010). Hasat artıkları tedarik zincirine yönelik sistem tasarımı *In Proceedings of III. Ulusal Karadeniz Ormancılık Kongresi* (Vol. II, pp. 524-534): 20-22 May.
- [147] **Kent, T., Kofman, P. D., & Coates, E.** (2011). *Harvesting wood for energy - Cost-effective woodfuel supply chains in Irish forestry*. Dublin: COFORD, Department of Agriculture, Food and the Marine. Retrieved 24 May 2016, from http://www.coford.ie/media/coford/content/publications/projectreports/Harvesting_Wood_low_res_for_web.pdf.
- [148] **Loo, S. v., & Koppejan, J.** (Eds.). (2008). *The handbook of biomass combustion & co-firing*. London: Earthscan.
- [149] **Karlsson, L. G. a. Å.** (2001). CO₂ Mitigation Cost: A System Perspective on the Heating of Detached Houses with Bioenergy or Fossil Fuels In P. H. Paavo Pelkonen, Timo Karjalainen, Bernhard Schlamadinger (Ed.), *Woody Biomass as an Energy Source – Challenges in Europe*. Joensuu, Finland: European Forest Institute.
- [150] **Wiltsee, G.** (2000). *Lessons learned from existing biomass power plants*. USA: National Renewable Energy Laboratory (NREL), NREL Technical Monitor: Richard Bain. Retrieved 04 December 2016, from <http://www.nrel.gov/docs/fy00osti/26946.pdf>.

- [151] **Thomas F. McGowan, M. L. B., William S. Bulpitt, James L. Walsh, Jr.** (Ed.). (2009). *Biomass and alternate fuel systems - An engineering and economic guide*. New Jersey, USA: AIChE (American Institute of Chemical Engineers) and John Wiley & Sons.
- [152] **McKendry, P.** (2002). Energy production from biomass (part 3): gasification technologies. *BioresourceTechnology*, 83, 55–63.
- [153] **McKendry, P.** (2002). Energy production from biomass (part 2): conversion technologies. *BioresourceTechnology*, 83, 47–54.
- [154] **Brown, R. C.** (2011). Introduction of thermochemical processing of biomass into fuels, chemicals and power. In R. C. Brown (Ed.), *Thermochemical processing of biomass: conversion into fuels, chemicals and power*. USA: Wiley.
- [155] **Jameel, H., Keshwani, D. R., Carter, S. F., & Treasure, T. H.** (2010). Thermochemical conversion of biomass to power and fuels. In J. Cheng (Ed.), *Biomass to renewable energy processes*. Boca Raton: CRC Press/Taylor & Francis.
- [156] **Bain, R. L.** (2004). An overview of biomass combined heat and power technologies In *Proceedings of IEEE Power Engineering Society General Meeting* (Vol. 2, pp. 1657 - 1659). Denver, CO, 6-10 June.
- [157] **Bain, R. L., Overend, R. P., & Craig, K. R.** (1998). Biomass-fired power generation. *Fuel Processing Technology*, 54, 1-16.
- [158] **Kumar, A., Kumar, N., Baredar, P., & Shukla, A.** (2015). A review on biomass energy resources, potential, conversion and policy in India. *Renewable and Sustainable Energy Reviews*, 45, 530-539. doi: 10.1016/j.rser.2015.02.007
- [159] **Bilgili, M., Ozbek, A., Sahin, B., & Kahraman, A.** (2015). An overview of renewable electric power capacity and progress in new technologies in the world. *Renewable and Sustainable Energy Reviews*, 49, 323-334. doi: 10.1016/j.rser.2015.04.148
- [160] **Kirkels, A. F., & Verbong, G. P. J.** (2011). Biomass gasification: Still promising? A 30-year global overview. *Renewable and Sustainable Energy Reviews*, 15(1), 471-481. doi: 10.1016/j.rser.2010.09.046
- [161] **OECD.** (2010). *Bioheat, biopower and biogas: Developments and implications for agriculture*: OECD. Retrieved 01 December 2016, from <http://www.oecd.org/publications/bioheat-biopower-and-biogas-9789264085862-en.htm>.
- [162] **CCC** (Committee on Climate Change). (2011). *Bioenergy review technical paper 4: Biomass in power generation*. London. Retrieved 04 December 2016, from https://www.theccc.org.uk/archive/aws2/Bioenergy/1463%20CCC_Bio-TP4_power_FINALwithBkMks.pdf.
- [163] **Bauen, A., Berndes, G., Junginger, M., & Vuille, M. L.** (2009). *Bioenergy, a sustainable and reliable energy source*: IEA Bioenergy. Retrieved 30 November 2016, from <http://www.ieabioenergy.com/wp->

content/uploads/2013/10/MAIN-REPORT-Bioenergy-a-sustainable-and-reliable-energy-source.-A-review-of-status-and-prospects.pdf.

- [164] **Vamvuka, D., Mavrou, E., Bandelis, G., Tsoutsos, T., & Papamicheal, I.** (2007). Biomass cogeneration in Europe - economical, technical and environmental evaluation *In Proceedings of the Third European Combustion Meeting ECM 2007*. Crete, Greece, 11-13 April.
- [165] **Saidur, R., Abdelaziz, E. A., Demirbas, A., Hossain, M. S., & Mekhilef, S.** (2011). A review on biomass as a fuel for boilers. *Renewable and Sustainable Energy Reviews*, 15(5), 2262-2289. doi: 10.1016/j.rser.2011.02.015
- [166] **EPA** (U.S. Environmental Protection Agency). (2015). *Catalog of CHP technologies*. USA: Combined Heat and Power Partnership. Retrieved 04 December 2016, from https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_chp_technologies.pdf.
- [167] **I. Obernberger, & Thek, G.** (2008). Combustion and gasification of solid biomass for heat and power production in Europe - State-of-the-art and relevant future developments *In Proceedings of the 8th European Conference on Industrial Furnaces and Boilers*. Vilamoura, Portugal, April.
- [168] **Heinloth, K.** (Ed.). (2007). *Energy technologies - Subvolume C: Renewable energy*. Germany: Springer.
- [169] **Obernberger, I., Carlsen, H., & Biedermann, F.** (2003). State-of-the-art and future developments regarding small-scale biomass CHP systems with a special focus on ORC and Stirling engine technologies *In Proceedings of the International Nordic Bioenergy 2003 Conference*. 2-5 September.
- [170] **Eyidogan, M., Canka Kilic, F., Kaya, D., Coban, V., & Cagman, S.** (2016). Investigation of organic Rankine cycle (ORC) technologies in Turkey from the technical and economic point of view. *Renewable and Sustainable Energy Reviews*, 58, 885-895. doi: 10.1016/j.rser.2015.12.158
- [171] **TURBODEN**. *Organic Rankine cycle technology*. Retrieved 02 December 2016, from <http://www.turboden.eu/it/public/press/ORC%20Brochure%20leaflet.pdf>
- [172] **Bocci, E., Di Carlo, A., McPhail, S. J., Gallucci, K., Foscolo, P. U., Moneti, M., . . . Carlini, M.** (2014). Biomass to fuel cells state of the art: A review of the most innovative technology solutions. *International Journal of Hydrogen Energy*, 39(36), 21876-21895. doi: <http://dx.doi.org/10.1016/j.ijhydene.2014.09.022>
- [173] **Kan, T., & Strezov, V.** (2014). Combustion of biomass. In V. Strezov & T. J. Evans (Eds.), *Biomass processing technologies*. USA: CRC Press.
- [174] **Otepka, P.** (Ed.). (2013). *Guidebook on local bioenergy supply based on woody biomass: PromoBio project*. USA: Scientific & Academic Publishing.
- [175] **Khan, A. A., de Jong, W., Jansens, P. J., & Spliethoff, H.** (2009). Biomass combustion in fluidized bed boilers: Potential problems and remedies.

Fuel Processing Technology, 90(1), 21-50. doi: 10.1016/j.fuproc.2008.07.012

- [176] **The Renewable Energy Hub.** Retrieved 10 March 2016, from <https://www.renewableenergyhub.co.uk/biomass-boiler-information.html>
- [177] **IEE (Intelligent Energy Europe).** (n.d.). *A guide to specifying biomass heating systems: FOREST (fostering efficient long term supply partnerships)*. Retrieved 04 December 2016, from https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/forest_guide_for_designers_and_architects_en.pdf.
- [178] **Palmer, D., Ashford, C., Kinnibrugh, J., & Smith, G.** (2014). *Biomass heating*. UK: The Chartered Institution of Building Services Engineers (CIBSE). Retrieved 01 December 2016, from file:///C:/Users/ge/Downloads/CIBSE%20AM15%202014%20Biomass%20heating.pdf.
- [179] **Vos, J.** (2005). *Biomass energy for heating and hot water supply in Belarus best practice guidelines - Part A: Biomass combustion*: BTG Biomass Technology Group BV, Prepared for UNDP/GEF. Retrieved 04 December 2016, from <http://energoeffekt.gov.by/bioenergy/htdocs/en/practa.pdf>.
- [180] **Quaak, P., H., K., & Stassen, H.** (1999). *Energy from biomass: A review of combustion and gasification technologies*. Washington, D. C., USA: The World Bank. Retrieved 04 December 2016, from <http://documents.worldbank.org/curated/en/936651468740985551/pdf/multi-page.pdf>.
- [181] **Nussbaumer, T.** (2003). Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. *Energy & Fuels*, 17, 1510-1521.
- [182] **Arce, M., Saavedra, Á., Míguez, J., Granada, E., & Cacabelos, A.** (2013). Biomass fuel and combustion conditions selection in a fixed bed combustor. *Energies*, 6(11), 5973-5989. doi: 10.3390/en6115973
- [183] **Richard L. Bain, R. P. O., Kevin R. Craig.** (1998). Biomass-fired power generation. *Fuel Processing Technology*, 54, 1-16.
- [184] **Dincer, I., & Zamfirescu, C.** (2014). *Advanced power generation systems*. Canada: Elsevier.
- [185] **Khartchenko, N. V., & Kharchenko, V. M.** (2014). *Advanced Energy Systems* (Second ed.). FL: CRC Press.
- [186] **Johansson, T. B., Kelly, H., Reddy, A. K. N., & Williams, R. H.** (Eds.). (1993). *Renewable energy sources for fuel and electricity*. Washington: Island Press.
- [187] **Jenkins, B. M., Baxter, L. L., & Koppejan, J.** (2011). Biomass combustion. In R. C. Brown (Ed.), *Thermochemical processing of biomass, conversion into fuels, chemicals and power* USA: John Wiley & Sons.

- [188] **Singh, R., & Shukla, A.** (2014). A review on methods of flue gas cleaning from combustion of biomass. *Renewable and Sustainable Energy Reviews*, 29, 854-864. doi: 10.1016/j.rser.2013.09.005
- [189] **ASHRAE.** (2012). *2012 ASHRAE handbook-HVAC systems and equipment : SI edition*. Atlanta: ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers).
- [190] **Niu, Y., Tan, H., & Hui, S. e.** (2016). Ash-related issues during biomass combustion: Alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, corrosion, ash utilization, and related counter measures. *Progress in Energy and Combustion Science*, 52, 1-61. doi: 10.1016/j.pecs.2015.09.003
- [191] **Serup, H., Falster, H., Gamborg, C., Gundersen, P., Hansen, L., Heding, N., . . . Thomsen, I. M.** (2002). *Wood for energy production, technology, environment, economy*. Denmark: The Centre for Biomass Technology. Retrieved 01 December 2016, from <http://www.videncenter.dk/uk/engwood.htm>.
- [192] **Skøtt, T., & Hansen, M. T.** (2000). *Danish bioenergy solutions - reliable & efficient*. Denmark: The Centre for Biomass Technology. Retrieved 04 December 2016, from http://www.videncenter.dk/exportcat/combined_heat_and_power.pdf.
- [193] **CRES** (Centre for Renewable Energy Sources). (2003). *Austria: Biomass cogeneration network (BIOCOGEN)*. Retrieved 01 December 2016, from <http://www.cres.gr/biocogen/pdf/countries/Austria.pdf>.
- [194] **Jungmeier, G., Resch, G., & Spitzer, J.** (1998). Environmental burdens over the entire life cycle of a biomass CHP plant. *Biomass and Bioenergy*, 15(4), 311-323. doi: 10.1016/S0961-9534(98)00039-7
- [195] **Jungmeier, G., & Schwaiger, H. J.** (2003). Solid biomass CHP plants - The Austrian success story [PowerPoint Slides] *In Proceedings of Workshop of Current potentials for biomass CHP in Europe*. Athens, 26 February.
- [196] **Nikolaissen, L., Nielsen, C., Larsen, M. G., Nielsen, V., Zielke, U., Kristensen, J. K., & Holm-Christensen, B.** (1998). *Straw for energy production, technology, environment, economy*. Denmark: The Centre for Biomass Technology. Retrieved 01 December 2016, from <http://www.videncenter.dk/uk/index.htm>.
- [197] **CRES** (Centre for Renewable Energy Sources). (2003). *Denmark: Biomass cogeneration network (BIOCOGEN)*. Retrieved 01 December 2016, from <http://www.cres.gr/biocogen/pdf/countries/Denmark.pdf>.
- [198] **Obernberger, I., & Thek, G.** (2004). *Techno-economic evaluation of selected decentralised CHP applications based on biomass combustion in IEA partner countries final report*. Austria: BIOS BOIENERGIESYSTEME GmbH. Retrieved 04 December 2016, from <http://www.ieabcc.nl/publications/IEA-CHP-Q2-final.pdf>.

- [199] **B&W** (babcock&wilcox volund). (2010). *Biomass-fired CHP plant Assens, Denmark: Plant fact sheet*. Retrieved 04 December 2016, from http://www.volund.dk/~media/Downloads/Brochures_-_BIO/Assens_-_Denmark.pdf.
- [200] **CRES** (Centre for Renewable Energy Sources). (2003). *Finland: Biomass cogeneration network (BIOCOGEN)*. Retrieved 01 December 2016, from <http://www.cres.gr/biocogen/pdf/countries/Finland.pdf>.
- [201] **CRES** (Centre for Renewable Energy Sources). (2003). *Germany: Biomass cogeneration network (BIOCOGEN)*. Retrieved 01 December 2016, from <http://www.cres.gr/biocogen/pdf/countries/Germany.pdf>.
- [202] **B&W**. *Pfaffenhofen, Kraftanlagentechnik München GmbH, Germany*. Retrieved 04 December 2016, from http://www.volund.dk/Biomass_energy/References/Pfaffenhofen
- [203] **Wahlund B, Y. J., Westermarck M.** (2000). Comparative assessment of biofuel-based combined heat and power generation plants in Sweden *In Proceedings of the 1st World Conference on Biomass for Energy and Industry* (Vol. II, pp. 1852-1855). Spain, 5-9 June.
- [204] **Aalborg Energie Teknik a/s**. *Cofely SODC Orleans, France*. Retrieved 04 December 2016, from <http://www.aet-biomass.com/en-GB/Home/References/Biomass-Fired-Plants/Cofely-SODC-Orleans.aspx>
- [205] **Aalborg Energie Teknik a/s**. *Cofely GDF Suez, Bio Cogelyo Normandie, France*. Retrieved 09 November 2015, from <http://www.aet-biomass.com/en-GB/Home/References/Biomass-Fired-Plants/Cofely-BCN.aspx>
- [206] **Aalborg Energie Teknik a/s**. *Biomass fired plants - references*. Retrieved 04 December 2016, from <http://www.aet-biomass.com/en-GB/Home/References/Biomass-Fired-Plants.aspx>
- [207] **Aalborg Energie Teknik a/s**. *Linz-Mitte energie-Anlage, Austria*. Retrieved 04 December 2016, from <http://www.aet-biomass.com/en-GB/Home/References/Biomass-Fired-Plants/Linz-Mitte.aspx>
- [208] **Savola, T.** (2007). *Modelling biomass-fuelled small-scale CHP plants for process synthesis optimization*. (Doctoral Dissertation), Helsinki University of Technology, Department of Mechanical Engineering, Finland.
- [209] **Hagauer, D.** (2013). *Use of natural wood chips for producing electricity and heat in the largest Austrian biomass CHP plant at Vienna*. Retrieved 25 August 2015, from <http://adrianataylor.com/sites/adrianataylor.com/files/attachments/Attachment%204.5.6%20-%20Use%20of%20woodchips%20in%20largest%20Austrian%20Biomass%20CHP%20Plant.pdf>.
- [210] **Aalborg Energie Teknik a/s**. *Cofely GDF Suez, BES VSG (DRT), France*. Retrieved 04 December 2016, from <http://www.aet-biomass.com/en-GB/Home/References/Biomass-Fired-Plants/Cofely-BES-VSG.aspx>

- [211] **Puhakka, M.** (1997). *Biomass power plant at Forssa, Finland*: Osmo kaulamo engineering ltd. CADDET Renewable Energy Newsletter. Retrieved 04 December 2016, from <http://www.caddet-re.org/assets/1-97art1.pdf>.
- [212] **IEA** (International Energy Agency). *Bioenergy Task 32 Cofiring Database*. Retrieved 04 December 2016, from <http://www.ieabcc.nl/database/cofiring.php>
- [213] **CRES** (Centre for Renewable Energy Sources). (2003). *Sweden: Biomass cogeneration network (BIOCOGEN)*. Retrieved 01 December 2016, from <http://www.cres.gr/biocogen/pdf/countries/Sweden.pdf>.
- [214] **Evald, A., & Witt, J.** (2006). *Biomass CHP best practice guide/European BIO-CHP project*: European Commission Altener programme. Retrieved 04 December 2016, from <http://bio-chp.force.dk/wp-content/uploads/2015/07/Biomass-CHP-best-practice-guide.pdf>.
- [215] **Kelly, K. A., McManus, M. C., & Hammond, G. P.** (2014). An energy and carbon life cycle assessment of industrial CHP (combined heat and power) in the context of a low carbon UK. *Energy*, 77, 812-821. doi: 10.1016/j.energy.2014.09.051
- [216] **de Oliveira, D. L., Brandao, L. E., Igrejas, R., & Gomes, L. L.** (2014). Switching outputs in a bioenergy cogeneration project: A real options approach. *Renewable and Sustainable Energy Reviews*, 36, 74-82. doi: 10.1016/j.rser.2014.04.023
- [217] **Brown, P., & Whitney, G.** (2012). U.S. renewable electricity generation: Resources and challenges. In L. G. Irwin & R. Macias (Eds.), *Renewable electricity generation (resources, standards, challenges)*. New York: Nova Science Publishers.
- [218] **Yilmaz, S., & Selim, H.** (2013). A review on the methods for biomass to energy conversion systems design. *Renewable and Sustainable Energy Reviews*, 25, 420-430. doi: 10.1016/j.rser.2013.05.015
- [219] **Gasparatos, A., Doll, C. N. H., Esteban, M., Ahmed, A., & Olang, T. A.** (2017). Renewable energy and biodiversity: Implications for transitioning to a Green Economy. *Renewable and Sustainable Energy Reviews*, 70, 161-184. doi: 10.1016/j.rser.2016.08.030
- [220] **Cherubini, F., & Stromman, A. H.** (2011). Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresour Technol*, 102(2), 437-451. doi: 10.1016/j.biortech.2010.08.010
- [221] **Evans, A., Strezov, V., & Evans, T. J.** (2010). Sustainability considerations for electricity generation from biomass. *Renewable and Sustainable Energy Reviews*, 14(5), 1419-1427. doi: 10.1016/j.rser.2010.01.010
- [222] **Muench, S., & Guenther, E.** (2013). A systematic review of bioenergy life cycle assessments. *Applied Energy*, 112, 257-273. doi: 10.1016/j.apenergy.2013.06.001
- [223] **Guest, G., Bright, R. M., Cherubini, F., Michelsen, O., & Strømman, A. H.** (2011). Life Cycle Assessment of biomass-based Combined Heat and Power plants. *Journal of Industrial Ecology*, 15(6), 908-921. doi: 10.1111/j.1530-9290.2011.00375.x

- [224] **Njakou Djomo, S., Witters, N., Van Dael, M., Gabrielle, B., & Ceulemans, R.** (2015). Impact of feedstock, land use change, and soil organic carbon on energy and greenhouse gas performance of biomass cogeneration technologies. *Applied Energy*, 154, 122-130. doi: 10.1016/j.apenergy.2015.04.097
- [225] **Gustavsson, L., & Johansson, B.** (1994). Cogeneration: One way to use biomass efficiently. *Heat Recovery Systems & CHP*, 14(2), 117-127.
- [226] **Deborah, P., Francesca, V., & Giuseppe, G.** (2015). Analysis of the environmental impact of a biomass plant for the production of bioenergy. *Renewable and Sustainable Energy Reviews*, 51, 634-647. doi: 10.1016/j.rser.2015.06.048
- [227] **Prasad, S. B.** (1995). Biomass-fired steam power cogeneration system: A theoretical study. *Energy Conversion and Management*, 36(1), 65-77.
- [228] **Nussbaumer, T.** (2010). *Overview on technologies for biomass combustion and emission levels of particulate matter*. Zürich, Switzerland: Swiss Federal Office for the Environment (FOEN). Retrieved 01 October 2016, from http://www.citepa.org/old/forums/egtei/Nussbaumer_EGTEI-Report_final.pdf.
- [229] **Lineback, N., Dellinger, T., Shienvold, L. F., Witcher, B., Reynolds, A., & Brown, L. E.** (1999). Industrial greenhouse gas emissions: Does CO₂ from combustion of biomass residue for energy really matter? *Climate Research*, 13, 221-229.
- [230] **Muench, S.** (2015). Greenhouse gas mitigation potential of electricity from biomass. *Journal of Cleaner Production*, 103, 483-490. doi: 10.1016/j.jclepro.2014.08.082
- [231] **Haykırı-Acma, H.** (2003). Combustion characteristics of different biomass materials. *Energy Conversion and Management*, 44, 155-162.
- [232] **Capehart, B. L.** (2007). *Encyclopedia of energy engineering and technology*. USA: CRC Press/Taylor & Francis.
- [233] **Nunes, L. J. R., Matias, J. C. O., & Catalão, J. P. S.** (2016). Biomass combustion systems: A review on the physical and chemical properties of the ashes. *Renewable and Sustainable Energy Reviews*, 53, 235-242. doi: 10.1016/j.rser.2015.08.053
- [234] **Fogler, H. S., & Gurmen, N. M.** (2002). *Aspen Plus workshop for reaction engineering and design*. Ann Arbor, MI: The University of Michigan, Department of Chemical Engineering. <http://wp.auburn.edu/eden/wp-content/uploads/2012/03/Workshop-on-Reactions-in-Aspen.pdf>.
- [235] **AspenTech.** (2013). *Aspen Plus - Getting started building and running a process model V8.4*. USA: Aspen Technology. Retrieved 10 May 2015, from <https://support.aspentech.com/>.
- [236] **Eden, M. R.** (2012). *Introduction to Aspen Plus simulation*: Auburn University, Chemical Engineering Department. Retrieved 10 May 2015, from <http://wp.auburn.edu/eden/wp-content/uploads/2012/03/4460-Aspen-Notes-2012.pdf>.
- [237] **AspenTech.** Retrieved 01 June 2015, from <http://www.aspentech.com/>

- [238] **Thermoflow**. Retrieved 01 June 2015, from <http://www.thermoflow.com/>
- [239] **ProSim**. Retrieved 01 June 2015, from <http://www.prosim.net/>
- [240] **CHEMCAD**. Retrieved 01 June 2015, from <http://www.chemstations.com/>
- [241] **Schneider Electric**. Retrieved 01 June 2015, from <http://software.schneider-electric.com/>
- [242] **Elmegaard, B., & Houbak, N.** (2002). Software for Simulation of Power Plant Processes. Part B - Program Description and Application *In Proceedings of ECOS 2002*. Germany.
- [243] **UNWCED** (The United Nations World Commission on Environment and Development). (1992). *Rio Declaration on Environment and Development, The Rio Earth Summit*. Rio De Janeiro, Brazil: UN WCED. Retrieved 02 October 2015, from <http://www.un-documents.net/rio-dec.htm>.
- [244] **Jose Potting, S. G., Sebastien Bonnet, Joost van Buuren.** (2012). How to Approach the Assessment? In M. A. Curran (Ed.), *Life Cycle Assessment handbook - A guide for environmentally sustainable products*. USA: Scrivener Publishing.
- [245] **Canter, L. W.** (1996). *Environmental Impact Assessment* (Second ed.). Singapore: McGraw-Hill, Inc.
- [246] **EPA** (Environmental Protection Agency). (2006). *Life Cycle Assessment: principles and practice*. USA: Scientific Applications International Corporation (SAIC).
- [247] **Azapagic, A.** (2006). Life Cycle Assessment as an environmental sustainability tool. In J. Dewulf & H. V. Langenhove (Eds.), *Renewables-based technology : sustainability assessment* Hoboken, NJ: Wiley.
- [248] **Curran, M. A.** (1996). *Environmental Life-cycle Assessment*: McGraw-Hill.
- [249] **Azapagic, A.** (2011). Assessing Environmental Sustainability: Life Cycle Thinking and Life Cycle Assessment. In S. P. Adisa Azapagic (Ed.), *Sustainable Development in Practice Case Studies for Engineers and Scientists* (Second Edition ed.). Chichester, UK: John Wiley & Sons.
- [250] **Reinout Heijungs, J. B. G.** (2012). An overview of the Life Cycle Assessment method - past, present, and future. In M. A. Curran (Ed.), *Life Cycle Assessment handbook - A guide for environmentally sustainable products*. USA: Scrivener Publishing.
- [251] **UNEP/SETAC Life Cycle Initiative**. Retrieved 06 May 2016, from <http://www.lifecycleinitiative.org/>
- [252] **EPLCA** (European Platform on Life Cycle Assessment, European Commission, Joint Research Centre). Retrieved 06 May 2016, from <http://eplca.jrc.ec.europa.eu/>
- [253] **EPA** (United States Environmental Protection Agency). *Design for the Environment Life-Cycle Assessments*. Retrieved 06 May 2016, from <https://www.epa.gov/saferchoice/design-environment-life-cycle-assessments>

- [254] **ACLCA** (The American Center for Life Cycle Assessment). Retrieved 06 May 2016, from <http://www.lcacenter.org/>
- [255] **ALCAS** (The Australian Life Cycle Assessment Society). Retrieved 06 May 2016, from <http://www.alcas.asn.au/>
- [256] **Udo de Haes, H. A., & Heijungs, R.** (2007). Life-cycle assessment for energy analysis and management. *Applied Energy*, 84(7-8), 817-827. doi: 10.1016/j.apenergy.2007.01.012
- [257] **Azapagic, A.** (1999). Life cycle assessment and its application to process selection, design and optimization. *Chemical Engineering Journal*, 73, 1-21.
- [258] **ISO** (International Organization for Standardization). (2010). *Environmental labels and declarations - Type III environmental declarations - Principles and procedures (BS EN ISO 14025)*. London, UK: British Standards Institute.
- [259] **Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., & Meijer, E.** (2013). *Introduction to LCA with SimaPro: PRé*. Retrieved 05 June 2017, from www.pre-sustainability.com.
- [260] **SETAC** (The Society of Environmental Toxicology and Chemistry). Retrieved 09 May 2016, from <https://www.setac.org/>
- [261] **Pauli Miettinen, R. P. H.** (1997). How to benefit from decision analysis in environmental life cycle assessment (LCA). *European Journal of Operational Research*, 102, 279-294.
- [262] **Roedl, A.** (2010). Production and energetic utilization of wood from short rotation coppice—a life cycle assessment. *The International Journal of Life Cycle Assessment*, 15(6), 567-578. doi: 10.1007/s11367-010-0195-0
- [263] **Pehnt, M.** (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renewable Energy*, 31(1), 55-71. doi: 10.1016/j.renene.2005.03.002
- [264] **Ramjeawon, T.** (2008). Life cycle assessment of electricity generation from bagasse in Mauritius. *Journal of Cleaner Production*, 16(16), 1727-1734. doi: 10.1016/j.jclepro.2007.11.001
- [265] **Jungmeier, G., & Spitzer, J.** (2001). Greenhouse gas emissions of bioenergy from agriculture compared to fossil energy for heat and electricity supply. *Nutrient Cycling in Agroecosystems*, 60((1-3)), 267-273. doi: 10.1023/A:1012651614688
- [266] **Kimming, M., Sundberg, C., Nordberg, Å., Baky, A., Bernesson, S., Norén, O., & Hansson, P. A.** (2011). Biomass from agriculture in small-scale combined heat and power plants – A comparative life cycle assessment. *Biomass and Bioenergy*, 35(4), 1572-1581. doi: 10.1016/j.biombioe.2010.12.027
- [267] **Pilicka, I., Blumberga, D., & Romagnoli, F.** (2011). Life Cycle Assessment of Biogas Production from Marine Macroalgae: a Latvian Scenario. *Scientific Journal of Riga Technical University*, 6, 69-78.

- [268] Caserini, S., Livio, S., Giugliano, M., Grosso, M., & Rigamonti, L. (2010). LCA of domestic and centralized biomass combustion: The case of Lombardy (Italy). *Biomass and Bioenergy*, 34(4), 474-482. doi: 10.1016/j.biombioe.2009.12.011
- [269] Goglio, P., & Owende, P. M. O. (2009). A screening LCA of short rotation coppice willow (*Salix* sp.) feedstock production system for small-scale electricity generation. *Biosystems Engineering*, 103(3), 389-394. doi: 10.1016/j.biosystemseng.2009.03.003
- [270] Gasol, C. M., Gabarrell, X., Anton, A., Rigola, M., Carrasco, J., Ciria, P., & Rieradevall, J. (2009). LCA of poplar bioenergy system compared with *Brassica carinata* energy crop and natural gas in regional scenario. *Biomass and Bioenergy*, 33(1), 119-129. doi: 10.1016/j.biombioe.2008.04.020
- [271] Botha, T., & von Blottnitz, H. (2006). A comparison of the environmental benefits of bagasse-derived electricity and fuel ethanol on a life-cycle basis. *Energy Policy*, 34(17), 2654-2661. doi: 10.1016/j.enpol.2004.12.017
- [272] Cherubini, F., & Ulgiati, S. (2010). Crop residues as raw materials for biorefinery systems – A LCA case study. *Applied Energy*, 87(1), 47-57. doi: 10.1016/j.apenergy.2009.08.024
- [273] Cherubini, F., & Jungmeier, G. (2009). LCA of a biorefinery concept producing bioethanol, bioenergy, and chemicals from switchgrass. *The International Journal of Life Cycle Assessment*, 15(1), 53-66. doi: 10.1007/s11367-009-0124-2
- [274] Uihlein, A., & Schebek, L. (2009). Environmental impacts of a lignocellulose feedstock biorefinery system: An assessment. *Biomass and Bioenergy*, 33(5), 793-802. doi: 10.1016/j.biombioe.2008.12.001
- [275] Recchia, L., Cini, E., & Corsi, S. (2010). Multicriteria analysis to evaluate the energetic reuse of riparian vegetation. *Applied Energy*, 87(1), 310-319. doi: 10.1016/j.apenergy.2009.08.034
- [276] Guinée, J. B., Gorée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. d., . . . et.al. (2004). *Handbook on Life Cycle Assessment - Operational Guide to the ISO Standards*. USA: Kluwer Academic Publishers.
- [277] PRé. (2016). *SimaPro Database Manual - Methods Library, version 3.0*. Retrieved 05 June 2017, from <https://www.pre-sustainability.com/simapro-database-and-methods-library>.
- [278] Hans-Jörg Althaus, C. B., Gabor Doka, Roberto Dones, Rolf Frischknecht, Stefanie Hellweg, Sébastien Humbert, Niels Jungbluth, Thomas Köllner, Yves Loerincik, Manuele Margni, Thomas Nemecek (2010). *Implementation of Life Cycle Impact Assessment Methods*, v2.2 No. 3. Dübendorf, CH: Swiss Centre for Life Cycle Inventories.
- [279] Eriksson, O., Finnveden, G., Ekvall, T., & Björklund, A. (2007). Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion. *Energy Policy*, 35(2), 1346-1362. doi: 10.1016/j.enpol.2006.04.005

- [280] **Atilgan, B., & Azapagic, A.** (2017). Energy challenges for Turkey: Identifying sustainable options for future electricity generation up to 2050. *Sustainable Production and Consumption*. doi: 10.1016/j.spc.2017.02.001
- [281] **Ciroth, A.** (2012). Software for Life Cycle Assessment. In M. A. Curran (Ed.), *Life Cycle Assessment handbook - A guide for environmentally sustainable products*. USA: Scrivener Publishing.
- [282] **Ciroth, A.** (2006). A new open source LCA software *In Proceedings of the 7th Ecobalance Conference*. Tsukuba, Japan.
- [283] **CMLCA** (Institute of Environmental Sciences, Leiden University). Retrieved 07 May 2016, from <http://www.cmlca.eu/>
- [284] **GEMIS** (Global Emissions Model for integrated Systems, The International Institute for Sustainability Analysis and Strategy (IINAS)). Retrieved 07 May 2016, from <http://www.iinas.org/downloads-en.html>
- [285] **SimaPro 8.1.1.16** (PRéConsultants). Netherland. Retrieved 05 June 2017, from <https://www.pre-sustainability.com/simapro>
- [286] **GaBi, Thinkstep.** Retrieved 07 May 2016, from <http://www.gabi-software.com/>
- [287] **Umberto.** Retrieved 07 May 2016, from <http://www.umberto.de/en/>
- [288] **openLCA.** Retrieved 07 May 2016, from <http://www.openlca.org/>
- [289] **Curran, M. A.** (Ed.). (2015). *Life Cycle Assessment student handbook*. USA: Scrivener Publishing.
- [290] **Weidema B P, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, . . . G, W.** (2013). *Overview and methodology - data quality guideline for the ecoinvent database version 3*. St. Gallen: The Ecoinvent Center, Swiss Center for Life Cycle Inventories.
- [291] **Ecoinvent 3.1** (Ecoinvent Centre). Switzerland. Retrieved 05 June 2017, from <http://www.ecoinvent.org/>
- [292] **Bauer, C.** (2012). *Summary: Wood Energy*: The Ecoinvent Center, Swiss Center for Life Cycle Inventories.
- [293] **Heck, T.** (2012). *Summary: Combined Heat and Power*: The Ecoinvent Center, Swiss Center for Life Cycle Inventories.
- [294] **Dones, R., Bauer, C., Bolliger, R., Burger, B., Heck, T., Roder, A., . . . Tuchschnid, M.** (2007). *Life cycle inventories of energy systems: Results for current systems in Switzerland and other UCTE countries*: The Ecoinvent Center, Swiss Center for Life Cycle Inventories.
- [295] **Werner, F., Althaus, H., Kunniger, T., Richter, K., & Jungbluth, N.** (2007). *Life cycle inventories of wood as fuel and construction material.*: The Ecoinvent Center, Swiss Center for Life Cycle Inventories.
- [296] **Itten, R., Frischknecht, R., & Stucki, M.** (2014). *Life cycle inventories of electricity mixes and grid*: Paul Scherrer Institut (PSI), treeze Ltd., fair life cycle thinking.

- [297] **Lewandowska, A., Wawrzynkiewicz, Z., Noskowiak, A., & Foltynowicz, Z.** (2008). Adaptation of ecoinvent database to Polish conditions. *The International Journal of Life Cycle Assessment*, 13(4), 319-327. doi: 10.1007/s11367-008-0010-3
- [298] **NREL** (National Renewable Energy Laboratory). *Distributed generation renewable energy estimate of costs*. Retrieved 04 August 2017, from http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html
- [299] **EIA** (U.S. Energy Information Administration). (2016). *Capital cost estimates for utility scale electricity generating plants*: U.S. Department of Energy. Retrieved 11 May 2017, from https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf.
- [300] **Evans, A., Strezov, V., & Evans, T. J.** (2009). Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews*, 13(5), 1082-1088. doi: 10.1016/j.rser.2008.03.008
- [301] **IRENA** (The International Renewable Energy Agency). (2012). *Renewable energy technologies, cost analysis series: Biomass for power generation* (Vol. 1). Retrieved 11 May 2017, from https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf.
- [302] **Arne Olson, N. S., Kush Patel, Gabe Kwok** (2014). *Capital cost review of power generation technologies / Recommendations for WECC's 10- and 20-year studies*: Energy and Environmental Economics, Inc. Retrieved 03 August 2017, from https://www.wecc.biz/Reliability/2014_TEPPC_Generation_CapCost_Report_E3.pdf.
- [303] **WEC** (World Energy Council). (2013). *World energy perspective: Cost of energy technologies*. Retrieved 05 August 2017, from https://www.worldenergy.org/wp-content/uploads/2013/09/WEC_J1143_CostofTECHNOLOGIES_021013_WEB_Final.pdf.
- [304] **Börjesson, M., & Ahlgren, E.** (2012). Biomass CHP energy systems: A critical assessment. In A. Sayigh & D. J. Roddy (Eds.), *Comprehensive renewable energy: Volume 5: Biomass and biofuel production*. USA: Elsevier.
- [305] **Bilgen, S., Keleş, S., Sarıkaya, İ., & Kaygusuz, K.** (2015). A perspective for potential and technology of bioenergy in Turkey: Present case and future view. *Renewable and Sustainable Energy Reviews*, 48, 228-239. doi: 10.1016/j.rser.2015.03.096
- [306] **Uddin, S. N., & Barreto, L.** (2007). Biomass-fired cogeneration systems with CO₂ capture and storage. *Renewable Energy*, 32(6), 1006-1019. doi: 10.1016/j.renene.2006.04.009
- [307] **Gustavsson, L.** (1997). Energy efficiency and competitiveness of biomass-based energy systems. *Energy*, 22(10), 959-967.
- [308] **Turconi, R., Boldrin, A., & Astrup, T.** (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renewable and Sustainable Energy Reviews*, 28, 555-565. doi: 10.1016/j.rser.2013.08.013

- [309] **Varun, Bhat, I. K., & Prakash, R.** (2009). LCA of renewable energy for electricity generation systems—A review. *Renewable and Sustainable Energy Reviews*, 13(5), 1067-1073. doi: 10.1016/j.rser.2008.08.004
- [310] **Fthenakis, V., & Kim, H. C.** (2009). Land use and electricity generation: A life-cycle analysis. *Renewable and Sustainable Energy Reviews*, 13(6-7), 1465-1474. doi: 10.1016/j.rser.2008.09.017
- [311] **Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G., Schlamadinger, B., & Woess-Gallasch, S.** (2009). Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling*, 53(8), 434-447. doi: 10.1016/j.resconrec.2009.03.013
- [312] **Weisser, D.** (2007). A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy*, 32(9), 1543-1559. doi: 10.1016/j.energy.2007.01.008
- [313] **Perilhon, C., Alkadee, D., Descombes, G., & Lacour, S.** (2012). Life Cycle Assessment Applied to Electricity Generation from Renewable Biomass. *Energy Procedia*, 18, 165-176. doi: 10.1016/j.egypro.2012.05.028
- [314] **Butnar, I., Rodrigo, J., Gasol, C. M., & Castells, F.** (2010). Life-cycle assessment of electricity from biomass: Case studies of two biocrops in Spain. *Biomass and Bioenergy*, 34(12), 1780-1788. doi: 10.1016/j.biombioe.2010.07.013
- [315] **Chevalier, C., & Meunier, F.** (2005). Environmental assessment of biogas co- or tri-generation units by life cycle analysis methodology. *Applied Thermal Engineering*, 25(17-18), 3025-3041. doi: 10.1016/j.applthermaleng.2005.03.011
- [316] **Özdemir, M.** (2014-2017). Personal Communication. Marmara Ormancılık Araştırma Enstitüsü, Orman Genel Müdürlüğü, İstanbul. .
- [317] **Şahin, A.** (2015-2017). Personal Communication. Marmara Ormancılık Araştırma Enstitüsü, Orman Genel Müdürlüğü, İstanbul. .
- [318] **Kantay, R., & Köse, C.** (2006). Türkiye'de kabuk konusunda bugüne kadar yapılan çalışmalar ve değerlendirme. *Journal of the Faculty of Forestry Istanbul University*, 56(1), 1-15.
- [319] **Sefa Durmaz, S. K., Özlem Özgenç, Ümit C. Yıldız.** (2016). Bazı Odun Kabuklarının Kimyasal Analizi. *Düzce Üniversitesi Bilim ve Teknoloji Dergisi*(4), 438-442.
- [320] **İlhami Emrah Dönmez, Ş. D.** (2013). Ağaç kabuğunun yapısı ve yararlanma imkânları. *Journal of the Faculty of Forestry of Süleyman Demirel University*(14), 156-162.
- [321] **Dasappa, S.** (2014). Thermochemical Conversion of Biomass. In A. Hornung (Ed.), *Transformation of Biomass: Theory to Practice*. UK: John Wiley & Sons.
- [322] **Jenkins, B. M., Baxter, L. L., & Miles, T. R.** (1998). Combustion properties of biomass. *Fuel Processing Technology*, 54, 17-46.

- [323] **Klass, D. L.** (1998). *Thermal conversion: Combustion Biomass for renewable energy, fuels, and chemicals*. USA: Academic Press.
- [324] **Wise, L. E., & John, E. C.** (1952). *Wood Chemistry*. New York: Reinhold Publishing Corporation.
- [325] **Runkel, R. O., & Wilke, K. D.** (1951). *Holz Roh-Werkst* (Vol. 9, pp. 260-270).
- [326] **TAPPI.** (1992-1993). *TAPPI test methods*. USA: TAPPI Press.
- [327] **AspenTech.** (2013). *Getting started modeling processes with solids*. USA: Aspen Technology. Retrieved 01 December 2016, from <https://support.aspentech.com/>.
- [328] **AspenTech.** (2000). *Aspen Plus user guide*. USA: Aspen Technology. Retrieved 01 December 2016, from <https://support.aspentech.com/>.
- [329] **AspenTech.** (2013). *Aspen Plus physical property systems-physical property methods*. USA: Aspen Technology. Retrieved 01 December 2016, from <https://support.aspentech.com/>.
- [330] **AspenTech.** (2013). *Aspen Plus physical property systems-physical property models*. USA: Aspen Technology. Retrieved 01 December 2016, from <https://support.aspentech.com/>.
- [331] **Obernberger, I., Biedermann, F., Widmann, W., & Riedl, R.** (1997). Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions. *Biomass and Bioenergy*, 12(3), 211-224.
- [332] **EPA.** (2003). *Wood Residue Combustion in Boilers AP 42, Fifth Edition Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources*: US Environmental Protection Agency.
- [333] **EPA** (U.S. Environmental Protection Agency). (2007). *Biomass combined heat and power catalog of technologies. [Electronic version]*. USA: U.S. Environmental Protection Agency, Combined Heat and Power Partnership.
- [334] **EPA** (U.S. Environmental Protection Agency). (2008). *Catalog of CHP technologies. [Electronic version]*. USA: U.S. Environmental Protection Agency, Combined Heat and Power Partnership.
- [335] **Siemens** (2014). *Industrial Steam Turbines*: Siemens AG. Retrieved 20 November 2016, from <https://www.energy.siemens.com/hq/en/fossil-power-generation/steam-turbines/>.
- [336] **Phetteplace, G.** (1995). *Efficiency of steam and hot water heat distribution systems*: CRREL.
- [337] **CIBSE.** (2013). *Combined Heat and Power for Buildings* (Second ed.): CIBSE.
- [338] **Wade, D. W.** (2014). Low temperature heating distribution systems, RDA Engineering, Centrathem Inc. *In Proceedings of IDEA's 27th Annual Campus Energy Conference*. Atlanta, GA.
- [339] **Igen, A. K.** (n.d.). *How much biomass does a biomass power plant need to generate one MWh*. Retrieved 26 March 2017, from <https://www.scribd.com/document/226431361/Article-24#>.

- [340] **Haden, A.** (2015). Biomass technologies: Thermal energy and CHP, Wisewood Inc [PowerPoint Slides] *In Central Washington Biomass Energy Workshop*. April.
- [341] **ÇSB** (T. C. Çevre ve Şehircilik Bakanlığı). (2009). *Sanayi Kaynaklı Hava Kirliliğinin Kontrolü Yönetmeliği*. Retrieved 04 June 2017, from <http://www.csb.gov.tr/gm/cygm/index.php?Sayfa=sayfa&Tur=webmenu&Id=266>.
- [342] **U.S.DOE** (U.S. Department of Energy). (2012). *Minimize Boiler Blowdown: Advanced Manufacturing Office Energy Efficiency and Renewable Energy*. http://energy.gov/sites/prod/files/2014/05/f16/steam9_blowdown.pdf.
- [343] **Steven Wood, & Huisenga, M.** (2012). *Prefeasibility study for biomass power plant, Namibia, Power plant technical assessment*. South Africa: WSP Environment & Energy South Africa. Retrieved 05 June 2017, from http://www.nampower.com.na/public/docs/projects/renewable-energy/Final_Technical%20Report_NamPower%20EBtP%20Study.pdf.
- [344] **Goedkoop, M., Oele, M., Vieira, M., Leijting, J., Ponsioen, T., & Meijer, E.** (2013). *SimaPro Tutorial*: PRé. www.pre-sustainability.com.
- [345] **CML**. *Database, CML-IA Characterisation Factors*. Retrieved 27 February 2017, from <https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors>
- [346] **ReCiPe**. *ReCiPe methodology*. Retrieved 27 February 2017, from <http://www.lcia-recipe.net/>
- [347] **Aitor P. Acero, C. R., Andreas Ciroth** (2016). *LCIA methods: Impact assessment methods in Life Cycle Assessment and their impact categories*: GreenDelta GmbH. Retrieved 27 February 2017, from <http://www.openlca.org/wp-content/uploads/2015/11/LCIA-METHODS-v.1.5.4.pdf>.
- [348] **OSİB** (T.C. Orman ve Su İşleri Bakanlığı). (2014). *Ormancılık istatistikleri - Forestry statistics 2012*. Ankara: Türkiye İstatistik Kurumu.
- [349] **OGM** (Orman Genel Müdürlüğü). *Orman haritası*. Retrieved 13 May 2016, from <http://www.ogm.gov.tr/Sayfalar/OrmanHaritasi.aspx>
- [350] **OSİB** (T. C. Orman ve Su İşleri Bakanlığı). *GEODATA, Coğrafi Bilgi Sistemleri*. Retrieved 13 May 2016, from <http://cbs.ormansu.gov.tr/cob2011/?lang=tr>
- [351] **TEİAŞ** (Türkiye Elektrik İletim A.Ş.). *2015 yılı Türkiye elektrik enerjisi üretiminin kaynaklara göre dağılımı* Retrieved 02 March 2017, from <https://teias.gov.tr/tr/turkiye-elektrik-uretim-iletim-istatistikleri/2015>
- [352] **Filbakk, T., Høibø, O., & Nurmi, J.** (2011). Modelling natural drying efficiency in covered and uncovered piles of whole broadleaf trees for energy use. *Biomass and Bioenergy*, 35(1), 454-463. doi: 10.1016/j.biombioe.2010.09.003
- [353] **Valter Francescato, E. A., Luca Zuccoli Bergomi, Christian Metschina, Christian Schnedl, Nike Krajnc, Kajetan Kosci, Piort Gradziuk,**

- Gianfranco Nocentini, Stefano Stranieri.** (2009). *Wood fuels handbook: Production, quality requirements, trading* (S. Gelain, Trans.). Italy: AEBIOM-European Biomass Association, AIEL-Italian Agriforestry Energy Association.
- [354] **OGM** (Orman Genel Müdürlüğü). (2009). *Türkiye'de odunsu biyokütleden temiz enerji üretimi*. Ankara: Biyoenerji Çalışma Grubu. Retrieved 05 June 2017, from http://turkoted.org/admin/belgelerim/dosyalar/9EE_Biyoenerji_raporu.doc.
- [355] **Alakangas, E., & Virkkunen, M.** (2007). *Biomass fuel supply chains for solid biofuels: From small to large scale, EUBIONET II project*. Finland: Intelligent Energy for Europe.
- [356] **James, A. K., Thring, R. W., Rutherford, P. M., & Helle, S. S.** (2013). Characterization of Biomass Bottom Ash from an Industrial Scale Fixed-Bed Boiler by Fractionation. *Energy and Environment Research*, 3(2). doi: 10.5539/eer.v3n2p21
- [357] **Murphy, G.** (2005). Technology aids value recovery. *Focus on Forestry*, 18(2), 12-13.
- [358] **IEA-ETSAP** (International Energy Agency-Energy Technology Systems Analysis Programme). (2010). *Biomass for heat and power*. Retrieved 05 June 2017, from <https://iea-etsap.org/E-TechDS/PDF/E05-BiomassforHP-GS-AD-gct.pdf>.
- [359] **Evald, A., & Witt, J.** (2005). *Biomass CHP in practice/European BIO-CHP project*: European Commission Altener programme. Retrieved 17 January 2017, from <http://bio-chp.force.dk/wp-content/uploads/2015/07/Biomass-CHP-in-practice.pdf>.
- [360] **Bauer, C.** (2012). *Allocation according to exergy content*: The Ecoinvent Center, Swiss Center for Life Cycle Inventories.
- [361] **OSİB** (T. C. Orman ve Su İşleri Bakanlığı, Meteoroloji Genel Müdürlüğü). *Resmi istatistikler* Retrieved 17 March 2017, from <https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=A>
- [362] **Klvac, R., Ward, S., Owende, P. M. O., & Lyons, J.** (2003). Energy Audit of Wood Harvesting Systems. *Scandinavian Journal of Forest Research*, 18(2), 176-183. doi: 10.1080/02827580310003759
- [363] **Spielmann, M., Bauer, C., Dones, R., Tuchschnid, M.** (2007). *Transport Services. ecoinvent report No. 14*. Dübendorf: Swiss Centre for Life Cycle Inventories.
- [364] **IEA** (International Energy Agency). (2015). *IEA Bioenergy Task 43 TR2016:02 Biomass Feedstocks for Energy Markets - State of the art in sustainable biomass recovery technology/supply chain in forest operations*. Retrieved 05 June 2017, from <http://www.ieabioenergytask43.org/wp-content/uploads/2016/05/IEA-Bioenergy-Task-43-TR2016-02i.pdf>.
- [365] **Akay, A. E., Erdas, O., & Sessions, J.** (2004). Determining Productivity of Mechanized Harvesting Machines. *Journal of Applied Sciences*, 4(1), 100-105.

- [366] **Zhang, F., Johnson, D., & Wang, J.** (2015). Life-Cycle Energy and GHG Emissions of Forest Biomass Harvest and Transport for Biofuel Production in Michigan. *Energies*, 8(4), 3258-3271. doi: 10.3390/en8043258
- [367] **JohnDeere** *Forestry equipments-harvesters-770D-1070D-1270D-1470D*. Retrieved 03 March 2017, from https://www.deere.com/en_US/docs/non_current/harvesters/DKA1070WH.pdf.
- [368] **Bandit Industries, Inc.** Retrieved 16 November 2016, from <http://www.banditchippers.com/>
- [369] **Badger, P. C.** (2002). *Processing cost analysis for biomass feedstocks*. Oak Ridge National Laboratory: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program. Retrieved 05 June 2017, from http://boc.mtholyoke.edu/courses/tmillet/courses/geog_304B/ornlm-2002199.pdf.
- [370] **Schutte-Buffalo Hammermill.** Retrieved 21 November 2016, from <http://www.hammermills.com/>
- [371] **ECOSTAR.** *Dynamic disc screens*. Retrieved 21 November 2016, from <http://www.eco-star.it/en>
- [372] **Nemecek, T., & Kägi, T.** (2007). *Life cycle inventories of agricultural production systems*. Zurich and Dübendorf: ecoinvent centre, Swiss Centre for Life Cycle Inventories.
- [373] **FORCE Technology.** *CHP plants key figures, European BIO-CHP project, European Commission Alterner programme*. Retrieved 17 January 2017, from <https://bio-chp.force.dk/downloads/chp-plants-key-figures/>
- [374] **Wihersaari, M.** (2005). Greenhouse gas emissions from final harvest fuel chip production in Finland. *Biomass and Bioenergy*, 28(5), 435-443. doi: 10.1016/j.biombioe.2004.11.007
- [375] **OGM** (Orman Genel Müdürlüğü). (2014). *Ekosistem tabanlı fonksiyonel orman amenajman planlarının düzenlenmesine ait usul ve esaslar*.
- [376] **Şahin, A., Şahin, N., Çalışkan, A., & Ertaş, A.** (2013). Trakya'daki Meşe (*Quercus* sp.) Koruya Tahvil Meşcerelerindeki Uygulamaların Orman Amenajmanı ve Hasılatı ile Silvikültürel Esaslar Açısından İncelenmesi *In Proceedings of Ormancılıkta Sektörel Planlamanın 50. Yılı Uluslararası Sempozyumu* (pp. 548 – 561). Antalya, 26-28 November.
- [377] **Okmanis, M.** (2016). Preliminary data on productivity and cost of wood ash spreading in forest *In Proceedings of OSCAR Workshop-Mechanized and efficient silviculture*. Finland, 25-26 November.
- [378] **System Advisor Model (SAM) 2017.1.17** (National Renewable Energy Laboratory, NREL). USA. Retrieved 03 August 2017, from <https://sam.nrel.gov/>
- [379] **IGDAS.** (Istanbul Gas Distribution Industry and Trade Incorporated Company). *House gas prices*. Retrieved 07 August 2017, from <http://www.igdas.istanbul/satistarifesi?lang=en>

- [380] **Turconi, R., Tonini, D., Nielsen, C. F. B., Simonsen, C. G., & Astrup, T.** (2014). Environmental impacts of future low-carbon electricity systems: Detailed life cycle assessment of a Danish case study. *Applied Energy*, 132, 66-73. doi: 10.1016/j.apenergy.2014.06.078
- [381] **Atilgan, B., & Azapagic, A.** (2015). Life cycle environmental impacts of electricity from fossil fuels in Turkey. *Journal of Cleaner Production*, 106, 555-564. doi: 10.1016/j.jclepro.2014.07.046
- [382] **Taskiran, I.** (2010). *Orman biyokütlesi ve biyoenerji çalıştay - İklim değişikliği ve biyoenerji çalışma grubu müzakere belgeleri 1*. Kastamonu: Orman Genel Müdürlüğü.
- [383] **OGM** (Orman Genel Müdürlüğü). (2016). *Orman Genel Müdürlüğü stratejik plan (2017-2021)*. Retrieved 22 May 2017, from <https://www.ogm.gov.tr/ekutuphane/StratejikPlan/Forms/AllItems.aspx>.
- [384] **TÜBİTAK**. (The Scientific and Technological Research Council of Turkey). *TÜBİTAK çağrı planlaması (2015-2017)*. Retrieved 01 June 2017, from <http://www.tubitak.gov.tr/tr/icerik-tubitak-cagri-planlamasi>
- [385] **ÇOB** (T. C. Çevre ve Orman Bakanlığı). (2004). *Türkiye ulusal ormancılık programı 2004-2023*. Retrieved 28 May 2017, from https://www.ogm.gov.tr/ekutuphane/Dokumanlar/Ulusal_Ormancilik_Programi_2004_2023.pdf.
- [386] **KB** (T. C. Kalkınma Bakanlığı). (2013). *Onuncu kalkınma planı (2014-2018)*. Retrieved 22 May 2017, from <http://www.kalkinma.gov.tr/Pages/KalkinmaPlanlari.aspx>.
- [387] **KB** (T. C. Kalkınma Bakanlığı). (2014). *Onuncu kalkınma planı sürdürülebilir orman yönetimi özel ihtisas komisyon raporu*. Retrieved 22 May 2017, from http://tarim.kalkinma.gov.tr/wp-content/uploads/2014/12/Surdurulebilir_Orman_Yonetimi_oik.pdf.

APPENDICES

APPENDIX A: Mass and energy balances of Aspen Plus V8.4 process simulations for TR-Oak chip-fueled CBHBP plants (Case Study-1, -2, and -3).

APPENDIX B: Calculation procedures for stack gas emissions of CBHBP plants.

APPENDIX C: Calculation procedures for allocation factors used in the LCA study.

APPENDIX D: LCI used in the SimaPro software.



APPENDIX A

Mass and energy balances of Aspen Plus V8.4 process simulations for TR-Oak chip-fueled CBHBP plants (Case Study-1, -2, and -3):

Table A.1 : Mass and energy balances of Aspen Plus V8.4 process simulation for CS-1.

Unit Operation Block	Stream Name In	Mass Flow In (kg/h)	Energy Flow In (kW)	Stream Name Out	Mass Flow Out (kg/h)	Energy Flow Out (kW)
TR-Oak Chip Combustion Side						
DECOMP	BIOFUEL	3272.97	-7867.58	INBURNER	3272.97	-4326.59
				Q-DECOMP		-3540.99
COMBSTN	INBURNER	3272.97	-4326.59	COMBPROD	23,820.54	-11,271.41
	H-AIR	20,547.58	1017.68	Q-RGIBBS		4421.51
	Q-DECOMP		-3540.99			
SEPARATE	COMBPROD	23,820.54	-11,271.41	CMBGASES	23,778.39	-11,273.26
				TOTALASH	42.16	1.85
CMBHEAT	CMBGASES	23,778.39	-11,273.26	HFLUEGAS	23,778.26	-16,787.19
	Q-RGIBBS		4421.51	Q100EFF		9935.52
BOIEFF	Q100EFF		9935.52	QBOILER		8941.97
				LOSS		993.55
A-HEATEX	HFLUEGAS	23,778.26	-16,787.19	CFLUEGAS	23,778.26	-17,806.48
	C-AIR	20,547.58	-1.62	H-AIR	20,547.58	1017.68
Rankine Cycle (Steam Turbine) Side						
PUMP	CONDST-2	11,463.58	-49,427.09	HPWTR-1	11,463.58	-49,412.72
	WPUMP		14.37			
BOILER	HPWTR-2	11,463.58	-49,412.72	HPSTM-1	11,463.58	-40,470.75
	QBOILER		8941.97			
TURBINE	HPSTM-2	11,463.58	-40,470.75	LPSTM-1	11,463.58	-42,470.75
				WTRBN		2000.00
DHCONDSR	LPSTM-1	11,463.58	-42,470.75	CONDST-1	11,463.58	-49,427.09
				QDHCNDSR		6956.34
Total Energy Flow In and Out (kW)			-212,518.91			-212,518.82
Total Mass Flow In and Out (kg/h)		164,872.60			164,872.47	

Total Mass / Energy Balance Difference (% Total Flow In) = 0.0042 / 0.0080

Table A.2 : Mass and energy balances of Aspen Plus V8.4 process simulation for CS-2.

Unit Operation Block	Stream Name In	Mass Flow In (kg/h)	Energy Flow In (kW)	Stream Name Out	Mass Flow Out (kg/h)	Energy Flow Out (kW)
TR-Oak Chip Combustion Side						
DECOMP	BIOFUEL	7205.09	-17,319.65	INBURNER	7205.09	-9524.53
				Q-DECOMP		-7795.12
COMBSTN	INBURNER	7205.09	-9524.53	COMBPROD	52,438.42	-24,812.83
	H-AIR	45,233.33	2240.31	Q-RGIBBS		9733.48
	Q-DECOMP		-7795.12			
SEPARATE	COMBPROD	52,438.42	-24,812.83	CMBGASES	52,345.62	-24,816.90
				TOTALASH	92.80	4.07
CMBHEAT	CMBGASES	52,345.62	-24,816.90	HFLUEGAS	52,345.34	-36,955.22
	Q-RGIBBS		9733.48	Q100EFF		21,872.00
BOIEFF	Q100EFF		21,872.00	QBOILER		19,684.80
				LOSS		2187.20
A-HEATEX	HFLUEGAS	52,345.34	-36,955.22	CFLUEGAS	52,345.34	-39,199.09
	C-AIR	45,233.33	-3.56	H-AIR	45,233.33	2240.31
Rankine Cycle (Steam Turbine) Side						
PUMP	CONDST-2	24,336.66	-104,930.00	HPWTR-1	24,336.66	-104,880.00
	WPUMP		50.21			
BOILER	HPWTR-2	24,336.66	-104,880.00	HPSTM-1	24,336.66	-85,197.02
	QBOILER		19,684.80			
TURBINE	HPSTM-2	24,336.66	-85,197.02	LPSTM-1	24,336.66	-90,197.02
				WTRBN		5000.00
DHCONDSTR	LPSTM-1	24,336.66	-90,197.02	CONDST-1	24,336.66	-104,930.00
				QDHCNDSR		14,735.02
Total Energy Flow In and Out (kW)			-452,851.04			-452,850.85
Total Mass Flow In and Out (kg/h)		359,352.86			359,352.58	

Total Mass / Energy Balance Difference (% Total Flow In) = 0.0042 / 0.0078

Table A.3 : Mass and energy balances of Aspen Plus V8.4 process simulation for CS-3.

Unit Operation Block	Stream Name In	Mass Flow In (kg/h)	Energy Flow In (kW)	Stream Name Out	Mass Flow Out (kg/h)	Energy Flow Out (kW)
TR-Oak Chip Combustion Side						
DECOMP	BIOFUEL	13,699.28	-32,930.43	INBURNER	13,699.28	-18,109.31
				Q-DECOMP		-14,821.12
COMBSTN	INBURNER	13,699.28	-18,109.31	COMBPROD	99,702.91	-47,177.46
	H-AIR	86,003.63	4259.57	Q-RGIBBS		18,506.59
	Q-DECOMP		-14,821.12			
SEPARATE	COMBPROD	99,702.91	-47,177.46	CMBGASES	99,526.46	-47,185.19
				TOTALASH	176.45	7.73
CMBHEAT	CMBGASES	99,526.46	-47,185.19	HFLUEGAS	99,525.93	-70,264.19
	Q-RGIBBS		18,506.59	Q100EFF		41,585.97
BOIEFF	Q100EFF		41,585.97	QBOILER		37,427.37
				LOSS		4158.60
A-HEATEX	HFLUEGAS	99,525.93	-70,264.19	CFLUEGAS	99,525.93	-74,530.53
	C-AIR	86,003.63	-6.77	H-AIR	86,003.63	4259.57
Rankine Cycle (Steam Turbine) Side						
PUMP	CONDST-2	45,450.00	-195,970.00	HPWTR-1	45,450.00	-195,850.00
	WPUMP		115.86			
BOILER	HPWTR-2	45,450.00	-195,850.00	HPSTM-1	45,450.00	-158,420.00
	QBOILER		37,427.37			
TURBINE	HPSTM-2	45,450.00	-158,420.00	LPSTM-1	45,450.00	-168,420.00
				WTRBN		10,000.00
DHCONDSR	LPSTM-1	45,450.00	-168,420.00	CONDST-1	45,450.00	-195,970.00
				QDHCNDSR		27,543.23
Total Energy Flow In and Out (kW)			-847,259.12			
Total Mass Flow In and Out (kg/h)			679,961.12			679,960.59

Total Mass / Energy Balance Difference (% Total Flow In) = 0.0043 / 0.0078

APPENDIX B

Calculation procedures for stack gas emissions of CBHBP plants:

Concentration calculation of stack gas emissions in mg/m³:

Equation (B.1) is used to calculate the concentrations of stack gas emissions in mg/m³ at stack conditions based on the Aspen Plus process simulation outputs. These are the mass flow rates of the combustion gases in kg/h and the total volumetric flow rate in m³/h, as reported in Tables 3.5 to 3.7.

$$\text{Concentration } \left(\frac{\text{mg}}{\text{m}^3} \right) = \frac{\text{Mass Flow Rate } \left(\frac{\text{kg}}{\text{h}} \right)}{\text{Total Volumetric Flow Rate } \left(\frac{\text{m}^3}{\text{h}} \right)} \times \frac{10^6 \text{ (mg)}}{1 \text{ (kg)}} \quad (\text{B.1})$$

Concentration calculation of stack gas emissions in mg/Nm³:

Equation (B.2) is used to calculate the concentrations of stack gas emissions in mg/Nm³ under standard conditions (0 °C and 1 atm), based on the Aspen Plus process simulation outputs. These are the mass flow rates of the combustion gases in kg/h and the total molar flow rate in kmol/h, as reported in Tables 3.5 to 3.7. The molar volume at 0 °C and 1 atm is 22.4 Nm³/kmol.

$$\begin{aligned} \text{Concentration } \left(\frac{\text{mg}}{\text{Nm}^3} \right) \\ = \frac{\text{Mass Flow Rate } \left(\frac{\text{kg}}{\text{h}} \right)}{\text{Total Molar Flow Rate } \left(\frac{\text{kmol}}{\text{h}} \right) \times 22.4 \left(\frac{\text{Nm}^3}{\text{kmol}} \right)} \times \frac{10^6 \text{ (mg)}}{1 \text{ (kg)}} \end{aligned} \quad (\text{B.2})$$

Concentration calculation of stack gas emissions in ppmv:

Equation (B.3) and (B.4) are used to calculate the concentrations of stack gas emissions in ppmv based on the concentrations either in mg/m³ or mg/Nm³ as calculated in equation (B.1) and (B.2). The molecular weight of the combustion gases in kg/kmol and molar volume are calculated either for stack conditions in m³/kmol or for standard conditions in Nm³/kmol. While the molar volume in m³/kmol under stack conditions is determined by dividing the total volumetric flow rate in m³/h by the total molar flow rate in kmol/h (reported in Tables 3.5 to 3.7), the molar volume in Nm³/kmol is 22.4.

$$\text{Concentration (ppmv)} = \frac{\text{Concentration} \left(\frac{\text{mg}}{\text{m}^3} \right) \times \text{Molar Volume} \left(\frac{\text{m}^3}{\text{kmol}} \right)}{\text{Molecular Weight} \left(\frac{\text{kg}}{\text{kmol}} \right)} \quad (\text{B.3})$$

$$\text{Concentration (ppmv)} = \frac{\text{Concentration} \left(\frac{\text{mg}}{\text{Nm}^3} \right) \times 22.4 \left(\frac{\text{Nm}^3}{\text{kmol}} \right)}{\text{Molecular Weight} \left(\frac{\text{kg}}{\text{kmol}} \right)} \quad (\text{B.4})$$

PM-10 emission calculation in kg/h and mg/m³:

The PM-10 emission factor used in the thesis and the related information that belongs to “AP 42, Compilation of Air Pollutant Emission Factors” are provided in Table B.1 [332].

As seen in Table B.1, the emission factor is presented on an energy basis (pound of pollutant per million Btu of heat input). The emission factor is first converted from lb/MMBtu to lb/t by multiplying with (HHV*2000), where HHV is the higher heating value of the fuel, as indicated in EPA [332]; then converted to kg/t. After the necessary unit conversions have been made, the PM-10 emission factor used in this thesis is found (0.29426 kg/t).

The PM-10 emission mass flow rate (kg/h) is calculated by multiplying the PM-10 emission factor in kg/t by the biofuel input in t/h as provided in equation (B.5). After that, the PM-10 emission concentration under mg/m³ at stack conditions and mg/Nm³ under standard conditions are calculated using equations (B.1) and (B.2), respectively.

Table B.1 : PM-10 emission factor information of “AP 42, Compilation of Air Pollutant Emission Factor” [332].

Table Number	1.6-1
Table Name	Emission Factors for PM from Wood Residue Combustion
Fuel	All Fuels
PM control Device	Electrostatic Precipitator
Emission factor rating	D
Emission Factor (lb/MMBtu)	0.04 for Filterable PM-10
Emission Factor (kg/t) ^a	0.29426 for Filterable PM-10

^a Calculated.

$$\begin{aligned}
& PM \text{ Emission Mass Flow Rate } \left(\frac{kg}{h} \right) \\
& = PM \text{ Emission Factor } \left(\frac{kg}{ton} \right) \times Biofuel \text{ Input } \left(\frac{ton}{h} \right)
\end{aligned} \tag{B.5}$$

Concentration calculation under reference conditions in mg/Nm³:

Equation (B.6), (B.7), and (B.8) are used to calculate the concentrations of stack gas emissions (combustion gases and PM-10) under reference conditions, which are taken as 0 °C temperature, 1 atm pressure, 6% volumetric oxygen, and dry basis for stack gases, as stated in the “Industrial air pollution control regulation” of Turkey [341].

In equation (B.6), “Determined Concentration (mg/Nm³)” is the concentration in mg/Nm³ listed in Table 3.8. Formulas used to calculate the correction factors for oxygen and moisture are provided with the equations (B.7) and (B.8), respectively. In these equations, “% Determined Oxygen” and “% Determined Moisture” are the concentration values in ppmv. These are reported in Table 3.8, multiplied by 10⁻⁴. It is important to note that oxygen is determined on a wet basis and should also be corrected to dry conditions as indicated in equation (B.7).

$$\begin{aligned}
& \text{Concentration at reference conditions } \left(\frac{mg}{Nm^3} \right) \\
& = \text{Determined Concentration } \left(\frac{mg}{Nm^3} \right) \\
& \quad \times \text{Correction Factor for Oxygen} \\
& \quad \times \text{Correction Factor for Moisture}
\end{aligned} \tag{B.6}$$

$$\text{Correction Factor for Oxygen} = \frac{(21 - \% \text{ Reference Oxygen})}{(21 - \% \text{ Determined Oxygen, Dry})} \tag{B.7}$$

$$\text{Correction Factor for Moisture} = \frac{100}{(100 - \% \text{ Determined Moisture})} \tag{B.8}$$

APPENDIX C

Calculation procedures for allocation factors used in the LCA study:

Equation (C.1), the Carnot factor, is used to calculate the exergy content of bioheat (ζ_{th}). While T is the temperature of the steam released into the district heating system, T_u is the average surrounding temperature. Also, the temperatures have to be in Kelvins (K). T_u is calculated based on 8-month average temperatures (average values over long years, 1950–2015) of the Marmara Region in Turkey [361], as provided in Table C.1.

The exergy content of biopower (ζ_{el}) is 1.0. With the help of equations (C.1) and (C.2), equations (C.3) and (C.4) are used to calculate allocation factors for biopower and bioheat, respectively. Here, η_{el} and η_{th} are the CBHBP electrical and thermal efficiencies, respectively [34,194,223,262,360,361].

$$\zeta_{th} = \frac{(T - T_u)}{T} \quad (C.1)$$

$$\zeta_{plant} = (\zeta_{el} \times \eta_{el}) + (\zeta_{th} \times \eta_{th}) \quad (C.2)$$

$$Allocation_{el} = \frac{(\zeta_{el} \times \eta_{el})}{\zeta_{plant}} \quad (C.3)$$

$$Allocation_{th} = \frac{(\zeta_{th} \times \eta_{th})}{\zeta_{plant}} \quad (C.4)$$

Table C.1 : Average temperatures (average values over long years, 1950–2015) for Marmara Region in Turkey [361].

Cities	Months and Temperatures (°C)								Average
	January	February	March	April	September	October	November	December	
Balıkesir	4.9	5.9	8.3	13.0	20.7	15.7	10.4	6.7	10.7
Bilecik	2.6	3.7	6.6	11.5	18.4	13.8	9.0	4.7	8.8
Bursa	5.4	6.3	8.4	12.8	20.1	15.2	10.7	7.4	10.8
Çanakkale	6.3	6.7	8.3	12.6	20.9	16.0	11.9	8.5	11.4
Edirne	2.7	4.4	7.6	12.8	19.9	14.2	9.1	4.6	9.4
İstanbul	5.7	5.7	7.0	11.1	19.8	15.6	11.5	8.0	10.6
Kırklareli	2.9	4.0	6.9	12.0	19.2	13.9	9.0	5.0	9.1
Kocaeli	6.2	6.7	8.7	13.1	20.4	16.0	11.9	8.4	11.4
Sakarya	6.1	6.6	8.5	12.9	19.5	15.4	11.5	8.2	11.1
Tekirdağ	4.9	5.4	7.4	11.9	20.0	15.4	11.0	7.2	10.4
Yalova	6.5	6.8	8.3	12.4	20.0	15.7	11.7	8.7	11.3
Average									10.4

APPENDIX D

LCI used in the SimaPro software:

Following are the tables providing foreground inventories used in the LCA study. Basically, all inputs and outputs are based on Aspen Plus process simulation (Chapter 3) and LCA inventory (Chapter 4) studies as explained in previous chapters. Table D.1 provides the Turkish electricity mix inventory used in all processes in the LCA study. Table D.2 presents the LCI for CBHBP production in CS-1, -2, and -3. Subsequent tables (from Table D.3 to Table D.9) show the details for processes in Table D.2, along with their background process reference information. Tables D.10 to D.14 provide the LCI for CBHBP production using the eco-design parameters determined for the LCA study.

Table D.1 : Turkish electricity mix inventory.

INPUTS ^a	Unit	Amount
Electricity production		
Natural gas	kWh	0.379010663
Imported coal, hard coal, asphaltite	kWh	0.171248062
Lignite	kWh	0.119700867
Hydro (Dam)	kWh	0.181501577
Hydro (Natural lake and run of river)	kWh	0.074992532
Wind	kWh	0.044511990
Geothermal	kWh	0.013081425
Liquid fuels	kWh	0.008495191
Biomass	kWh	0.005158081
Waste heat	kWh	0.001558159
Solar	kWh	0.000741453
Transmission network ^b	km	6.89910E-09
Transmission losses ^b	kWh	0.05655
OUTPUTS		
Products		
Electricity	kWh	1
Emissions to air ^b		
Dinitrogen monoxide	kg	0.000005
Ozone	kg	4.15773E-06

^a Input amounts for electricity production are based on the distribution of Turkey's gross electricity production, by energy source, at the end of 2015 [351].

^{a,b} Electricity production processes, transmission network and losses, and emissions to air from the transmission network are from the "Electricity, high voltage {TR}" market for "Alloc Def, U" process in ecoinvent v3.1 [285,291].

Table D.2 : LCI for CBHBP production.

INPUTS ^a	Unit	Amount		
		Case Study-1	Case Study-2	Case Study-3
TR-Oak chip supply at roadside (dry)	kg	0.260921169	0.260675535	0.260533963
TR-Oak chip transport from roadside to CBHBP plant (with mc ^b)	tkm	0.018637226	0.018619681	0.018609569
TR-Oak chip feedstock preparation at CBHBP plant (dry)	kg	0.255805068	0.255564250	0.255425454
Treated water use	kg	0.051197616	0.049326863	0.048424179
Lubrication oil use	kg	0.000011808	0.000011808	0.000011808
TR-Oak ash transport from CBHBP plant to forest	tkm	0.002791458	0.002697702	0.002652442
TR-Oak ash spreading in forest	ha	9.41070E-06	9.40184E-06	9.39673E-06
Const & decom for CBHBP plant	p	1	1	1
Const & decom for TR-oak chip supply chain	p	1	1	1
CBHBP plant own biopower consumption	kWh	0.017864442	0.020268543	0.02130877
OUTPUTS^a				
Products				
Biopower production (gross), CBHBP plant	kWh	0.2233	0.2534	0.2664
Bioheat production (gross), CBHBP plant	kWh	0.7767	0.7466	0.7336
Emissions to air				
Carbon monoxide	kg	3.60881E-08	3.60541E-08	3.60345E-08
Nitric oxide	kg	0.000352344	0.000352012	0.000351821
Nitrogen dioxide	kg	4.22036E-06	4.21639E-06	4.21410E-06
Dinitrogen monoxide	kg	2.87524E-08	2.87252E-08	2.87096E-08
Sulfur dioxide	kg	0.000437300	0.000436888	0.000436651
Sulfur trioxide	kg	2.83242E-05	2.82975E-05	2.82821E-05
Particulates, < 10 µm	kg	7.52732E-05	7.52023E-05	7.51615E-05
Wastes				
TR-Oak ash	kg	0.004631539	0.00462718	0.004624666
Waste water	kg	0.051197616	0.049326863	0.048424179
Waste lubrication oil to treatment	kg	0.000011808	0.000011808	0.000011808

^a All input and output values are based on Aspen Plus process simulation outputs and LCA inventory calculations for CS-1, -2, and -3. All information related to the processes in the table is provided separately.

^b mc: moisture content.

Table D.3 : LCI for TR-Oak chip supply at roadside.

INPUTS^a	Unit	Amount
TR-Oak coppices (dry)	t	110.6752572
Harvesting operation ^b	h	36.89175240
Collecting and forwarding operation ^c	h	23.61072153
Chipping operation ^d	h	6.626027034
OUTPUTS^a		
Products		
TR-Oak chip at roadside (dry)	t	102.0408163
Dry matter losses	t	8.634440865

^a All input and output amounts are based on LCA inventory calculations. The amounts are valid for all cases.

^b The “Harvesting operation” is adapted from the “Harvesting, forestry harvester {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^c The “Collecting and forwarding operation” is adapted from the “Forwarding, forwarder {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^d The “Chipping operation” is adapted from the “Wood chipping, chipper, mobile, diesel, at forest road {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^{b, c, d} The adapted processes use the Turkish electricity mix, and do not include cons & decom data for harvester, forwarder, and mobile chipper.

Table D.4 : LCI for TR-Oak chip feedstock preparation at CBHBP plant.

INPUTS^a	Unit	Amount
Receiving (Front-end loader) operation ^b	h	14.28571429
OUTPUTS^a		
Products		
TR-Oak chip feedstock (dry)	t	100
Dry-matter losses	t	2.040816327

^a All input and output amounts are based on LCA inventory calculations. The amounts are valid for all cases.

^b Process details are provided in Table D.5.

Table D.5 : LCI for receiving (front-end loader) operation.

INPUTS	Unit	Amount
Diesel use ^a	kg	3.179736
OUTPUTS		
Products		
Receiving (Front-end loader) operation	h	1
Emissions to air ^b		
Copper	kg	5.40555E-06
Nitrogen oxides	kg	0.123980532
Cadmium	kg	3.17974E-08
Benzo(a)pyrene	kg	9.53921E-08
Ammonia	kg	6.35947E-05
Particulates, < 2.5 µm	kg	0.015606961
Zinc	kg	3.17974E-06
Dinitrogen monoxide	kg	0.000381568
Selenium	kg	3.17974E-08
NMVOC, non-methane volatile organic compounds	kg	0.006818929
PAH, polycyclic aromatic hydrocarbons	kg	1.04613E-05
Methane, fossil	kg	0.000410186
Nickel	kg	2.22582E-07
Carbon dioxide, fossil	kg	9.920776320
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	kg	1.90530E-13
Carbon monoxide, fossil	kg	0.018670010

^a The amount of diesel use is based on the literature [151].

^b The “Emissions to air” is calculated based on the emission factors reported in the literature [372] and the “Transport, tractor and trailer, agricultural {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

Table D.6 : LCI for TR-Oak ash spreading in forest [285,291,377].

INPUTS ^a	Unit	Amount
TR-Oak ash spreading operation ^a	h	1
OUTPUTS		
Products		
TR-Oak ash spreading ^b	ha	0.7

^a The “TR-Oak ash spreading operation” is adapted from the “Forwarding, forwarder {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291]. The adapted process does not include cons & decomp data for forwarder.

^b The “TR-Oak ash spreading” amount is based on the literature [377].

Table D.7 : LCI for const & decom of CBHBP plants.

INPUTS ^a	Unit	Amount		
		CS-1	CS-2	CS-3
Common components for heat and electricity ^b	p	1.06727E-09	1.08049E-09	1.07719E-09
Components for electricity only ^c	p	1.06727E-09	1.08049E-09	1.07719E-09
Building ^d	p	2.66817E-10	2.70123E-10	2.69297E-10
Receiving equipment ^e	p	8.20976E-10	7.45167E-10	5.87558E-10
Sizing equipment ^f	p	8.20976E-10	3.72584E-10	1.95853E-10
Grinding equipment ^g	p	8.20976E-10	3.72584E-10	1.95853E-10
ESP ^h	p	8.20976E-10	3.72584E-10	1.95853E-10
TR-Oak chips storage silo ⁱ	p	2.05244E-10	9.31459E-11	4.89632E-11
TR-Oak ash storage silo ⁱ	p	2.05244E-10	9.31459E-11	4.89632E-11
OUTPUTS				
Products				
Const & decom, CBHBP plant	p	1	1	1

^a All input amounts are calculated based on the annual biopower and bioheat production of the simulated CBHBP plants and their lifetime.

^b The “Common components for heat and electricity” process is adapted from the “Heat and power co-generation unit, 6400kW thermal, common components for heat+electricity, {GLO}| construction | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^c The “Components for electricity only” process is adapted from the “Heat and power co-generation unit, 6400kW thermal, components for electricity only, {GLO}| construction | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^d The “Building” is adapted from the “Heat and power co-generation unit, 6400kW thermal, building, {GLO}| construction | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^{b, c, d} All input amounts are based on the scaling factors calculated as 1.3 for CS-1, 2.9 for CS-2, and 5.5 for CS-3.

^e The “Receiving equipment” is adapted from the “Tractor, 4-wheel, agricultural, {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^{f, g} The “Sizing equipment” and the “Grinding equipment” are adapted from the “Agricultural machinery, unspecified, {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^h The “ESP” is adapted from the “Dust collector, electrostatic precipitator, for industrial use, {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

ⁱ Steel used in the design of the storage silos is adapted from the “Steel, low-alloyed, hot rolled, {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

Table D.8 : LCI for const & decom of TR-Oak chip supply chain.

INPUTS ^a	Unit	Amount		
		CS-1	CS-2	CS-3
Harvester ^b	p	8.20976E-10	3.72584E-10	1.95853E-10
Forwarder ^c	p	8.20976E-10	3.72584E-10	1.95853E-10
Mobile chipper ^d	p	8.20976E-10	3.72584E-10	1.95853E-10
OUTPUTS				
Products				
Const & decom, TR-oak chip supply chain	p	1	1	1

^a All input amounts are calculated based on the annual biopower and bioheat production of the simulated CBHBP plants and their lifetime.

^b The “Harvester” is adapted from the “Forestry harvester, {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^c The “Forwarder” is adapted from the “Forwarder, {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

^d The “Mobile chipper” is adapted from the “Chipper, mobile, diesel, {TR} electricity, {GLO}| market for | Alloc Def, U” process in ecoinvent v3.1 [285,291].

Table D.9 : LCI information for other processes used in CBHBP production.

Processes	Remark
Transport	
TR-Oak chip transport from roadside to CBHBP plant (with mc ^a)	Transportation is adapted from the “Transport, freight, lorry 16-32 metric ton, EURO5 {GLO} market for Alloc Def, U” process in ecoinvent v3.1 [285,291]. The adapted process includes cons & decom data for the lorry vehicle and road infrastructure.
TR-Oak ash transport from CBHBP plant to forest	
Treated water use	Treated water production is adapted from the “Water, decarbonised, at user, {GLO} market for Alloc Def, U” process in ecoinvent v3.1 [285,291].
Lubrication oil use	Lubrication oil production is adapted from the “Lubricating oil, {GLO} market for Alloc Def, U” process in ecoinvent v3.1 [285,291].
Diesel use	Diesel production is based on the “Diesel, low-sulfur, {TR} electricity, {GLO} market for Alloc Def, U” process designed in SimaPro software, which is adapted from the “Diesel, low-sulfur {CH} market for Alloc Def, U”, the “Diesel, low-sulfur {Europe without Switzerland} market for Alloc Def, U”, and the “Diesel, low-sulfur {RoW} market for Alloc Def, U” processes in ecoinvent v3.1 [285,291].

^a mc: moisture content.

Table D.10 : LCI for CBHBP production, CS-1 (2 MW_e): Eco-design approach for moisture content of (20, 40, 50) %.

INPUTS ^a	Unit	Moisture Contents (%)		
		20	40	50
TR-Oak chip supply at roadside (dry)	kg	0.253221474	0.271950179	0.289052116
TR-Oak chip transport from roadside to CBHBP plant (with mc ^b)	tkm	0.018087248 ^c	0.022662515	0.028905212
TR-Oak chip feedstock preparation at CBHBP plant (dry)	kg	0.248256347	0.266617823	0.283384428
Treated water use	kg	0.051197616	0.051197616	0.051197616
Lubrication oil use	kg	0.000011808	0.000011808	0.000011808
TR-Oak ash transport from CBHBP plant to forest	tkm	0.002784624	0.002801246	0.002816425
TR-Oak ash spreading in forest	ha	9.132989E-6	9.808481E-6	1.042530E-5
Const & decom for CBHBP plant	p	1	1	1
Const & decom for TR-oak chip supply chain	p	1	1	1
CBHBP plant own biopower consumption	kWh	0.017864442	0.017864442	0.017864442
OUTPUTS^a				
Products				
Biopower production (gross), CBHBP plant	kWh	0.2233	0.2233	0.2233
Bioheat production (gross), CBHBP plant	kWh	0.7767	0.7767	0.7767
Emissions to air				
Carbon monoxide	kg	3.454090E-8	3.829355E-8	4.169226E-8
Nitric oxide	kg	0.000341948	0.000367238	0.000390332
Nitrogen dioxide	kg	4.153047E-6	4.320672E-6	4.483260E-6
Dinitrogen monoxide	kg	2.829359E-8	2.943580E-8	3.054362E-8
Sulfur dioxide	kg	0.000424106	0.000456185	0.000485432
Sulfur trioxide	kg	2.785326E-5	2.902271E-5	3.014952E-5
Particulates, < 10 µm	kg	7.305191E-5	7.845496E-5	8.338870E-5
Wastes				
TR-Oak ash	kg	0.004494865	0.004827313	0.005130885
Waste water	kg	0.051197616	0.051197616	0.051197616
Waste lubrication oil to treatment	kg	0.000011808	0.000011808	0.000011808

^a All input and output values are based on Aspen Plus process simulation outputs and LCA inventory calculations for CS-1 with different moisture contents of TR-Oak chip feedstock.

^b mc: moisture content, ^c Transported with a mc of 30%.

Table D.11 : LCI for CBHBP production, CS-1 (2 MW_e): Eco-design approach for excess air ratio of (1.2, 1.8, 2.0).

INPUTS ^a	Unit	Excess Air Ratio		
		1.2	1.8	2.0
TR-Oak chip supply at roadside (dry)	kg	0.257431183	0.264504028	0.266947528
TR-Oak chip transport from roadside to CBHBP plant (with mc ^b)	tkm	0.018387942	0.018893145	0.019067681
TR-Oak chip feedstock preparation at CBHBP plant (dry)	kg	0.252383513	0.259317675	0.261713263
Treated water use	kg	0.051197616	0.051197616	0.051197616
Lubrication oil use	kg	0.000011808	0.000011808	0.000011808
TR-Oak ash transport from CBHBP plant to forest	tkm	0.002788360	0.002794638	0.002796806
TR-Oak ash spreading in forest	ha	9.284822E-6	9.539920E-6	9.628050E-6
Const & decom for CBHBP plant	p	1	1	1
Const & decom for TR-oak chip supply chain	p	1	1	1
CBHBP plant own biopower consumption	kWh	0.017864442	0.017864442	0.017864442
OUTPUTS^a				
Products				
Biopower production (gross), CBHBP plant	kWh	0.2233	0.2233	0.2233
Bioheat production (gross), CBHBP plant	kWh	0.7767	0.7767	0.7767
Emissions to air				
Carbon monoxide	kg	5.133124E-8	3.129113E-8	2.958865E-8
Nitric oxide	kg	0.000196318	0.000495123	0.000588971
Nitrogen dioxide	kg	1.631079E-6	6.933670E-6	8.803072E-6
Dinitrogen monoxide	kg	1.574538E-8	4.088646E-8	4.893149E-8
Sulfur dioxide	kg	0.000438064	0.000439643	0.000442005
Sulfur trioxide	kg	1.968108E-5	3.329242E-5	3.572424E-5
Particulates, < 10 µm	kg	7.426637E-5	7.630682E-5	7.701175E-5
Wastes				
TR-Oak ash	kg	0.004569591	0.004695138	0.004738513
Waste water	kg	0.051197616	0.051197616	0.051197616
Waste lubrication oil to treatment	kg	0.000011808	0.000011808	0.000011808

^a All input and output values are based on Aspen Plus process simulation outputs and LCA inventory calculations for CS-1 with different excess air ratios.

^b mc: moisture content (30%).

Table D.12 : LCI for CBHBP production, CS-1 (2 MW_e): Eco-design approach for excess air ratio of (2.2, 2.5).

INPUTS ^a	Unit	Excess Air Ratio	
		2.2	2.5
TR-Oak chip supply at roadside (dry)	kg	0.269435034	0.273254901
TR-Oak chip transport from roadside to CBHBP plant (with mc ^b)	tkm	0.019245360	0.019518207
TR-Oak chip feedstock preparation at CBHBP plant (dry)	kg	0.264151994	0.267896961
Treated water use	kg	0.051197616	0.051197616
Lubrication oil use	kg	0.000011808	0.000011808
TR-Oak ash transport from CBHBP plant to forest	tkm	0.002799014	0.002802404
TR-Oak ash spreading in forest	ha	9.717767E-6	9.855539E-6
Const & decom for CBHBP plant	p	1	1
Const & decom for TR-oak chip supply chain	p	1	1
CBHBP plant own biopower consumption	kWh	0.017864442	0.017864442
OUTPUTS^a			
Products			
Biopower production (gross), CBHBP plant	kWh	0.2233	0.2233
Bioheat production (gross), CBHBP plant	kWh	0.7767	0.7767
Emissions to air			
Carbon monoxide	kg	2.844611E-8	2.733628E-8
Nitric oxide	kg	0.000683029	0.000825657
Nitrogen dioxide	kg	1.071788E-5	1.367312E-5
Dinitrogen monoxide	kg	5.703067E-8	6.935970E-8
Sulfur dioxide	kg	0.000444774	0.000449499
Sulfur trioxide	kg	3.774021E-5	4.025246E-5
Particulates, < 10 µm	kg	7.772937E-5	7.883136E-5
Wastes			
TR-Oak ash	kg	0.004782668	0.004850473
Waste water	kg	0.051197616	0.051197616
Waste lubrication oil to treatment	kg	0.000011808	0.000011808

^a All input and output values are based on Aspen Plus process simulation outputs and LCA inventory calculations for CS-1 with different excess air ratios.

^b mc: moisture content (30%).

Table D.13 : LCI for CBHBP production, CS-1 (2 MW_e): Eco-design approach for furnace temperature of (850, 900, 1000) °C.

INPUTS ^a	Unit	Furnace Temperature (°C)		
		850	900	1000
TR-Oak chip supply at roadside (dry)	kg	0.260842565	0.260879714	0.260972748
TR-Oak chip transport from roadside to CBHBP plant (with mc ^b)	tkm	0.018631612	0.018634265	0.018640911
TR-Oak chip feedstock preparation at CBHBP plant (dry)	kg	0.255728005	0.255764426	0.255855635
Treated water use	kg	0.051197616	0.051197616	0.051197616
Lubrication oil use	kg	0.000011808	0.000011808	0.000011808
TR-Oak ash transport from CBHBP plant to forest	tkm	0.002791388	0.002791421	0.002791504
TR-Oak ash spreading in forest	ha	9.407861E-6	9.409201E-6	9.412556E-6
Const & decom for CBHBP plant	p	1	1	1
Const & decom for TR-oak chip supply chain	p	1	1	1
CBHBP plant own biopower consumption	kWh	0.017864442	0.017864442	0.017864442
OUTPUTS^a				
Products				
Biopower production (gross), CBHBP plant	kWh	0.2233	0.2233	0.2233
Bioheat production (gross), CBHBP plant	kWh	0.7767	0.7767	0.7767
Emissions to air				
Carbon monoxide	kg	3.054507E-9	1.107112E-8	1.071302E-7
Nitric oxide	kg	0.000159627	0.000241192	0.000499632
Nitrogen dioxide	kg	3.182137E-6	3.686484E-6	4.781239E-6
Dinitrogen monoxide	kg	1.375584E-8	2.019162E-8	3.986015E-8
Sulfur dioxide	kg	0.000410169	0.000426713	0.000444204
Sulfur trioxide	kg	6.206086E-5	4.146766E-5	1.981231E-5
Particulates, < 10 µm	kg	7.525052E-5	7.526124E-5	7.528808E-5
Wastes				
TR-Oak ash	kg	0.004630144	0.004630804	0.004632456
Waste water	kg	0.051197616	0.051197616	0.051197616
Waste lubrication oil to treatment	kg	0.000011808	0.000011808	0.000011808

^a All input and output values are based on Aspen Plus process simulation outputs and LCA inventory calculations for CS-1 with different furnace temperatures.

^b mc: moisture content (30%).

Table D.14 : LCI for CBHBP production, CS-1 (2 MW_e): Eco-design approach for furnace temperature of (1100, 1200) °C.

INPUTS ^a	Unit	Furnace Temperature (°C)	
		1100	1200
TR-Oak chip supply at roadside (dry)	kg	0.261101097	0.261278713
TR-Oak chip transport from roadside to CBHBP plant (with mc ^b)	tkm	0.018650078	0.018662765
TR-Oak chip feedstock preparation at CBHBP plant (dry)	kg	0.255981468	0.256155601
Treated water use	kg	0.051197616	0.051197616
Lubrication oil use	kg	0.000011808	0.000011808
TR-Oak ash transport from CBHBP plant to forest	tkm	0.002791617	0.002791775
TR-Oak ash spreading in forest	ha	9.417185E-6	9.423592E-6
Const & decom for CBHBP plant	p	1	1
Const & decom for TR-oak chip supply chain	p	1	1
CBHBP plant own biopower consumption	kWh	0.017864442	0.017864442
OUTPUTS^a			
Products			
Biopower production (gross), CBHBP plant	kWh	0.2233	0.2233
Bioheat production (gross), CBHBP plant	kWh	0.7767	0.7767
Emissions to air			
Carbon monoxide	kg	7.428537E-7	3.951425E-6
Nitric oxide	kg	0.000930755	0.001593153
Nitrogen dioxide	kg	5.972898E-6	7.240235E-6
Dinitrogen monoxide	kg	7.150611E-8	1.188276E-7
Sulfur dioxide	kg	0.000451969	0.000455856
Sulfur trioxide	kg	1.039118E-5	5.923961E-6
Particulates, < 10 µm	kg	7.532511E-5	7.537635E-5
Wastes			
TR-Oak ash	kg	0.004634733	0.004637888
Waste water	kg	0.051197616	0.051197616
Waste lubrication oil to treatment	kg	0.000011808	0.000011808

^a All input and output values are based on Aspen Plus process simulation outputs and LCA inventory calculations for CS-1 with different furnace temperatures.

^b mc: moisture content (30%).



CURRICULUM VITAE



Name Surname : Güner Ekşi

Place and Date of Birth : İkizdere / Rize, 30 August 1970

E-Mail : geksi@itu.edu.tr
guner.eksi@gmail.com

EDUCATION:

- **M.Sc.** : 1995, Chemical Engineering Department
College of Engineering
University of Maine, Maine, USA
- **B.Sc.** : 1991, Chemical Engineering Department
Faculty of Chemical and Metallurgical Engineering
Istanbul Technical University, Istanbul, Turkey

REWARDS:

- (02/1995) Appreciation Letter from Turkish Government
For achievements made during M.Sc. studies in the USA
The Council of Higher Education (YÖK) in Turkey
- (09/1992) Graduate Student Scholarship from Turkish Government
1st Scholar in Chemical Engineering
To pursue M.Sc. studies in the USA
The Republic of Turkey Ministry of National Education
- (07/1991) 1st Degree of the Faculty with 80.31/100 GPA (B.Sc.)
Chemical Engineering Department
Faculty of Chemical and Metallurgical Engineering
Istanbul Technical University

PROFESSIONAL EXPERIENCE:

- (10/2013–Present) Freelance Scientist
- (08/2009–10/2013) Lecturer
Energy Systems Engineering Department,
Yalova University, Yalova
- (04/2007–08/2009) Freelance Project Manager
- (04/1998–04/2007) Specialist
OLMUKSA (International Paper & SABANCI
Packaging Industry and Trading Inc.), Istanbul
- (11/1995–04/1998) Engineer
SEKA (Turkish State Pulp and Paper
Enterprise), Izmit

Recent Projects and Activities:

- Vice moderator, 05/2017–Present
“Istanbul Climate Change Action Plan Stakeholder Analysis” project
Istanbul Metropolitan Municipality, <https://www.iklim.istanbul>
- Organizing committee member, 26 April 2017
IV. Istanbul Carbon Summit, Carbon Management, Technologies & Trade
Istanbul, <http://www.istanbulcarbonsummit.org>
- Radio program expert guest, 04 May 2016, and 06 May 2015
Çerçeve, TRT Radyo 1, Istanbul
Subject: Sustainable production and consumption
- Chair of the youth committee, 14–15 April 2016
III. Istanbul Carbon Summit, Carbon Management, Technologies & Trade
Istanbul, <http://www.istanbulcarbonsummit.org>
- Chair of the student committee, 25–27 May 2015
38th IAEE International Conference, Antalya, <http://iaee2015.org>
- Chair of the youth board, 5–6 March 2015
Istanbul Electrical and Electronics Waste Summit
Istanbul, <http://www.istanbuleews.org>
- Consultant, 03/2010–06/2013
“Establishment of İbrahim Müteferrika Paper Museum” project
Yalova Municipality, Yalova
- Specialist, 09/2009–08/2011
“Preparation of the Council of Higher Education (YÖK) blueprint documents
for the establishment of Yalova University Paper Science and Engineering
Department” project
Yalova University, Yalova
- Organizing committee member, 28 December 2010
1st National Life Cycle Assessment (LCA) Workshop
Yalova University, Yalova

Classes Given:

- Research Methods
- Biofuels Technology
- Biomass Conversion Technologies (*Graduate School*)
- Project Management in Energy Sector (*Graduate School*)

Refereeing:

- Renewable & Sustainable Energy Reviews, Elsevier
<https://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews/>
- Turkish Journal of Agriculture and Forestry, TÜBİTAK
<http://journals.tubitak.gov.tr/agriculture/>

Certificates:

- Project Management Professional (PMP), PMP ID #: 1516594
Project Management Institute (PMI), USA
- Microsoft Certified Systems Engineer (MCSE), MCP ID #: 2365604
Microsoft, USA

Scientific and Professional Memberships:

- Sustainable Production and Consumption Association (SPCA)
Executive Board member, <http://www.sut-d.org>
- Turkish Association for Energy Economics (TRAEE), <http://www.traee.org>
- International Association for Energy Economics (IAEE), <http://www.iaee.org>
- Project Management Institute (PMI), <https://www.pmi.org>
- University of Maine Alumni Association, <http://www.umainealumni.com>
- Istanbul Technical University Alumni Association, <http://www.itumd.org.tr>

PUBLICATIONS ON THE THESIS:

- **Eksi, G., & Karaosmanoglu, F. (2017).** Combined bioheat and biopower: A technology review and an assessment for Turkey. *Renewable and Sustainable Energy Reviews*, 73, 1313-1332. doi: 10.1016/j.rser.2017.01.093.
- **Eksi, G., & Karaosmanoglu, F. (2016).** Combined bioheat and biopower production and forest biomass *In Proceedings of the 10th International Clean Energy Symposium* (pp. 120-131). Istanbul, Turkey, 24–26 October.

PRESENTATIONS ON THE THESIS:

- **Eksi, G. (recorded in 2017).** Combined bioheat and biopower: A technology review and an assessment for Turkey. *Elsevier AudioSlides Presentation on ScienceDirect*. Available on <http://www.sciencedirect.com> for an indefinite period of time.
- **Eksi, G. (2016, 08 December).** Biomass energy and combined bioheat and biopower production. *3rd Cogeneration & Trigeneration Energy Efficiency Conference*, Istanbul, Turkey.
- **Eksi, G. (2016, 25 October).** Combined bioheat and biopower production and forest biomass. *10th International Clean Energy Symposium*, Istanbul, Turkey, <http://www.utes.itu.edu.tr>.

OTHER PUBLICATIONS:

Book Chapter:

- **Eksi, G.** (2013). The chronology of paper. In Vural, A. & Irmak, E. N. (Eds.), *Kağıthane-i Yalakabad* (pp. 66-69). Yalova: Yalova Municipality-İbrahim Müteferrika Paper Museum.

E-book:

- **Eksi, G.** (Ed.). (2017). *IV. Istanbul Carbon Summit presentation e-book* (in Turkish and in English), <http://www.istanbulcarbonsummit.org> and <http://www.sut-d.org>.
- **Eksi, G.** (Ed.). (2016). *III. Istanbul Carbon Summit presentation e-book* (in Turkish and in English), <http://www.istanbulcarbonsummit.org> and <http://www.sut-d.org>.
- **Eksi, G.** (Ed.). (2015). *II. Istanbul Carbon Summit presentation e-book* (in Turkish and in English), <http://www.istanbulcarbonsummit.org> and <http://www.sut-d.org>.
- **Eksi, G.** (Ed.). (2015). *I. Istanbul Electrical and Electronics Waste Summit presentation e-book* (in Turkish and in English), <http://www.istanbuleews.org> and <http://www.sut-d.org>.

Journal Article:

- **Eksi, G., & Bousfield, D. W.** (1997). Modeling of coating structure development. *Tappi Journal*, 80(2), 125-135.

Conference Proceeding:

- **Eksi, G., & Bousfield, D. W.** (1996). Modeling of coating structure development *In Proceedings of 1996 Coating Conference* (pp. 283-296). Atlanta, USA: Tappi Press.
- **Eksi, G., Ardal, D. Y., Yavuz, R., & Kucukbayrak, S.** (1992). Constancy of calorific value of coal *In Proceedings of the Turkish VIIIth National Symposium on Chemistry and Chemical Engineering, Istanbul, Turkey, 7–11 September*.