T.C.
BAHCESEHIR UNIVERSITY
GRADUATE SCHOOL OF EDUCATION
ELECTRICAL - ELECTRONICS ENGINEERING DEPARTMENT

OPERATIONAL AND EMISSION IMPROVEMENTS IN THE POWER DISTRIBUTION GRID AND MULTI-ENERGY NETWORK CONNECTED DATA CENTER WITH ALTERNATIVE ENERGY SYSTEMS

PhD THESIS

İLHAN KESKİN

ISTANBUL 2023

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ABSTRACT

OPERATIONAL AND EMISSION IMPROVEMENTS IN THE POWER DISTRIBUTION GRID AND MULTI-ENERGY NETWORK CONNECTED DATA CENTER WITH ALTERNATIVE ENERGY SYSTEMS

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PhD Program in Electrical-Electronics Engineering

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As the number of data centers is increasing worldwide, there are concerns about their growing electricity demand on power grids and their environmental impact. These demand and emission concerns can be mitigated at the urban scale by multi-energy hub integration with the regions, utilizing a combined cooling heating and power (CCHP), renewable-based electricity generation, and waste heat recovery systems. The main objective of this thesis is to perform a comprehensive analysis of these proposed alternative systems for application in data centers to asses operational and emission impacts on the power distribution grid and the data center. In this study, a cost-optimization model for the data center has been used to satisfy the critical electricity and cooling demand of the data center, utilizing waste heat from the data center and addressing residential electricity, heating and cooling demands. Different cases were created to understand the individual effect of CCHP, PV, and district energy network connections. Furthermore, investment and life-cycle cost (LCC) analysis has been presented. In conclusion, the thesis suggests the use of alternative energy systems and district energy connections for the data centers to achieve cleaner, more sustainable, more resilient, more flexible, and more environmentally friendly data center operations. The proposed systems contribute to the power distribution grid and region with energy saving, peak demand reduction, power losses decrease, voltage regulation, and emission reductions.

Key Words: Combined Cooling, Heating, and Power; Data Center; Power Distribution Grid; District Energy Networks; Emission

ÖZET

ALTERNATİF ENERJİ SİSTEMLERİ İLE GÜÇ DAĞITIM ŞEBEKESİ VE ÇOKLU ENERJİ AĞINA BAĞLI VERİ MERKEZİNDE OPERASYONEL VE EMİSYON İYİLEŞTİRMELERİ

İlhan Keskin

Elektrik-Elektronik Mühendisliği Doktora Programı

Tez Danışmanı: Dr. Öğr. Üyesi Gürkan Soykan

Temmuz 2023, 135 sayfa

Veri merkezlerinin sayısı dünya çapında arttıkça, elektrik şebekeleri üzerindeki elektrik talebi ve bunun çevresel etkisi konusunda endişeler ortaya çıkmaktadır. Bu enerji ve emisyon endişeleri, bölgesel ölçekte çoklu enerji bağlantılı, birleşik soğutma, ısı ve güç sistemleri kullanımı, yenilenebilir enerji kaynakli elektrik üretimi ve atık ısı geri kazanımı sistemleri yoluyla azaltılabilir. Bu tezin temel amacı, alternatif enerji sistemlerinin veri merkezlerinde kullanımının, elektrik dağıtım sebekesinde ve veri merkezindeki operasyonel ve emisyon açısından etkisinin kapsamlı bir analizini sunmaktır. Bu tezde, veri merkezinin kritik elektrik ve soğutma taleplerini karşılayan, veri merkezinde oluşan atık ısıyı kullanan, bölgedeki konutlarda oluşan elektrik, ısınma ve soğutma taleplerine destek olan ve veri merkezinin enerji maliyet optimizasyonunu da içeren matematiksel bir model geliştirilmiştir. Birleşik soğutma ısı ve güç sistemleri, güneş enerji sistemleri ve bölgesel enerji ağı bağlantılarının bireysel etkisini anlamak için farklı senaryolar oluşturulmuştur. Ayrıca, yatırım ve yaşam döngüsü maliyeti (LCC) analizi sunulmuştur. Sonuç olarak, bu tez, veri merkezlerinin daha temiz, daha sürdürülebilir, daha esnek ve daha çevre dostu veri merkezi operasyonları gerçekleştirmesi ve topluma katkı sunması için alternatif enerji sistemlerinin ve bölgesel enerji bağlantılarının kullanılmasını önermektedir. Önerilen sistemler, enerji tasarrufu, puant talebin azaltılması, güç kayıplarının azaltılması, gerilim regülasyonu ve emisyon azaltımı ile elektrik dağıtım şebekesine ve bölgeye katkı sağlar.

Anahtar Sözcükler: Birleşik Soğutma, Isı ve Güç; Bölgesel Enerji Şebekesi; Emisyon; Elektrik Dağıtım Şebekesi; Veri Merkezi

To my dear parents and my beloved wife…

ACKNOWLEDGEMENTS

I have always believed that engineering is like flying with two wings. One wing represents theory and studies, while the other represents practice and applications. In pursuit of this, I have strived to stay motivated to increase my knowledge and theory while working on real-life engineering projects in the field. As Einstein once said, "I have no special talent. I am only passionately curious." This curiosity has driven me to work hard during my Ph.D. journey and bring this thesis to fruition. I am a firm believer in keeping the environment clean and protecting it as much as possible. Hence, I have aimed to contribute to this mission within my field by utilizing my knowledge and studies.

Throughout this long journey, my thesis advisor, Assist. Prof. Dr. Gürkan Soykan, provided invaluable insights, time, and extreme patience, which ultimately led to the success of this thesis and our internationally published academic works.

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I would like to convey my sincere gratitude to my parents, sister, and brother for their education and timeless family life lessons, which have instilled in me the values of being a good man beyond just being successful. They have always believed in me and supported me throughout my life with love and enthusiasm.

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ABS	Absorption chiller
CCHP	Combined cooling, heating, and power
CHP	Combined heat and power
CRAC	Computer room air conditioning (DX)
CRAH	Computer room air handling unit
DC	District cooling
DH	District heating
DMS	Geographical coordinates by degree, minute and second
ENE	Annual energy-saving cost
GHG	Greenhouse gas emissions
IT	Information technology
IC	Initial/acquisition cost
IEEE	The Institute of Electrical and Electronics Engineers
LCC	Life-cycle cost
LV	Low voltage
NPV	Net present value
MILP	Mixed-integer linear programming
MTBF	Mean time between failures
MTTR	Mean time to repair
MV	Medium voltage
O&M	Operation and maintenance cost
PV	Photovoltaic panels
REL	Reliability-related exposure cost
RBD	Reliability block diagram
SBS	UPS static bypass
SLA	Service level agreement
SLD	Single line diagram
SPN	Stochastic petri network
UPS	Uninterruptible power supply

Absorption chiller mode surplus electricity [kWh]	: E_{feed_abs}
Absorption chiller’s cooling energy output [kWh]	: Q_{abs}
Absorption chiller’s nominal cooling energy output [kWh]	: $Q_{abs\_nominal}$
Availability	: A
Average hourly consumption of domestic hot water [m^3]	: S_w
Average number of people in dwellings	: N_p
Building heat gain for cooling load [kWh]	: H_{b_cool}
Building solar heat gain [kWh]	: H_{shg}
Carbon emission equivalent of CCHP operation [kg CO_2 -eq]	: CE_{ops_cchp}
Carbon emission equivalent of grid operation [kg CO_2 -eq]	: CE_{ops_grid}
Carbon emission factor of district heating [kg CO_2 -eq/kWh]	: Cf_{dist_h}
Carbon emission factor of district cooling [kg CO_2 -eq/kWh]	: Cf_{dist_q}
Carbon emission factor of feed-in to grid [kg CO_2 -eq/kWh]	: Cf_{feed}
Carbon emission factor of natural gas [kg CO_2 -eq/Sm3]	: Cf_{ng}
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CCHP’s electrical energy output [kWh]	: E_{e_cchp}
CCHP’s maximum electrical energy output [kWh]	: $E_{e\_cchp\_max}$
CCHP’s nominal electrical energy output [kWh]	: $E_{e\_cchp\_nominal}$
CHP-fed operation hourly energy cost [EUR]	: C_{ops_chp}
CHP’s electrical energy output [kWh]	: E_{e_cchp}
CHP’s maximum electrical energy output [kWh]	: $E_{e\_chp\_max}$
CHP’s natural gas consumption [Sm^3]	: V_{ng}
Coefficient of performance for absorption chiller [%]	: COP_{abs}
Coefficient of performance for electric chiller [%]	: COP_{ech}
Components in reliability and availiability diagrams	: C
Cooling tower’s nominal cooling energy output [kWh]	: $Q_{CT\_nominal}$
Data center heat pump’s coefficient of performance [%]	: COP_{hp}
Data center’s cooling demand [kWh]	: Q_{demand}
Discount rate	: r
Electric chiller mode surplus electricity [kWh]	: E_{feed_ech}

Electric chiller's cooling energy output [kWh]	: Q_{ech}
Electric chiller's nominal cooling energy output [kWh]	: Q_{ech}
Electric chiller's cooling energy output [kWh]	: $Q_{elc\_nominal}$
Electricity consumption data center's auxiliary systems [kWh]	: E_{Aux}
Electricity consumption of absorption chiller (internal) [kWh]	: E_{abs}
Electricity consumption of computer room air handling [kWh]	: E_{CRAH}
Electricity consumption of cooling tower [kWh]	: E_{CT}
Electricity consumption of data center's cooling system [kWh]	: $E_{Cooling}$
Electricity consumption of electric chiller [kWh]	: E_{ech}
Electricity consumption of free cooling operation [kWh]	: E_{frc}
Electricity consumption of heat pump [kWh]	: E_{hp}
Electricity consumption of IT devices [kWh]	: E_{IT}
Electricity consumption of MV ring with CCHP [kWh]	: $E_{mv\_ring\_w\_cchp}$
Electricity consumption of MV ring without CCHP [kWh]	: $E_{mv\_ring\_wo\_cchp}$
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Electricity generation of PV panels [kWh]	: E_{pv}
Electricity losses from power distribution [kWh]	: E_{Power_Losses}
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Input energy of CHP [kWh]	: E_{chp}
In-plane irradiance for the PV panels [W/m^2]	: G_{solar}
Input heat energy for absorption chiller [kWh]	: H_{abs}
Internal efficiency of PV panel [%]	: η_{pv}
Loading factor of CHP [%]	: LF
Minimum required number or capacity of a system	: N
Natural gas heating value [kJ/m3]	: H_{ng}
Natural gas purchase price [EUR/ Sm^3]	: C_{ng}
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Nominal useful waste heat energy of CHP [kWh]	: H_{waste_nom}
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Number of dwellings	: N_d
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Output high-degree water heat efficiency of CHP [%]	: η_{hw}
Output low-degree water heat efficiency of CHP [%]	: η_{lw}
Output mechanical efficiency of CHP [%]	: η_{m_chp}
Output mechanical energy of CHP [kWh]	: E_{m_chp}
Overall operation hourly energy cost [EUR]	: C_{ops}

Overall system cooling energy generation [kWh] : Q_{gen}

Purchase price for electricity [EUR/kWh] : C_{grid}

Purchase price for natural gas [EUR/ Sm^3] : C_{ng}

PV cell's ambient temperature [°C] : $T_{ambient}$

PV cell's actual temperature [°C] : T_{cell}

PV cell's reference temperature [°C] : T_{cell_ref}

Reduced electricity demand on mv ring [kWh] : $E_{reduction}$

Reference building floor thermal transmittance [W/ m2.K] : U_{floors}

Reference building roof thermal transmittance [W/ m2.K] : U_{roof}

Reference building wall thermal transmittance [W/ m2.K] : U_{walls}

Reference building windows thermal transmt. [W/ m2.K] : $U_{windows}$

Reference efficiency of PV panel at a certain tempera. [%] : η_{ref}

Reliability : R

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Requirements for roof thermal transmittance [W/ m2.K] : U_{roof_req}

Requirements for wall thermal transmittance [W/ m2.K] : U_{walls_req}

Requirements for windows thermal transmt. [W/ m2.K] : $U_{windows\_req}$

Resid. heat pump's electricity usage at heating mode [kWh] : E_{hp_heat}

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Residential cooling system set temperature [°C] : T_{set_c}

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Residential heating system set temperature [°C] : T_{set_h}

Residential power usage [kWh] : E_{dwel_elc}

Solar irradiance to windows [W/ m^2] : I_i

Surface area of the floors [m2] : A_{floors}

Surface area of the roofs [m2] : A_{roofs}

Surface area of the PV panels [m^2] : A_{pv}

Surface area of the walls [m^2] : A_{walls}

Surface area of the windows [m^2] : A_{walls}

Surplus cooling energy for district cooling [kWh] : Q_{dist}

Surplus electricity selling price [EUR/kWh]	: C_{feed}
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Temperature coefficient for the efficiency	: β
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Total duration in years	: T
Total electricity demand of the overall system [kWh]	: E_{Demand}
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Total residential electricity demand [kWh]	: E_{res_elc}
Total residential heating demand [kWh]	: H_{b_total}
Total residential space heating demand [kWh]	: H_{b_heat}
Total thermal transmittance of reference building [W/ m2.K]	: $U_{building}$
Total waste heat energy of CHP [kWh]	: H_{chp}
Useful waste heat energy of CHP (utilized) [kWh]	: H_{waste}
Windows shading factor	: r_i

Chapter 1

Introduction

1.1 Introduction

The utilization of digital technology is increasing rapidly, causing a growth in the number of data centers around the world. Data centers are buildings that facilitate IT equipment such as servers, storage, network devices, etc., and offer various digital technology services. A data center is a facility designed to support essential operations for its intended purposes, such as serving a bank, military base, hospital, or global telecommunications traffic. This makes them known as mission-critical facilities.

As the demand for new data centers increases, so does the global energy demand. Therefore, it is essential to develop more energy-efficient solutions for data centers to support future energy networks and society. As society continues decarbonizing, the data center industry also plans transitions to cleaner, more sustainable, and environmentally friendly energy usage.

On the other hand, the power grids are facing challenges as a result of rising electricity demand, peak power consumption, and volatility in energy consumption caused by grid-connected large energy consumers such as data centers.

The data center industry is already acting on the energy and emission problems in a positive way such as by purchasing renewable energy certificates or emission credits, renewable power purchase agreements, and using energy-efficient technologies. However, these actions are limited or have a partial contribution to the target of a carbon-free industry.

To overcome these problems, on-site generation, renewable energy sources, waste heat recovery, and regional energy connections can provide more reliable, energy-efficient, cost-effective, environmentally friendly, energy-flexible, and sustainable solutions.

While data centers trying to achieve more sustainable and energy-aware operations, they should also provide highly reliable and available operations for their mission-critical services. Hence, the evaluation of alternative energy systems for a data center should be executed comprehensively based on energy distribution grid electrical performance, emission, energy cost, investment, reliability, and availability.

This thesis presents a comprehensive analysis of proposed alternative systems for application in data centers to asses operational and emission impacts on the power distribution grid and the data center. In this study, a cost-optimization model for the data center has been used by satisfying the critical electricity and cooling demand of the data center, utilizing waste heat from the data center, and addressing residential electricity, heating and cooling demands. The thesis also captures the reliability and availability analysis, energy cost savings, investment, and life-cycle cost considerations.

1.2 Problem Statement

Data centers are energy-intensive, and their energy consumption is typically 10-40 times higher than that of a typical office building (Darrow and Hedman, 2009). As the number of data centers is increasing worldwide, there are concerns about their growing electricity demand on power grids and its impact on the environment. On the other hand, data center operators and investors have worries about the fragility of the power grid to cope with their potential expansions.

The electrical grid capacity is becoming a concern for grid providers and the public. As a recent example, The Dutch government has halted new big data center projects with a 9-month moratorium to be able to secure the power grid, protect the other regional electricity demands, and find more sustainable solutions (Judge, 2022). Therefore, it is essential to develop more energy-efficient and sustainable solutions for data centers to support future energy networks and society.

Sustainability is another concern for the data center industry. In the Netherlands, some farmers and activists protested data centers' grid occupancy by some mega data center investors to stop their investments in the country. So, the data center industry is under pressure from governments, investors, clients, and activists for reacting to climate change. Although many data center providers committed to being climate neutral by 2030, there is a lot to do for the industry for doing more than limited actions or greenwashing claims (Vermeulen and Patel, 2020).

According to the goal of the EU directive, the use of the efficient alternative systems listed below shall be assessed for new buildings (The European Parliament and the Council, 2010):

- Cogeneration,
- Renewable-sourced decentralized energy supply systems,
- District heating and cooling,
- Heat pumps.

These proposed systems are partially or separately investigated in the literature and implemented in some data center projects. However, these systems can be deployed together to achieve a more sustainable data center and region. Currently, some countries also putting into place new requirements for reusing waste heat recovery and on-site renewable installation for new data center developments. However, industry associations are willing to have a holistic approach and studies to understand the possibilities instead of determining rigid and hard-to-achieve obligations (Judge, 2023). Therefore, there is a need for a comprehensive study to analyze these systems together with also additional other environmentally friendly solutions such as free cooling and data center waste heat recovery technologies.

Modern ICT systems enhance the evolution of energy management solutions in data centers and provide the possibility for different scenarios (Basmadjian, 2019). Energy management plays an significant role in the safety of energy supply and generation, reducing volatility of the energy networks, giving flexibility to operators, and reducing energy costs. Optimization techniques can provide better scheduling for the energy sources in the multi-energy hubs. Thus, optimization can be utilized in the scheduling problems of alternative energy sources in data centers integrated with multi-energy hubs.

Nevertheless, the electrical distribution grids were originally created to accommodate unidirectional power flows and were not designed to handle the extensive integration of localized power generation and active final-users (Morvaj, 2017). Therefore, there is an urgent need to investigate the impact of multi-energy systems on data centers in terms of the distribution grid electrical performance such as power losses, voltage drops, short-circuit levels, and peak power demands.

On the other hand, data centers are mission-critical facilities. Given the vital nature of data centers, the reliability and availability of these facilities are also crucial. Reliable electricity and cooling supplies are very crucial for the data center’s operation, and nearly all data centers depend on the power grid to feed their electrical and cooling systems. However, the power grid is considered an unreliable source in the data center industry. An alternative to the power grid is a sustainable CCHP system, which can supply continuous electricity and cooling to a data center while also providing local energy generation, energy cost saving, and emission benefits. As a consequence, the CCHP system’s impact on data centers has to be investigated in terms of reliability and availability.

1.3 Motivation and Novel Contributions

It has been expected that energy and environmental issues caused by massive energy consumers, such as data centers, could be resolved at the urban scale with the concept of “Net-Zero Energy Districts (NZED)” (Nematchoua et al., 2018). Therefore, efficient use of primary and secondary energy sources, energy exchange, and demand management strategies become more important for data centers to achieve cleaner, more sustainable, more environmentally friendly, and more flexible energy networks.

To address all the aforementioned problems, the target of this thesis is to propose a solution and comprehensive analysis for data centers. While proposing a solution that is in line with the European Directive, we also aimed to fill the research gap in the literature on energy management of data centers. Firstly, we used the mathematical model of critical electricity and cooling demand of the data center, waste heat from the data center, and residential electricity, heating and cooling demands. Secondly, we utilized an optimization model to provide cost-optimized data center operation. Thirdly, distribution grid electrical parameter, peak demand reduction and carbon emission savings were analyzed for multiple cases. Fourthly, energy cost saving and financial investment analysis were analyzed. Additionally, the reliability and availability of a CCHP system integration to the data center were demonstrated.

Many researchers in the data center literature neglect free-cooling operation, the combination of these aforementioned alternative energy systems, seasonal impacts throughout a year, hourly outdoor temperatures, demand-side energy models such as residential customers, the evaluation of grid parameters effects, and the reliability and availability impacts for both electricity and cooling supplies. These considerations are included in the simulations, analysis, and evaluations of this thesis as a comprehensive analysis.

This thesis also helps to data center industry for the achievement of several of the Sustainable Development Goals established by the United Nations, such as sustainable cities and communities, affordable and clean energy, responsible consumption and production, industry, innovation, and infrastructure, and climate action. The sub-contributions of the thesis are as follows:

- Designing a comprehensive model for a data center and residential customers that covers the CCHP, PV, and data center’s residual heat reuse.
- Designing a more realistic system that considers electric chiller, absorption chiller, and free cooling system.
- Operating the CCHP-PV-based data center with district heating and district cooling network integration by minimizing the overall energy cost.
- Creating comparative case studies for the proposed energy systems to understand the impact of CCHP, PV, and district energy connection individually.
- Modeling residential customers’ energy demands, unlike the literature.
- Analyzing the power grid electrical performance parameters in terms of power losses, voltage deviation, and short-circuit levels for large-connected customers such as data centers.
- Investigating the electricity peak demand and energy consumption changes on the energy networks considering CCHP-PV-based data center and residential customers.
- Taking seasonal impact into account for residential and data center energy flows by using hourly outdoor temperatures throughout the year.
- Demonstrating the carbon dioxide equivalent emission reduction on the power grid considering not only data center demands but also residential electricity, heating, and cooling demands.
- Creating a reliability and availability model for an up-to-date data center design that considers both electricity and cooling supply,

- Proposing the integration of a CCHP system to enhance the safety of the data center's operation without affecting the electrical and cooling Tier requirements of a 2N topology data center,
- Analyzing the impact of integrating a CCHP system into a grid-fed data center on its reliability and availability,
- Incorporating reliability and failure rate into LCC analysis and providing sensitivity analysis based on the total cost of downtime in order to facilitate better decision-making by data center investors and operators.
- Indicating the economic benefit of the CCHP and regional energy integration for data centers, as well as promoting the application of CCHP systems not only for cold weather regions but also for warm and hot weather regions.
- Demonstrating the return on investment, net present value, and internal rate of return financial parameters.

1.4 Thesis Outline

The remainder of this thesis is organized as follows. Chapter 2 provides background information for data centers, their energy-related concerns, energy-saving opportunities, sustainability issues and data center performance classifications. In Chapter 3, a literature survey on the data center, CCHP and data center energy-related studies are given. Chapter 4 presents the methodology. The system modeling of the components and overall demand and supply calculations for the proposed model are given in this chapter. The optimization model is utilized to determine the energy management scheduling of the data center considering energy cost-optimized operation. This chapter also presents the electricity demand reductions and carbon emission reductions on the power grid by the proposed system in a multi-energy hub connection. In Chapter 5, the simulation and results for the numerical study are given according to different case studies in terms of energy demand and consumption reduction, distribution grid parameters, investment analysis is demonstrated. Chapter 6 introduces reliability, availability and life-cycle cost analysis for grid-fed data centers and CCHP-integrated data centers. Chapter 7 presents the conclusions. Finally, future works are given in Chapter 8.

Chapter 2

Background

2.1 Growth in Digital Technology and Data Centers

In the past ten years, our dependence on on-demand technology has transformed the way technology is implemented, and the demand for digital services is increasing rapidly (Cisco, 2020):

- In the year 2023, approximately 66 % of the global population is anticipated to have Internet access.
- By the year 2023, it is estimated that the quantity of devices connected to IP networks will surpass three times the global population.
- Mobile connectivity is predicted to be available to over 70% of the global population by 2023.

The complexity of IT infrastructures is increasing as they must now accommodate a greater number and variety of end-user devices, data storage options, mobile services, big data, real-time computing, cloud services, and Internet of Things (IoT) connections. Figure 1 presents the global IP traffic between 2016 and 2021 (Cisco, 2020).

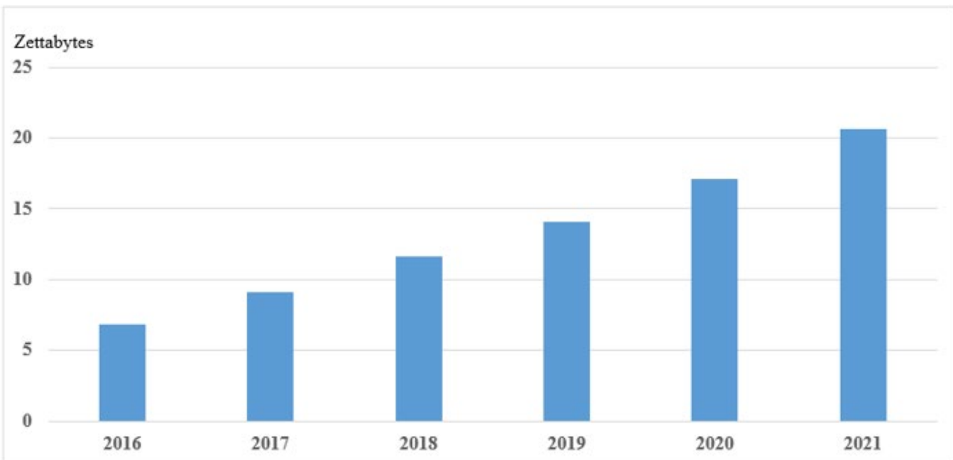


Figure 1. Global Data Center IP Traffic Growth (Cisco, 2020)

Data centers are buildings that host IT racks for servers, storage, and network devices, among other things, to provide various types of digital services. The rapid growth of digital technology is also increasing the workload of data centers. Cloud workloads are gaining importance and are projected to make up the majority of the total workload of data centers each year.

Figure 2 displays the global IP traffic and data center workload forecast between 2012 and 2030, comparing cloud and traditional data centers (The European Union, 2014).

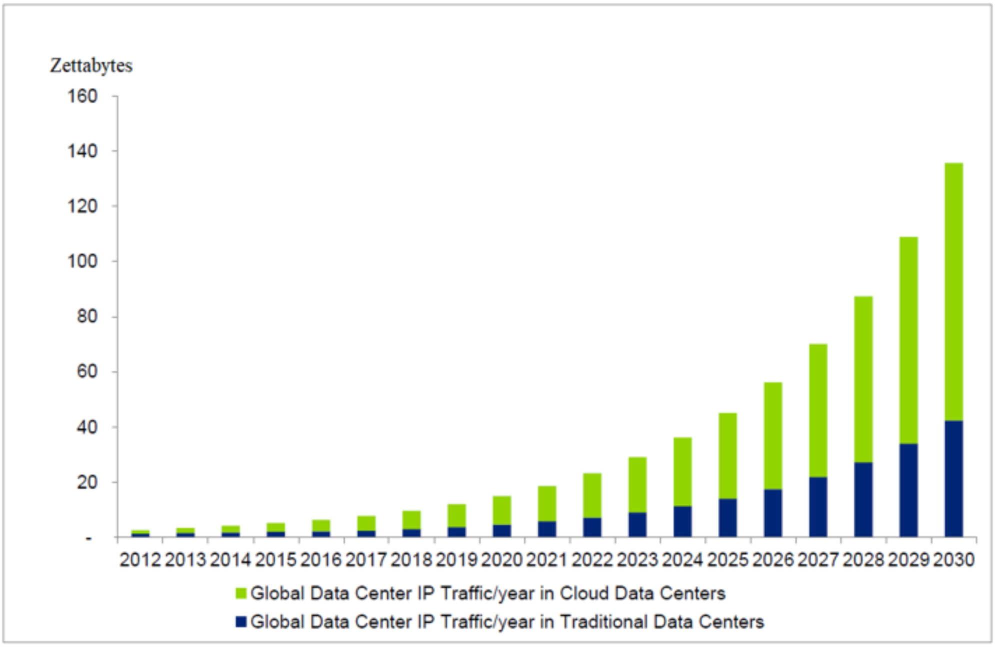


Figure 2. Global IP-Traffic Yearly Forecast 2012 – 2030 (The European Union, 2014)

The increasing workload of data centers causes the creation of new data centers globally, and the industry has grown fivefold since 2018.

2.2 Data Center Energy Consumption and Future Projection

The IT racks in a data center are responsible for hosting information and communications technology (ICT) devices. For these sensitive electronic devices, data centers require supporting infrastructure, including a continuous power system and a cooling system.

Reliable electricity and cooling supplies are vital for the data center's operation, and almost all data centers rely on the power grid to feed their electrical and cooling systems. There is no tolerance for power down in a data center. To safeguard the IT devices in a data center against unplanned outages and voltage spikes, uninterruptible power systems (UPS) are installed. Every data center is equipped with at least one emergency generator to supply emergency power to data center during grid outages or low-quality power supply. In such cases, UPSs ensure a smooth transfer from the power grid to the emergency generators by utilizing the stored electrical energy from their batteries.

IT devices are the primary electricity consumers and cooling is a critical requirement for data centers. IT devices generate heat while using electrical power, and this heat is dissipated into the data halls. It is essential to remove the excess heat from the data halls and maintain the temperature and humidity within specific limits. Cooling technologies are utilized within the data halls, but they also consume electricity.

In addition to power and cooling, auxiliary services like lighting and building services also require electricity. Figure 3 shows a typical breakdown of power consumption by systems in a data center (Emerson Network Power).

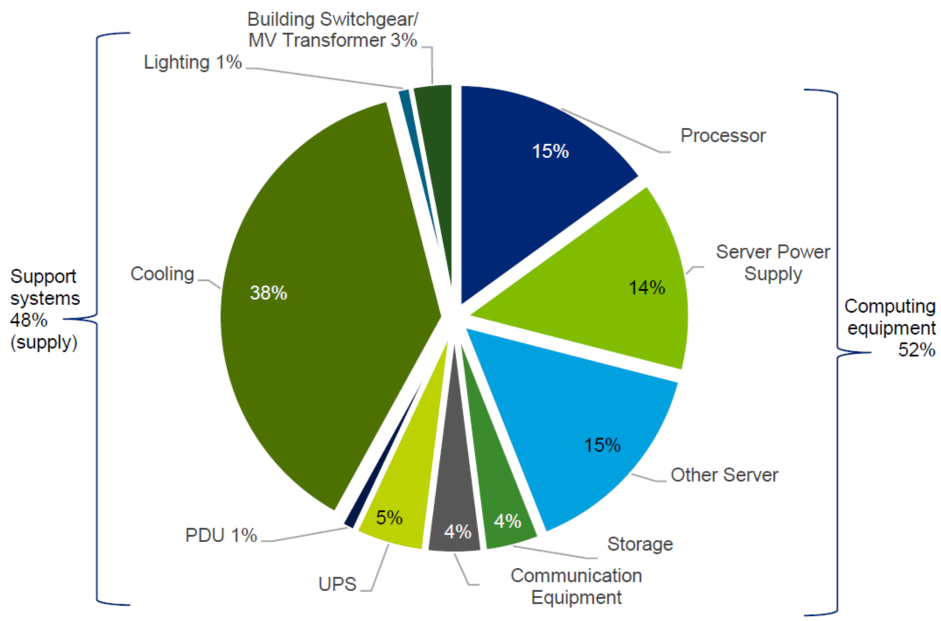


Figure 3. Breakdown of Power Consumption by Systems in a Data Center (Emerson Network Power)

Larger data centers typically exhibit higher efficiency compared to smaller ones. Hyperscale data centers typically aim to maximize efficiency by having larger whitespace areas and more efficient operations. They achieve high efficiency through economies of better scaling, user aggregation, better server utilization, flexible operations, energy-aware management, and environmental considerations.

In the world of data centers, the calculation of efficiency differs from traditional methods. The total electricity used in the operation is divided by the electricity consumption of the IT equipment to determine the Power Usage Effectiveness (PUE). This metric can be easily measured using advanced energy monitoring systems and is commonly used within the data center world to determine the efficiency of a data center and to evaluate the performance of their own data centers during operational hours. PUE can be calculated using the following formula:

$$PUE = \frac{\text{Total data center power demand}}{\text{IT equipment power demand}} \tag{1}$$

Based on respondents to the Uptime Institute survey, the average annual PUE in 2022 was 1.55. This indicates that the average data center consumes 55% more energy on cooling, power distribution, and auxiliary facility services compared to IT electricity consumption. Figure 4 displays the global progression of PUE over the years, as reported by the 669 survey participants (Uptime Institute, 2023).

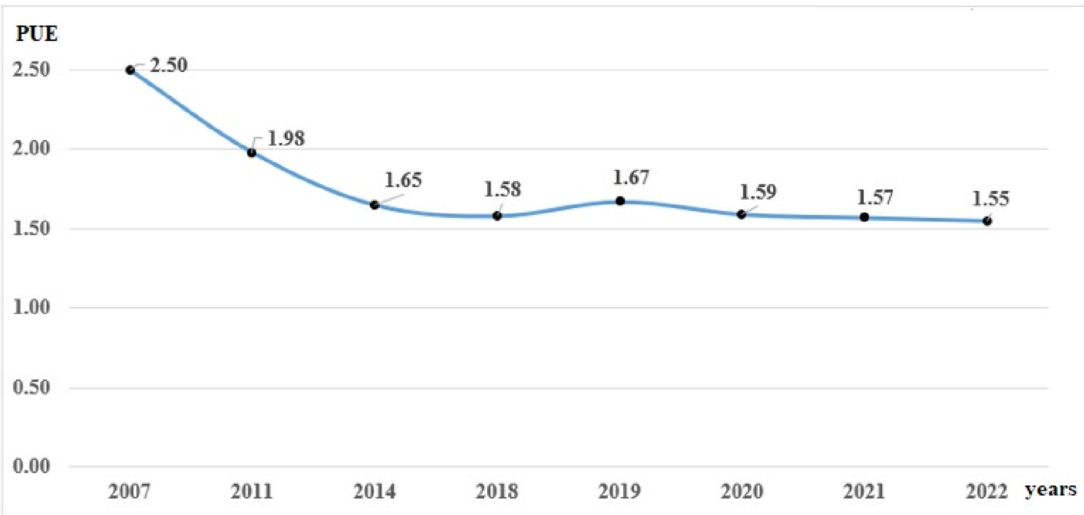


Figure 4. Average Annual PUE Progress in Years (Uptime Institute, 2023)

Data centers that are newly built and located in cold climates generally have a lower PUE compared to other data centers. Despite this, current trends suggest that there is still much that global data center investors and operators can do to further reduce the global PUE in the future.

In the European Union (EU), the energy consumption of data center increased by only 20%, from 27.3 to 33.0 TWh per year. Similar to global trends, the PUE in the EU also improved, with an average decrease from 2.03 in 2010 to 1.75 in 2018 across 28 countries.

According to (International Energy Agency, 2022), global data center energy consumption was estimated to be between 220 and 320 TWh in 2021, which represents approximately 1.3% of global final electricity consumption. It should be noted that this estimate excludes electricity consumption for cryptocurrency mining. Table 1 provides a summary of the global indicators for electricity and data (International Energy Agency, 2022).

Table 1

Global Trends in Digital and Energy Indicators, 2015 and 2021 (International Energy Agency, 2022).

Item	**2015**	**2021**	**Change**
Internet users	3 billion	4.9 billion	+ 60%
Internet traffic	0.6 Zettabytes	3.4 Zettabytes	+ 440%
Data center workloads	180 million	650 million	+ 260%
Data center energy usage (Excl. crypto mining)	200 TWh	220-320 TWh	+ 10-60%
Crypto mining energy usage	4 TWh	100-140 TWh	+ 2300 – 3300 %
Data transmission network usage	220 TWh	260-340 TWh	+ 20-60%

According to (European Commission, 2020), data centers in the European Union (EU) consumed 76.8 TWh of energy in 2018, accounting for 2.7% of the EU's electricity demand. For instance, in one of the popular data center locations, Ireland, data centers consumed 14% of the total electricity consumption in 2021 (International Energy Agency, 2022).

Literature studies on the development of data center energy consumption suggest that their consumption is forecasted to continue rising significantly. This is mainly because of increasing demand for computing, internet traffic, and storage capacity.

To forecast data center energy consumption in the future, various studies have been conducted. However, the forecasts widely vary due to different assumptions regarding digital technology demands and energy efficiency trends in the future. According to European Commission’s report in 2020, these forecasts for global data center energy consumption for 2030 range from 500 TWh to 3,000 TWh annually. Figure 5 shows six different forecasts for data center energy consumption globally.

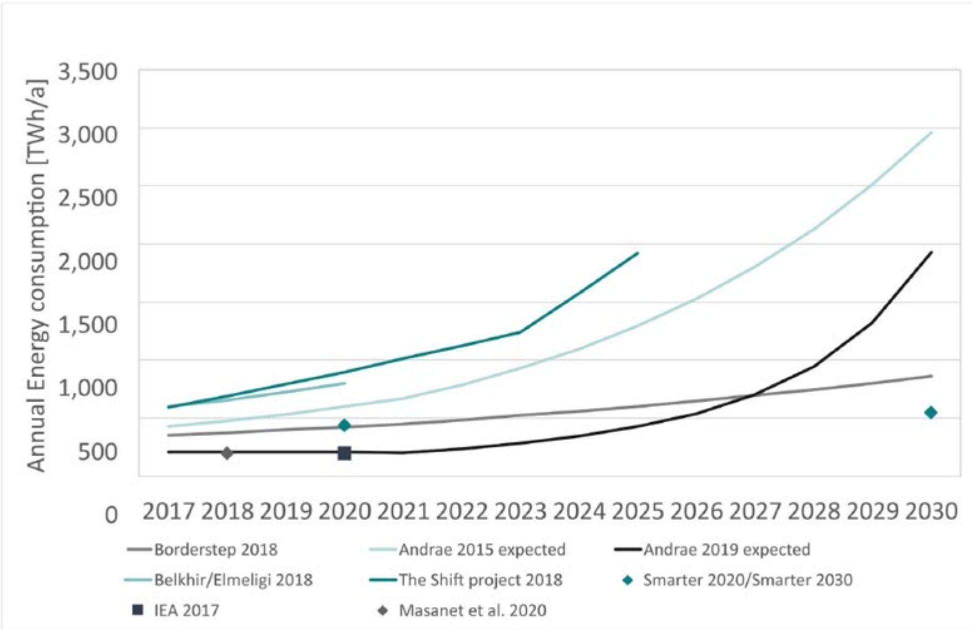


Figure 5. Different Forecasts for Global Energy Consumption of Data Centers (European Commission, 2020)

According to a report by the European Commission, data centers in Europe will consume 98.5 TWh of energy per year in 2030, which represents a 28% increase compared to 2018 levels. This would make data centers account for 3.21% of the total energy consumption in Europe (European Commission, 2020).

Several potential scenarios could affect the upward trend, but they could also lead to a decrease in total energy usage. This is a positive perspective.

Future developments in energy-efficient cloud technologies, energy policies, improvements in IT equipment efficiency, cooling technologies, waste heat reuse, and PUE improvements could all contribute to a reduction in electricity consumption by data centers. Figure 6 illustrates the future energy consumption forecasts by data centers in the European Union.

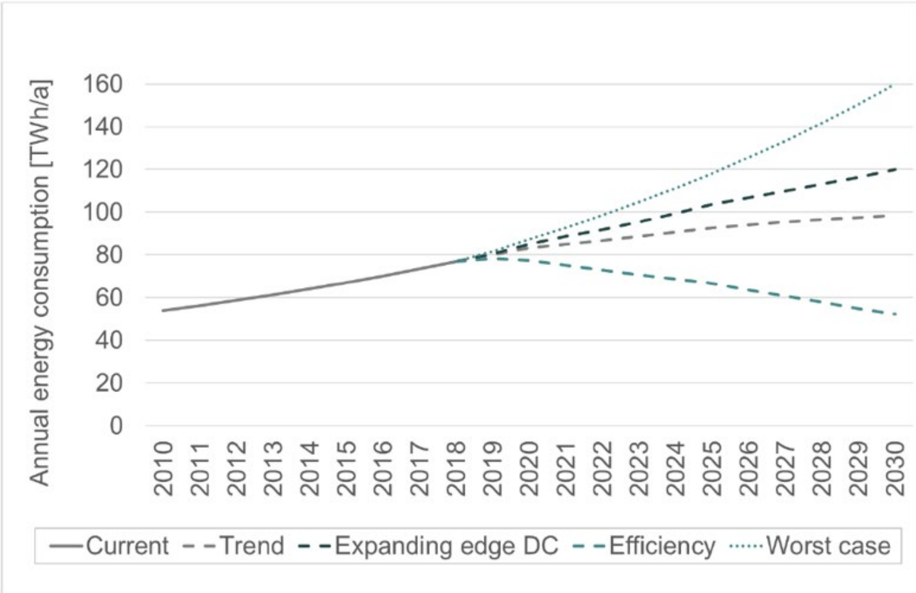


Figure 6. Possible Scenarios for the Energy Consumption of EU Data Centers (European Commission, 2020)

2.3 Energy Saving Technologies in Data Centers

The European Union has established certain climate goals for 2030 by reducing the greenhouse emissions, increasing the share of renewable-based energy sources and increasing the energy efficiency (European Commission).

Alongside these objectives, the European Commission has established the European Code of Conduct for Data Centers, which aims to decrease energy consumption in data centers. This is aimed at reducing the emissions, costs, and global warming potential associated with data centers (Bertoldi et al., 2022).

The Code of Conduct focuses on two major consumers:

- IT devices' consumption
- Infrastructure consumption by electrical and cooling systems (Bertoldi et al., 2017)

Improvements in the energy efficiency of IT devices and infrastructure have helped to restrain the growth of energy demand from data centers. If energy efficiency can be further increased, it is expected that the rate of increase in global data center energy consumption would slow down (European Commission, 2020).

The use of Energy Star© and EU Ecolabel© compliant IT equipment and regulations regarding eco-design requirements for motors, ventilation fans, electronic devices, computers, computer servers, power supply devices, network devices, and communication devices, contribute to reduce the energy usage of both IT devices and infrastructure (The European Union, 2014).

According to European Commission reports, the following and more best practices are also advised for energy consumption reduction goals in the data center (Bertoldi et al., 2022):

- Free cooling technologies
- Alternative cooling sources (ground source or seawater cooling etc.)
- Direct liquid cooling of IT devices
- Hot-Cold aisle containment application
- Alternative power generation technologies (CCHP, fuel-cells etc.)
- Thermal energy storage
- Energy management
- Renewable energy generation (Solar, Wind, Geothermal)
- Data center waste heat reuse
- Return plenum usage for hot air
- Operating temperature optimization
- Air flow control optimization
- Variable speed drivers' usage for compressors, pumps and fans
- Demand response programs
- IT Workloads shifting and unnecessary device shutdown
- Geographical IT load balancing
- Powering of devices via the IT cabling
- High-efficiency UPS use
- Electrical power factor correction
- Automatic lighting control and energy efficient lighting fixture

2.3.1 Combined cooling, heating, and power systems. CHP, or combined heating and power, also known as cogeneration, is a method of electrical power generation that makes use of waste heat generated during power generation as a by-product. CCHP, or combined cooling, heating, and power, also known as trigeneration, is an extended version of CHP that includes the production of cooling in addition to providing electricity, heating, and cooling simultaneously (Whitmire, 2009). Generating electricity and thermal energy simultaneously is more efficient than producing them separately, and it requires fewer primary energy sources (U.S. Environmental Protection Academy, 2015). In contrast, a properly designed CHP system, while efficiencies may vary based on site-specific or manufacturer parameters, typically operates with an overall efficiency of 65-85%. Figure 7 demonstrates an example comparison between separate generation and CHP generation for the same energy output.

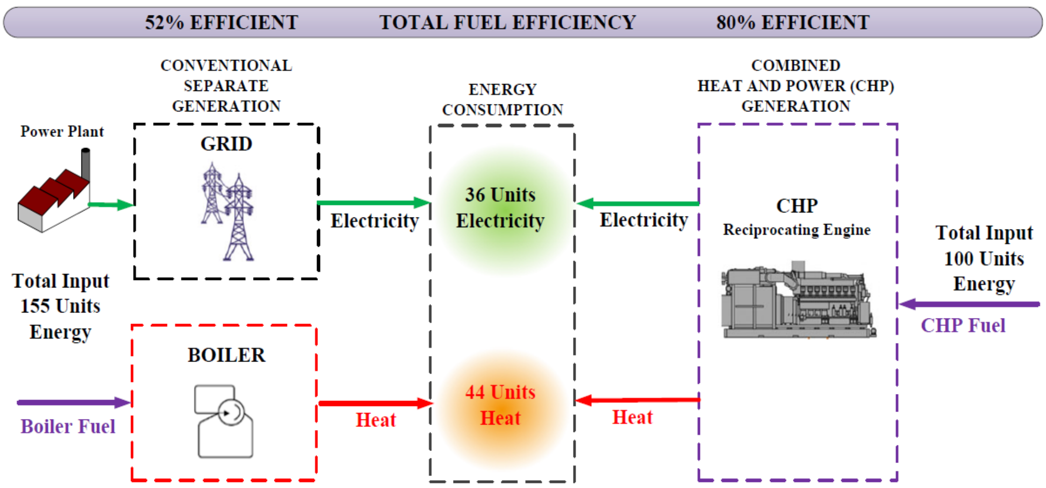


Figure 7. An Example Comparison Between Separate Generation and CHP Generation

CHP systems are classified based on the type of prime mover used. There are five major technologies commonly used for CHP systems:

- Reciprocating (internal combustion) engines,
- Gas turbines,
- Microturbines,
- Fuel cells,
- Boiler/steam turbines.

Each of these technologies has unique advantages and disadvantages. Therefore, the selection of technology for CHP systems is dependent on several critical parameters, such as application type, location, primary energy source availability, energy capacity requirements, operational constraints, operational costs, and investment costs (U.S. Department of Energy, 2016).

CCHP system utilizes the heat from a gas turbine or gas engine and converts the heat to a useful cooling via a cooling device such as an absorption chiller. A CCHP system can generate continuous electricity, heat, and cooling at the same time. In Figure 8**,** the most common energy flows are shown for a typical trigeneration application with CCHP.

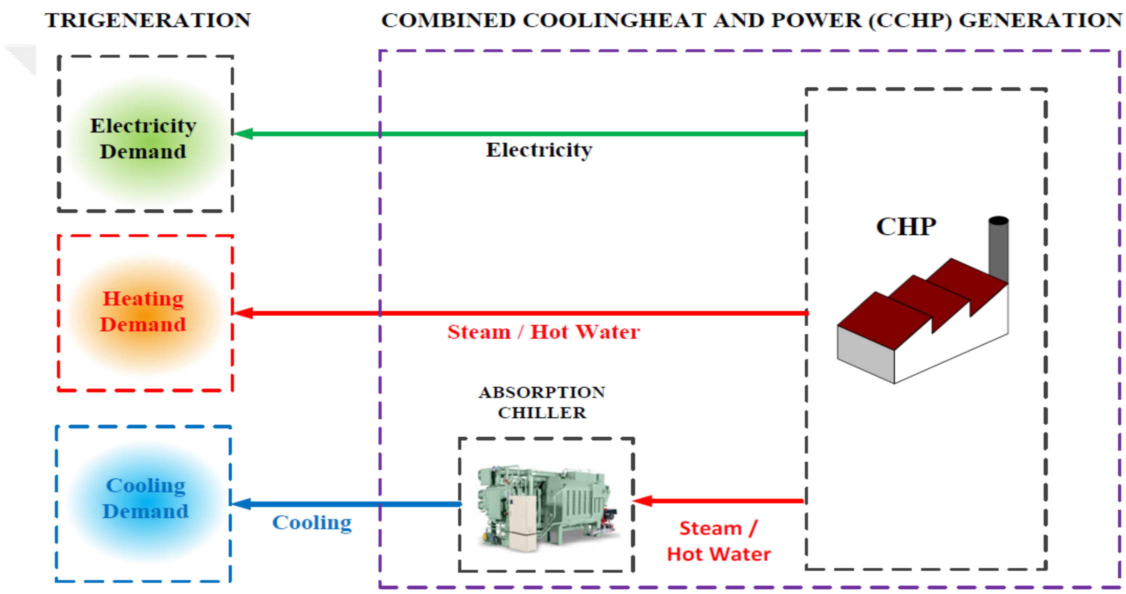


Figure 8. The Most Common Energy Flows for a Typical Application with CCHP

CHP and CCHP has multiple benefits for its user such as data centers and regions:

- Decreased energy costs
- Enhanced energy resiliency
- Increased financial competitiveness.

A region can also benefit from the CHP systems as follows:

- Alternative fuels such as natural gas, biogas or biomass,
- Opportunity to reduce fossil fuels,

- Lower CO2 emissions,
- Increased reliability for the critical infrastructure,
- Reduced investment in energy system infrastructure,
- Supports local economic growth and competitiveness,
- Peak shaving,
- Waste heat recovery and district heating/cooling opportunity.

CHP is a widely used technology across the world. According to the DOE's USA database, there are currently 4,395 CHP units installed in the country, with a total capacity of 82,598 MW. Figure 9 illustrates the breakdown of the different CHP technologies used in these installations.

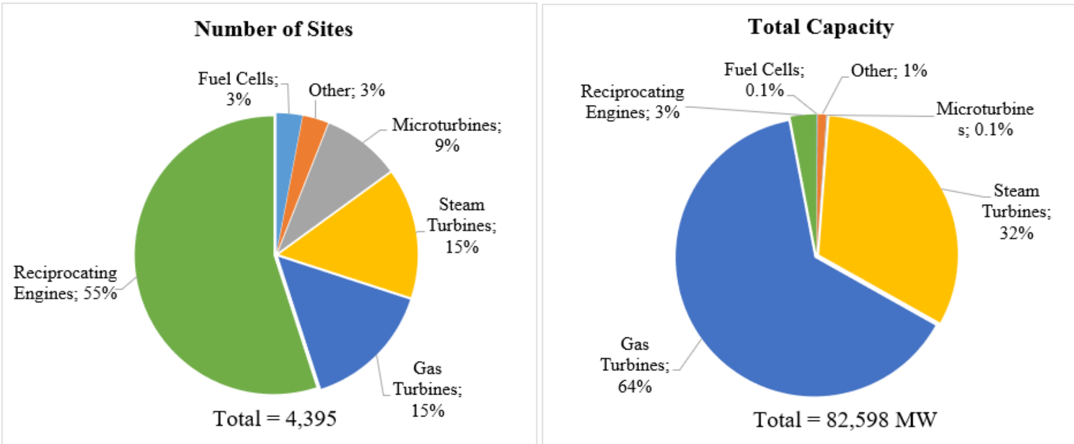


Figure 9. Breakdown of the Different CHP Technologies (U.S. Department of Energy, 2016)

In 2012, the International Energy Agency (IEA) reported that heating and cooling energy consumption accounted for nearly 46% of the world's total energy consumption (International Energy Agency, 2012). And CCHP systems are commonly utilized in modern district heating and cooling networks.

Many CCHP systems are installed in different data centers, globally. As a recent example, a data center operator ClusterPower bought hydrogen-ready natural gas engines for CCHP application to use in the first phase of its 200MW data center (Barun and Al-Abdeli, 2017). CHP and CCHP systems are also favorable for the data center industry with many examples in the U.S. (U.S. Environmental Protection Agency Combined Heat and Power Partnership, 2007).

In Europe, heat energy constitutes almost 50% of the end-use energy. The Heat Roadmap Europe strategy report states that the goal is to increase the proportion of thermal energy supplied by district energy networks from the current level of 13% to 50% by 2050 (Heat RoadMap Europe, 2021).

Achieving this objective will require enhancements in energy management, waste heat recovery, thermal energy storage, and power grid connectivity. In Finland, district heating covers nearly 50% of the total heating energy market, and CHP plants supply almost 80% of the demand for district heating.

The Finnish example and the European Union Heat RoadMap demonstrate the crucial role played by CHP in the production of district heat and indicate that it is an outdated technology (Heat RoadMap Europe, 2021; Wahlroos et al., 2018).

CHP is also well-used in Scandinavian countries. In Denmark, CHP systems account for over 50% of total power generation (Environmental and Energy Study Institute). In 2007 Summit, G8 leaders called on participants to accelerate the utilization of CHP for the purpose of electricity generation.

CHP and CCHP applications in the world are accelerating and they have dominance, particularly in the district energy networks. In Denmark, CHP covers approximately 52% of the country's power generation. CHP share in total national power production is expected to rise in G8+5 countries (International Energy Agency, 2008).

The development of an energy management strategy is essential for the effective application of CCHP systems, and the strategy employed should be determined to suit the requirements of each specific application. Some applications may require a constant supply of electrical power, while others may require a constant supply of heating or cooling. The most frequently used energy management strategies are the Following Electric Load (FEL) and the Following Thermal Load (FTL) approaches.

The FEL strategy involves following the electric load of the consumer to meet the electricity demand. This strategy is commonly employed in electricity generation facilities, such as power plants. In FEL operation, if the thermal demand is not satisfied, it can be met using additional boilers and electric air-conditioners. The FTL strategy involves following the thermal load of the consumer to satisfy the demand for heating or cooling. This approach is typically used in district heating and cooling applications. In FTL operation, if the electricity demand is not met, it can be supplied via the power grid. In summary, appropriate operational strategy should be determined in advance to avoid additional costs and emissions compared to conventional generation (Barun and Al-Abdeli, 2017).

In addition to conventional operating principles, new optimization techniques can be employed to improve the efficiency of CCHP systems based on different criteria.

The literature many studies describe mainly four different optimization criteria that can be utilized individually or in combination using complex optimization methods. The four optimization criteria are:

- Primary energy consumption optimization
- Operating cost optimization
- Emission saving optimization
- System reliability optimization

Some studies have employed multi-objective optimization criteria with sophisticated optimization techniques to achieve optimal system performance with a combination of these aforementioned criteria.

A CCHP system can be an ideal solution for providing uninterrupted power and cooling to a data center, due to its ability to match the center's demand for stable and consistent energy (Keskin and Soykan, 2022). The latest CHP systems used in the industry are capable of producing nearly equal amounts of power and heat energy, with a ratio between 0.95 and 1.01 (Jenbacher). In the same way, the electrical power (kWe) and cooling (kWth) requirements of data centers are almost equal, making CCHP systems well-suited for providing continuous power and cooling to the centers (Keskin and Soykan, 2019). Additional benefits include enhanced energy resiliency, improved primary energy consumption efficiency, and reduced energy expenses (U.S. Environmental Protection Academy, 2015). Similar to on-site renewables energy generation, a CCHP can also decrease the data center’s Greenhouse Gas (GHG) Protocol defined Scope-2 emissions associated with grid electricity consumption (Keskin and Soykan, 2017, 2023).

Figure 10 shows the energy flow comparison of a grid-based and CCHP-based data center.

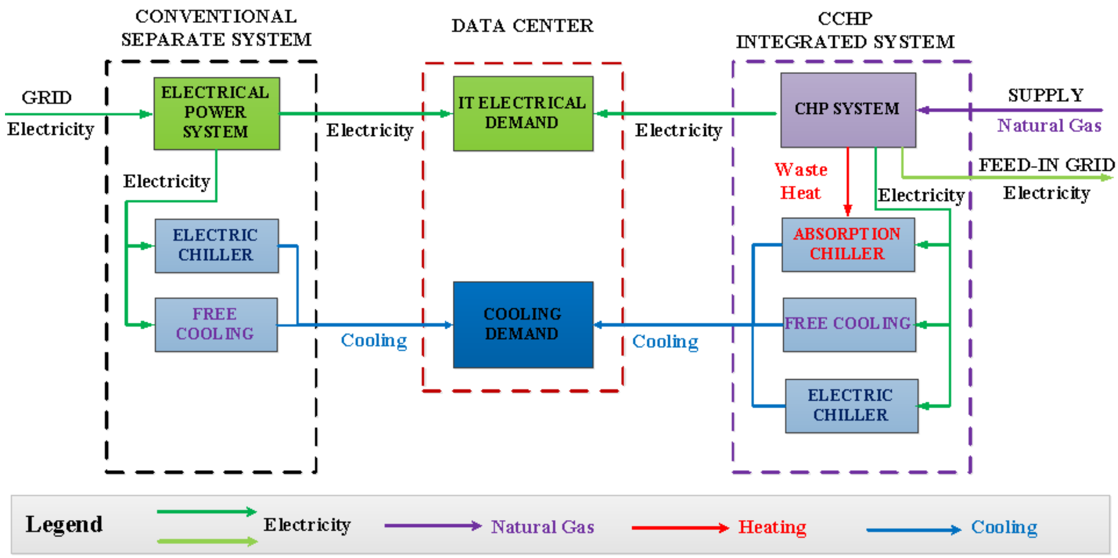


Figure 10. Energy Flow Comparison of a Grid-based and CCHP-based Data Center

2.3.2 Cooling technologies and free-cooling. A huge amount of cooling is necessary in the data centers and there are typically two different types of cooling techniques:

- Liquid-cooling systems
- Air-cooling systems

Liquid cooling involves circulating a coolant liquid through a closed system that removes heat from the data halls. Liquid cooling can transfer more heat compared to air cooling, allowing for more intensive electronic processing within a similar IT footprint. Despite its numerous advantages, liquid cooling has not been widely adopted due to the higher investment costs, risk of coolant leakage, and operational challenges associated with it. Liquid cooling is currently mainly used in high-intensity IT rack projects with power densities greater than 20kW (TechTarget). As the global demand for cloud computing, electronic processing, and fast computing continues to increase and investment costs tend to decrease, there could be more interest in the use of liquid-cooling in the future.

On the other hand, air-cooling is widely used method and involves circulating cool air through the data halls to remove heat. Air-cooling systems are used by the majority of existing and newly developing data centers. Air-cooling is a less expensive and easier-to-operate cooling technique than liquid-cooling and is well-known by data center operators.

Although air-cooling has some drawbacks, such as the potential for hot spots, it is still a safe and reliable cooling technique for data centers.

As per the design, the hot air in the data hall needs to be removed from the data hall cooling units using various cooling systems. Three distinct cooling systems are employed for air-cooling techniques (Ebrahimi et al., 2014):

- Air-cooled
- Water-cooled
- Two-phase cooled systems

Air-cooled and water-cooled systems are very common in data centers. Large and hyper-scale data centers generally favor water-cooled systems for increased efficiency. The water-cooled system includes a chiller and Computer Room Air Handling (CRAH) unit for the cooling operation, and water or a water-mixture liquid is used in the primary circuit. The CRAH units in the data hall have fans and convert cooling energy in chilled water to cool air, which is then blown into the data hall via the fans.

Air-cooled systems are primarily used for medium and small data centers, as well as IT server rooms. An air-cooled system consists of a Direct Expansion (DX) outdoor unit and indoor Computer Room Air Conditioning (CRAC) unit for the cooling operation. The system utilizes refrigerant in the primary circuit. The CRAC unit has fans, converts cooling energy in the refrigerant to cool air, and blows it into the data hall via its fans.

In two-phase cooling systems, heat is transferred through the evaporation and condensation of a portion or all of the working fluid (Advanced Cooling Technologies). Although the system has some limitations, such as the requirement for high pumping power and reliability issues, two-phase cooling has been proven to remove high heat fluxes from the system (Ebrahimi et al., 2014).

Free cooling operation mode provides opportunity as energy saving operation. When the outside temperature is lower than the set temperature inside the IT room, free cooling economizers utilize the cool and dry outdoor climate conditions to partially or fully eliminate the need for cooling using refrigeration compressors (Bertoldi et al., 2017). This elimination helps to reduce electricity use by cooling devices.

Free cooling technology is categorized into two techniques:

- Air-side free cooling
- Water-side free cooling.

Air-side free cooling systems make use of cooler outdoor air to cool data centers. When the outside air is appropriate, air-side economizers either draw the outside air directly inside or use a heat exchanger to indirectly utilize the cold air (Lee and Chen, 2013).

Direct air-side free cooling is generally not favored by data centers due to the risk of contamination, even with proper filtration options (Zhang et al., 2014). However, air-side free cooling is not always the most optimal solution for all climate zones. In dry and humid climate zones, more energy is required for fans and humidification/dehumidification, which decreases the benefits of this technology (Lee and Chen, 2013).

Water-side free cooling employs a natural cold source through a cooling water system, allowing for free cooling without compromising the internal environment. Water-side cooling is the most efficient cooling technology for data centers, with EU data centers reporting a minimum PUE of 1.1, which is the closest to the ideal PUE of 1.0 (Bertoldi et al., 2017).

There are three types of water-side cooling systems:

- Direct-water cooled system,
- Air-cooled system,
- Cooling tower system.

The direct water-cooled system uses naturally cooled water, but it is not frequently used for data centers due to resource availability. The air-cooled system utilizes water circulating to CRAC when the wet-bulb temperature of the outside air is appropriate.

A cooling tower system utilizes a cooling tower that is based on evaporative cooling. When the outdoor temperature is suitable, the cooling tower system bypasses the electric chiller.

It is possible to obtain partial cooling production from an electric chiller. The wet-bulb temperature (WBT) is always lower than the air-bulb temperature (ABT) of the air. A cooling tower system operates based on WBT can provide benefits for longer periods throughout the year compared to other systems.

Oro et al. (Oro et al., 2015) investigated the free cooling potential for a 1250kW data center located in various European cities. Their findings showed that the electricity consumption of the cooling system decreased between 15% and 22%, depending on the location. Based on economic analysis for the required additional systems, they found that Amsterdam, Barcelona, Frankfurt, and London were feasible locations for free cooling implementation. Atwood and Miner (Atwood and Miner, 2008) also conducted a study and they found that a free cooling system resulted in a 67% reduction in cooling energy consumption in a desert climate with low humidity.

The benefits of free cooling in data centers depend on the outside temperature (Liikamaa, 2019). To utilize free cooling for longer hours, the indoor set temperature of the cooling system can be increased. Thus, more energy can be saved.

2.3.3 Residual (waste) heat recovery. Despite the availability of multiple heat recovery techniques and the possibility of reuse within data centers, data center operators usually do not reuse the residual heat generated by IT devices. The excess heat produced by IT devices is considered a low-grade heat that can typically be captured at a temperature between 25 °C and 50 °C, depending on the system. Different methods for recovering low-grade heat are discussed in the literature and utilized in the industry, as outlined in (Ebrahimi et al., 2014). Space heating and district heating are considered the most flexible and stable methods of reusing a data center's residual heat (Pei et al., 2019). In the air-cooling technique, the residual heat can be harvested from different locations based on the cooling systems used. In a water-cooled system, excess heat can be captured from either the hot air return plenum via an air-to-water heat exchanger (HEX) or from the chiller return pipeline via a water-to-water HEX. Harvesting residual heat from the return air plenum has a significant advantage because it allows the heat recovery system to be independent of the critical cooling system. This method provides more independent and safer operation for the critical cooling systems (Davies et al., 2016).

Figure 11 and Figure 12 displays the different harvest of residual heat in an air-cooled data center.

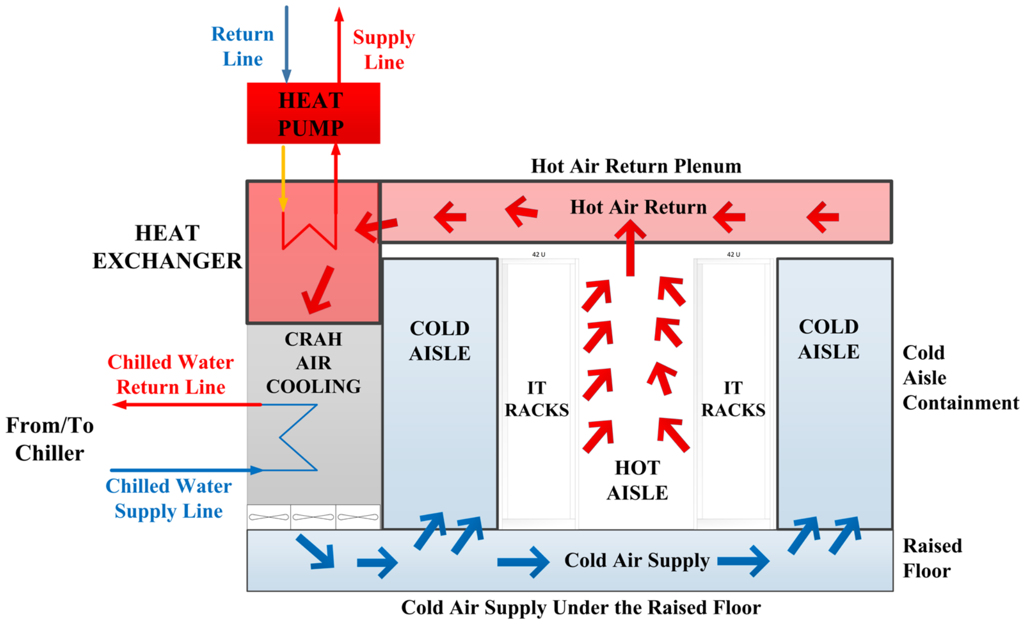


Figure 11. Harvest of Residual Heat from the Hot-Air Return Plenum via Air-to-Water

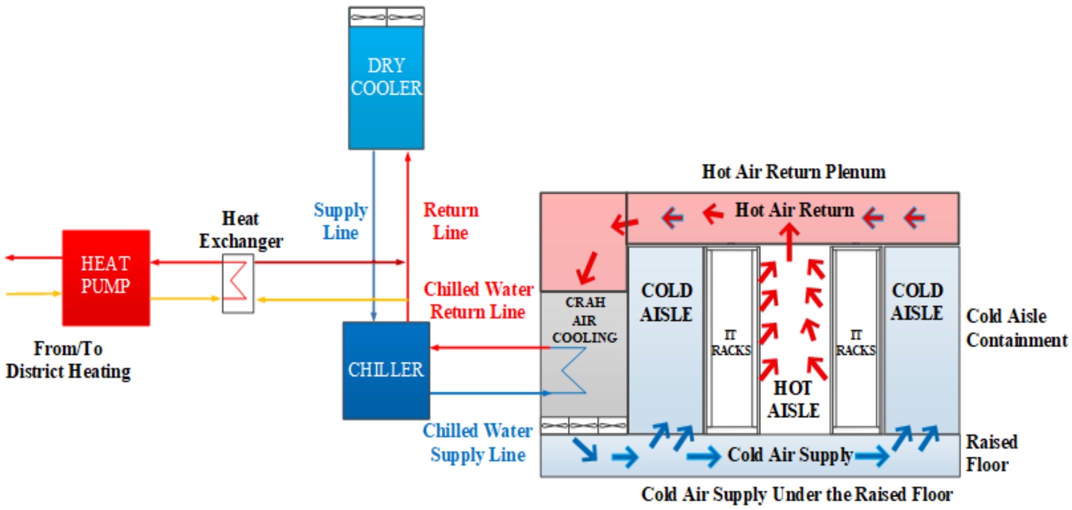


Figure 12. The Harvest of Residual Heat from the Chiller Circuit Water-to-Water

While the residual heat can be used locally for space heating or domestic hot water demand, the hourly heating demand does not match the continuous residual heat production of data centers (Balaras et al., 2017). Therefore, to avoid waste, the remaining residual heat from data centers should be utilized.

District heating provides a flexible alternative for the connection of the data center's total residual heat. Many customers in district heating networks can use a data center's relatively large residual heat production. However, the data center's residual heat is low-temperature heat and requires upgrading through a proper heat pump to a temperature between 60°C and 90°C to be used in existing district heating networks (Keskin and Soykan, 2022).

Figure 13 illustrates how a data center can supply residual heat to district heating networks using a water-to-water heat pump.

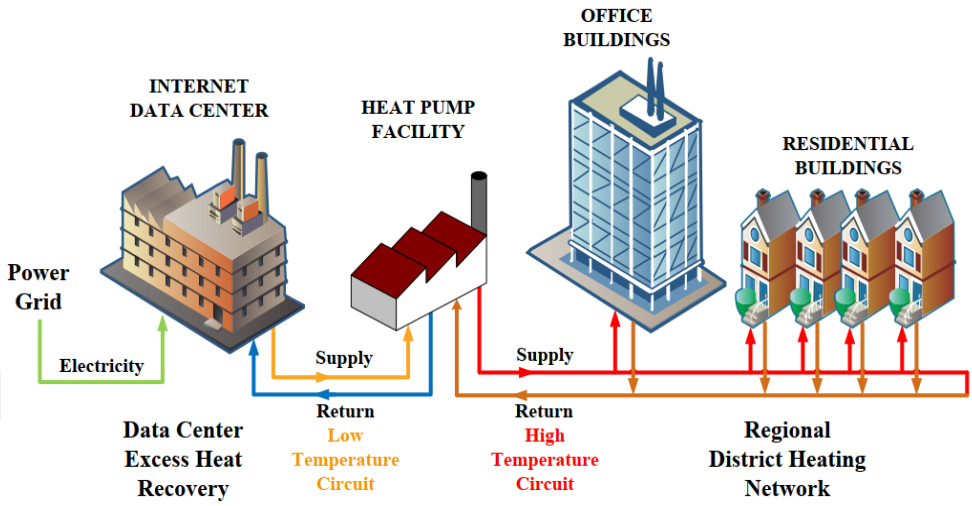


Figure 13. Data center's residual heat (low-temp) recovery system integration to district heating network (high-temp)

Table 2 provides examples of the district heating design temperatures for various countries (Skagestad and Mildenstein, 1999).

Table 2

Examples of Temperatures Used for the Design of Central Heating Systems (Skagestad and Mildenstein, 1999)

Country	Supply Temperature	Return Temperature	Hot Water
Denmark	70	40	<60
Finland	70	40	55
Korea	70	50	55
Romania	95	75	-
Russia	95	75	50
United Kingdom	83	70	65
Poland	85	71	55
Germany	80	60	55

Table 3 provides examples of the district heating design temperatures for various cities in Turkiye (Izmir Jeotermal, 2019).

Table 3

Examples of the District Heating Design Temperatures for Various Cities in Turkiye (Izmir Geothermal, 2019).

City	Location	Production Capacity (m^3/hour)	Temperature (ºC)
Afyon	Sandıklı	1440	80
Ağrı	Diyadin	180	78 - 85
Ankara	Kızılcahamam	63	75
Balıkesir	Gönen	-	60 - 70
Balıkesir	Edremit	1440	58
Balıkesir	Bigadiç	54	98
Bursa	Merkez	1080	88
Denizli	Sarayköy	260	145
İzmir	Balçova - Narlıdere	2020	90 - 144
İzmir	Bergama	180	65
İzmir	Dikili	200	80
İzmir	Çeşme	49	57
Kırşehir	-	983	55
Kütahya	Simav	928	130 - 150
Manisa	Salihli	540	88
Nevşehir	Kozaklı	-	94
Yozgat	Sarıkaya	180	57
Yozgat	Yerköy	648	65

For high-temperature district heating connections, data centers required heat pumps to convert low-temperature heat to high-temperature. A heat pump also consumes electricity. To eliminate the use of heat pumps, a low-temperature district heating network (LTDH) can be used for district heating. LTDH is a kind of district heating network that operates at lower temperatures as low as 50°C/25°C with high insulated pipes and relatively smaller inner diameters. In the future, more LTDH systems are expected to be installed to provide low-temperature waste heat sources for newly built houses, such as net-zero emission buildings. It improves energy efficiency and gives more opportunity to renewable energy sources (Yang et al., 2016). However, Legionella bacteria in domestic hot water (DHW) can limit the application of LTDH in conventional networks (Yang et al., 2016). Different methods must be implemented to eliminate this risk and provide healthy domestic hot water.

Data center residual heat also shows promise for meeting heating demands in the region. Studies suggest that data centers in Europe have the potential to supply approximately 60TWh of residual heat, making them an important contributor to Net-Zero Energy Districts (NZED) through their connection to district energy networks (Pärssinen et al., 2019). The municipality of Amsterdam has set an ambitious goal to expand its district heating network within the city and plans to connect 27,000 homes to regional district heating networks by 2041. By utilizing waste heat from industrial facilities and data centers in Amsterdam city, this district heating network will be able to warm up approximately 41% of both new and existing buildings (Niessing and Rösler, 2015).

Residual heat from data centers is already being used to serve residential homes in some countries. One data center company in Finland is currently providing residual heat energy for domestic hot water for 20,000 inhabitants (European Commission, 2020). Another data center owner has also started to recover waste heat from its Danish data center by connecting it to a nearby district heating system (Edelman, 2020).

2.3.4 Renewable energy systems. Society's growing concern for sustainability is leading to an increased focus on environmentally friendly practices. Data center investors are now insisting on renewable-based energy sources to power their operations. The U.S. Energy Information Association (EIA) has identified five major sources of renewable energy that can be used for generating power (Gillin, 2022). These are as follows:

- Solar
- Wind
- Geothermal
- Biomass
- Hydropower

Renewable energy sources are intermittent, and while they can be predicted, they are difficult to control. Both wind and solar power generation fluctuate based on factors like weather and time of day, and there are times when there is no wind or sunlight available.

Hydropower varies seasonally and requires sufficient water to be available in rivers or reservoirs. To compensate for the fluctuations in renewable energy generation, alternative energy sources must be used in a process known as "firming" (Mytton, 2021).

Installing renewable energy systems requires careful consideration of factors such as geographic location, capital investment, and installation time. This is why many data center operators are opting to purchase renewable energy-sourced electricity through Renewable Energy Certificates (RECs) or Power Purchase Agreements (PPAs) rather than directly installing renewable energy systems.

When a unit of renewable energy is generated, a Renewable Energy Certificate (REC) is created specifically for that unit. These certificates are traded separately from the energy itself and can be purchased to allow buyers to match their electricity consumption with an equivalent amount of renewable energy. However, in a portfolio of renewable energy products, RECs are typically considered low quality because they do not guarantee that the renewable energy was consumed actually, or that new renewable energy capacity was built to match demand.

A Power Purchase Agreement (PPA) is a contract between a supplier and a customer, in which the customer agrees to buy renewable power from the supplier for a fixed period at a set price. PPAs are classified as either direct/physical PPAs or financial/virtual PPAs. Direct/physical PPAs ensure that electricity is physically delivered to the grid at a fixed price, which protects the buyer against price increases. However, if prices fall, the buyer may be locked into a long-term contract at a higher price than the retail price. In a portfolio of renewable energy products, direct/physical PPAs are considered high quality because the buyer can identify the exact resources providing the power. Financial/virtual PPAs do not involve the physical delivery of energy to the buyer. Instead, the buyer agrees to a "strike price" for each unit of energy, and the generator sells the power into the local wholesale market, which may be in a different location from the buyer. If the wholesale price is higher than the strike price, the supplier pays the buyer the difference. If the wholesale price is lower, the buyer must pay the difference to the supplier. Therefore, a virtual PPA typically involves taking on some financial risk (Mytton, 2021).

Data center operators that have advanced sustainability programs have been working towards their renewable energy goals for over a decade. Some operators already achieved their goal of matching 100% of their energy consumption with renewables. The initiatives taken by data center operators to match their energy consumption with renewables may sound good on paper or in the news, but they do not guarantee the complete decarbonization of the power grid. Simply matching with renewables does not necessarily lead to the creation of new sources of renewable energy generation. To avoid accusations of greenwashing, data center investors should consider investing in renewable energy generation themselves, rather than just relying on renewable energy certificates or power purchase agreements.

Given the huge electricity consumption of data centers, it is often the case that renewable-based energy resources can only partially provide their electricity demand. While this is still a step in the right direction, data center operators need to continue to work towards increasing the proportion of renewable energy sources in their energy mix. This can be done through a variety of methods, including investing in on-site or nearby renewable energy generation, and working with utility companies to increase the amount of renewable energy in the grid. This is especially important until the entire grid is fully decarbonized.

2.4 Sustainability and Emission Issues for Data Centers

The EU has set a target to achieve climate neutrality by 2050, which means having an economy with net-zero greenhouse gas emissions (European Commission). While achieving climate neutrality is challenging, it presents an opportunity for a better future for everyone. Society, in a broad sense, has a significant impact in achieving these targets. Data centers are significant contributors to energy consumption, and they can contribute to society by transitioning from being mere consumers to becoming producers of energy. In 2018, data centers in 28 European countries were responsible for greenhouse gas emissions ranging from 0.4 to 0.6%. If data centers in the EU28 can become climate-neutral, it could help to a big decrease in greenhouse gas emissions inhabitants (European Commission, 2020).

Data center operators in Europe have committed to the Climate Neutral Data Centre Pact, which targets to have data centers climate-neutral by 2030. This ambitious target aligns with the European Commission's objective to achieve a CO2-neutral data center industry by 2030 (Vermeulen and Patel, 2020).

In the past few decades, the significance of sustainability has grown substantially. The United Nations, established in 1945 and comprising 193 developed and developing countries, places great emphasis on sustainability (United Nations, 2015). They have created 17 Sustainable Development Goals (SDGs) that call for urgent action from all countries. Data centers, with their energy and water consumption, as well as their provision of services to society, infrastructure, and development, fall within the scope of many SDG goals (United Nations). Thse goal numbers 6, 7, 8, 9, 11, 12 and 13 are directly related to data center operations and energy consumption.

The greenhouse gas emissions (GHG) Protocol is the globally accepted standard framework for measuring and managing GHG from both private and public sector operations, value chains, and mitigation actions. The term "Corporate Carbon Footprint" is calculated using the "carbon dioxide equivalent" (CO_2e) metric, which takes into account the different global warming potentials (GWPs) of various greenhouse gases.

The GHG Protocol Corporate Standard categorizes the greenhouse gas emissions associated with a company's Corporate Carbon Footprint (CCF) as follows (The Greenhouse Gas Protocol, 2015):

- Scope 1: Direct emissions
- Scope 2: Indirect emissions
- Scope 3: Indirect value chain emissions

A data center is not only an organizational company but also a facility that consumes a substantial amount of energy. Consequently, a data center is closely linked to all three scopes of emissions throughout its life cycle. Scope 1 emissions are direct emissions such as emissions from on-site diesel generators.

Scope 2 emissions refer to the indirect greenhouse gas emissions resulting from the purchase or acquisition of energy, such as electricity, steam, heat, or cooling, that is generated off-site and consumed by a data center. For instance, the greenhouse gas emissions associated with producing electricity for the power grid are proportionate to the amount of grid power consumed by a data center. Compared to other phases in the life cycle of a data center, the use phase, with its substantial energy consumption, generates significant emissions and is therefore closely associated with Scope 2 emissions. Improvements in the operational energy consumption of data centers can lead to a reduction in data center-related emissions on a global scale and contribute to environmental benefits.

It is possible to reduce Scope-2 emissions by using alternative, more efficient, and cleaner systems in data operations. The European Parliament and Council Directive on the energy performance of buildings requires that technical, environmental, and economic feasibility of the following alternative energy systems must be evaluated (The European Parliament and the Council, 2010):

- CHP,
- Renewable-sourced decentralized energy generation,
- District heating and cooling,
- Heat pumps.

Additionally, the following systems and technologies can facilitate and contribute to more sustainable data centers:

- Free-cooling technology
- Waste heat recovery and utilization
- Energy-efficient innovations and using more energy-efficient systems and assets.

Alternative energy generation systems, such as CHP, fuel cells, and renewable power systems, can help reduce emissions caused by data centers' electricity consumption from the power grid (U.S. Environmental Protection Agency Combined Heat and Power Partnership, 2007).

2.5 Data Center Performance Classifications and Standards

Standards enable the industries to effectively advance faster and further. For data center world, the first step has been done by The Telecommunications Industry Association (TIA) in 2015. TIA provided to address data center infrastructure with the TIA-942 Telecommunications Infrastructure Standards for Data Centers. It is intended for data center designers (The Telecommunications Industry Association). Performance classifications are Tier 1, Tier 2, Tier 3 and Tier 4.

Trusted Site Infrastructure (TSI) is another criteria established in 2002. It considers the relevant EN and DIN standards - especially EN 50600 – but also VDE guidelines and VdS publications (TÜV Nord Group). Performance classifications are from Level 1 to Level 4.

Uptime Institute are the most known international standard for data center performance. Performance classifications are divided into four Tiers and the Tier levels are progressive (Uptime Institute).

According to Uptime Institute, Table 4 summarize the performance specifications for each Tier class (Uptime Institute).

Table 4

Tier Classifications and Performance Specifications as per Uptime Institute

Attributes	**Tier I**	**Tier I**	**Tier III**	**Tier IV**
Minimum capacity components to support the IT load	N	N+1	N+1	N - After any failure
Distribution paths – electrical backbone	1	1	1 active and 1 alternate	2 simultaneously active
Critical power distribution	1	1	2 simultaneously active	2 simultaneously active
Concurrently Maintainable	No	No	Yes	Yes
Fault tolerance	No	No	No	Yes
Compartmentalization	No	No	No	Yes
Continuous cooling	No	No	No	Yes

ANSI/BICSI Data Center Design and Implementation is another standard developed by BICSI. BISCI is a professional association and standard is called Data Center Design and Implementation Best Practices (Bisci, 2019). It is arranged as a guide for data center design, construction, and operation. Ratings are defined from Class 0 to Class 4.

Besides these voluntary-based standards, there is also a governmental standard in the European Union called The EN 50600. It represents the first European standard and has been created by CENELEC (European Committee for Electrotechnical

Standardization). Classifications are divided into four availability classes from ``low`` to ``very high`` (Dutch Data Center Association, 2020):

Although all aforementioned institutions, classifies data centers in four different levels, it has been seen that different institutions consider and focus on different criteria such as (Dutch Data Center Association, 2020):

- Maintenance capabilities,
- Power topology,
- Cooling topology,
- Fault capabilities,
- Site space and layout,
- Cabling infrastructure,
- Fire Protection, Alarm & Extinguishing Systems

It is hard to say one is better than the others due to different criteria in the evaluation stage. Reliability and availability values for the power and cooling are also not certain and comparable since they take different topologies and criteria into account. Among these voluntary-based standards, the most suitable standard must be chosen as per the need of the data center sponsor and the aim of the data center.

Chapter 3

Literature Review

In this chapter, the literature on energy savings, waste heat recovery, CCHP, renewables, and district energy network connection of the data center will be presented.

To decelerate the energy consumption of data centers, and minimize their impact on the power grids, best practices primarily focus on physical, equipment-based, and operational improvements. In addition to these, demand response programs were investigated in the literature. These programs typically involve IT equipment shutdown, data load shifting, data load migration, and geographical load balancing (GLB) (Cioara et al., 2020; Hu et al., 2021). However, IT equipment-based programs have a limited impact on data center energy management and require complex IT operations that may not be acceptable to end users.

Modern Information and Communication Technology (ICT) systems have advanced the development of energy management solutions in data centers and provided the possibility for various scenarios, including reduction of peak power demand and demand response (Basmadjian, 2019). Lombardi et al. (Lombardi et al., 2019) proposed an thermal storage and ice storage to reduce the data center's electricity demand from the grid to achieve more sustanaible operations. Yang et al. (Yang et al., 2018) investigated the scheduling of data resources in a data center with renewable energy sources in order to control IT load demand response, which improved operational flexibility. Ajayi and Heymann (Ajayi and Heymann, 2021) developed a model that uses dynamic prediction of data center energy demand to achieve cost-efficient and environmentally friendly energy management. Wang et al. (Wang et al., 2014) analyzed the integration of solar electricity generation and cloud computing systems, where the smart grid determines the optimal electricity pricing to control the cloud computing system and shifts the computational load to data centers in different geographical locations. Tian et al. (Tian et al., 2021) integrated a data center with a CCHP by utilizing a robust energy management system that coordinated renewable energy and energy storage. Saberi et al. (Saberi et al., 2019) achieved a reduction in operational costs and carbon emissions through their implementation of real-time demand response. Wang et al. (Wang et al., 2021) created a control system optimization for an energy net integrated with a data center and residential and commercial buildings. However, the literature discussed above did not consider the recovery of waste heat from the data center, the use of free-cooling technologies, residential energy demand models, or the effects of seasonal weather on the energy demands.

CHP and CCHP research in the literature consists of the optimum system sizing, feasibility, and performance assessments, modeling, optimal operation strategies, and other aspects of CCHP systems for various applications. CCHP's integration into residential buildings or district heating and cooling networks requires complex control and scheduling algorithms for the optimum cost of operation. Barun and Abdeli (Barun and Al-Abdeli, 2017) described the commonly used CCHP power management strategies. They used two types of load management which are: ``Following the Thermal Load (FTL)`` and ``Following the Electrical Power Load (FEL)``. Kim et al. (Kim et al., 2016) used MILP to find the optimal electrical and thermal outputs and schedule the operational hours of CHP and thermal storage. They demonstrated that an optimized operation of CHP with thermal storage could save 14% of operational costs. Boyaghchi and Heidarnejad (Boyaghchi and Heidarnejad, 2015) introduced a new solar micro-CHP. The results indicated that efficiencies and product cost rates varied in summer and winter.

CHP systems have been extensively researched but their applications in data centers have received limited attention in the recent literature (Song et al., 2016). Data center integrated systems generally investigated a local integration of the CCHP for data centers. Data center integrated systems generally investigated a local integration of the CCHP for data centers. Xu and Qu (Xu and Qu, 2013) found that CCHP could be a beneficial solution for data centers and they proposed a locally-used gas-turbine CCHP. Keskin and Soykan (Keskin and Soykan, 2019) studied the enhancement of reliability and energy saving at a data center through the use of CHP. Wan et al. (Wan et al., 2021) offered a cost-conscious energy management strategy for the CCHP and waste heat recovery technologies. Fu et al. (Fu et al., 2021) analyzed the difference between a CCHP-PV-integrated data center and a conventional grid-fed data center.

However, the literature above does not examine the regional energy integration of CCHP and renewable-based data centers.

To minimize costs and reduce peak loads, researchers have explored optimal scheduling models for CCHP and renewable energy in the literature. Kialashaki (Kialashaki, 2018) found that the financial benefits of a CCHP system could be increased when it was operated with optimal cost optimization and surplus electricity was provided to the power grid. Zhao et al. (Zhao et al., 2018) studied a microgrid that was integrated with CCHP and alternative energy systems with optimal operation. Keskin and Soykan (Keskin and Soykan, 2022) investigated the cost-optimized scheduling of a CCHP-based data center and supplied surplus thermal energy to nearby district energy networks. The main research area of the above literature is energy management optimization for various energy sources, and they do not assess the impacts of thermal and electricity demands on the region.

Pärssinen et al. networks (Pärssinen et al., 2019) indicated that there is limited research on utilizing residual heat in data centers. However, data center residual heat recovery system is also another way of energy saving from the waste heat, besides the CCHP's waste heat recovery. It is found beneficial in terms of power, carbon emission, and cost reduction. He et al. (He et al., 2018) indicated that the excess heat recovered from a data center in China could save nearly 10% of the annual electricity for the studied data center. From the point of the district heat network operator, the data center's residual heat recovery system is also found promising. Huang et al. (Huang et al., 2020) estimated that up to 68% of the residual heat generated in data centers can be reused. Davies et al. (Davies et al., 2016) and Wang et al. (Wang et al., 2015) discovered that heat recovery can lead to a reduction in emissions and energy costs. Balaras et al. (Balaras et al., 2017) found that the hourly heating demand of customers in district heating networks does not align with the continuous waste heat production in data centers. As a result, energy self-usage and trade-off flexibility become increasingly important for data centers and regions to achieve energy cost savings and reduce emissions (Wahlroos et al., 2017).

In the literature, some studies have only explored the combination of PV generation with data centers for partial reduction of the grid demand. Guo et al. (Guo et al., 2014) suggested geographical load balancing and workload scheduling to enhance the utilization of on-site renewable energy sources. However, the effect of on-site PV generation shall be evaluated, both technically and economically (Chen and Wemhoff, 2019). It is possible that a large disparity can occur between the electricity generation from PV and the electricity demand of data centers. Also, Li et al. (Li et al., 2011) did not recommend incorporating energy storage as a financial solution to address this mismatch in large data centers due to their massive electricity demand. On the other hand, Leitner et al. (Leitner et al., 2019) a technical assessment method for the integration of low-temperature district heating and electrical distribution networks, including the integration of different capacities of PV systems. According to the authors, the most critical performance parameters on an electrical distribution grid are voltage fluctuations, loads, and generation. However, the study did not focus on data centers.

As reviewed in the literature, various combinations of CCHP systems, renewables, residual heat utilization, and free cooling have been researched separately or in conjunction with each other for use in data centers. However, the potential impacts of multi-energy hub-connected data centers on grid-side emissions reduction, energy demand reduction, reliability and availability impact on data center, power loss mitigation, voltage drop prevention, and short-circuit level changes, have not been addressed so far.

Chapter 4

Methodology

The study aims to assess the CCHP and other alternative systems' integration into data centers. Besides these technologies, distribution power grid electrical performances and emission savings are evaluated. Optimization is also utilized in order to cost-minimize the operation of data center energy systems.

Figure 14 shows the block diagram of the methodology used in this study. Firstly, model inputs and mathematical models of the components are created. A cost-optimization model is utilized for the scheduling of the proposed energy systems while satisfying the data center's electricity and cooling demand. Based on the outputs of the optimization model, energy, cost, and emission calculations have been done. Lastly, load flow and short-circuit analysis have been executed to find the voltage drop, power loss, electricity demand reduction, and short-circuit level parameters.

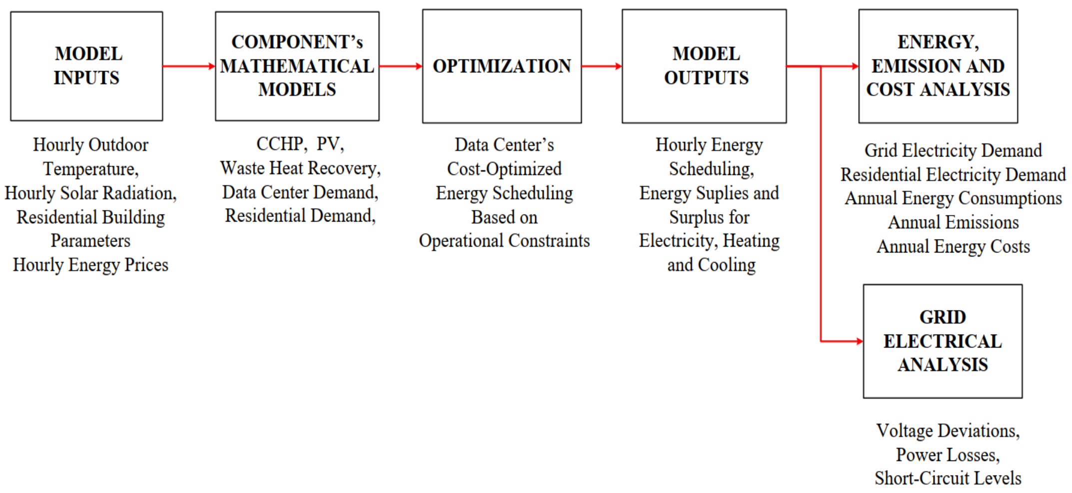


Figure 14. Block Diagram of the Methodology

In this study deterministic models were utilized to calculate the total energy demand and supplies in the hourly energy flow. The mathematical model of each component and optimization model for the comprehensive system were created in the Phyton programming software. To solve the optimization model, open source PuLP software was used. The total computational time was approximately 3 hours for a yearly (8760 hours) simulation of each case study.

For the distribution grid electrical analysis, the load flow and short-circuit analysis were run on an electrical network analysis software to investigate the MV distribution power losses, voltage, and short circuit levels of the specific connection points at the MV grid. The total computational time for each load flow or short-circuit analysis was 5 seconds for each case study.

Following sections present the system modeling, system operational modes, energy supply and demand calculations, optimization modeling, power grid electricity deamnd reductions and carbon equivalent emissions reductions.

4.1 System Modeling

The simulation model has been created from the component's mathematical models. The law of thermodynamics, energy equations, and manufacturer's partial load efficiency data are used for creating the mathematical equations (Yu and Chan, 2008). These mathematical equations are supported with the manufacturer's efficiency datasheets to create a more realistic and successful system for the literature. Hence, the success of this system can provide a better evaluation. Figure 15 illustrates the main components and energy flow of the proposed CCHP-PV-based data center that is connected to district energy networks.

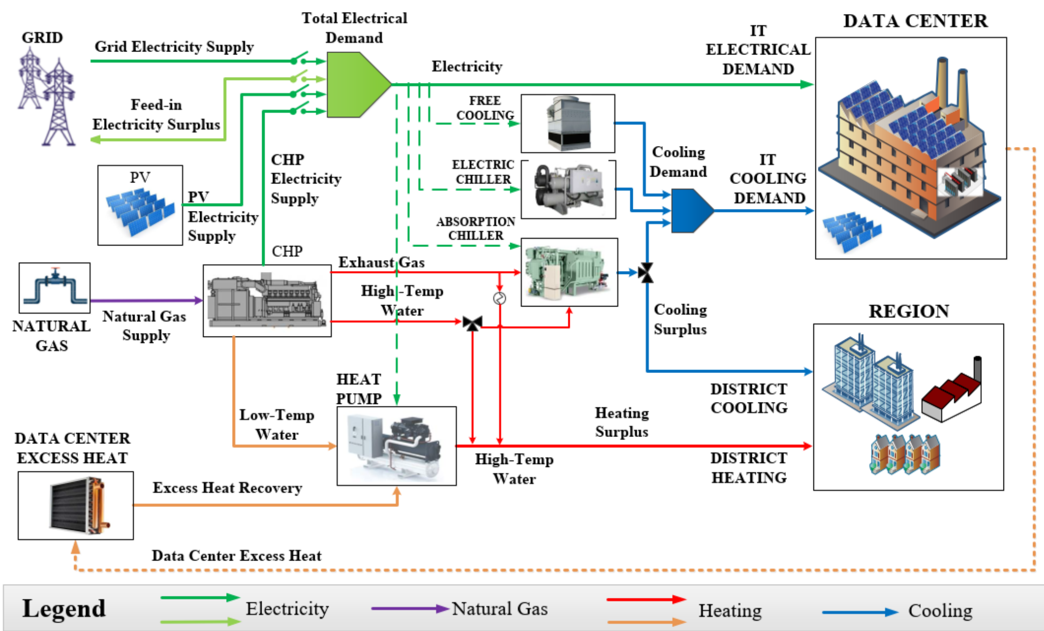


Figure 15. Energy Flow of CCHP-PV-based Data Center with District Heating and District Cooling Connection

In the following sections, the mathematical modeling of several systems and sub-component were presented:

- CHP modeling,
- Data center cooling systems modeling,
- Data center heat pump modeling,
- PV system modeling,
- Residential building modeling,
- Residential heating and cooling demand model,
- Residential heat pump,

Other system components with relatively minor energy impacts on overall energy consumptions, such as pipes, valves, and heat exchangers, are neglected to simplify the overall system. Description of the notations, variables and their corresponding units can be found in the The List of Abbreviations and Symbols.

The proposed data center using CCHP-PV systems is located in a region where residential customers can potentially consume surplus electricity, heating, and cooling energy generated by the data center. This comprehensive system considers CCHP utilization, PV installation, data center residual heat recovery, free cooling, hourly outdoor temperatures, hourly energy prices, and residential customers in the same grid ring as the data center.

To assess the impact of the CCHP-PV-based data center with a district energy network connection on the electrical distribution grid, it is crucial to evaluate its performance based on various electrical parameters. Hence, the data center and residential customers are connected to the same medium-voltage (MV) grid with a ring topology, as shown in Figure 16. This MV ring comprises four residential areas and a data center.

4.1.1 CHP modeling. A CHP unit consists of a gas engine and a synchronous generator that generates electricity and thermal heat energy while consuming natural gas. CHP's hourly natural gas consumption (V_{ng}) is captured from the manufacturer's datasheet based on the actual load and CHP's required input energy in kWh (E_{chp}) with the following formula:

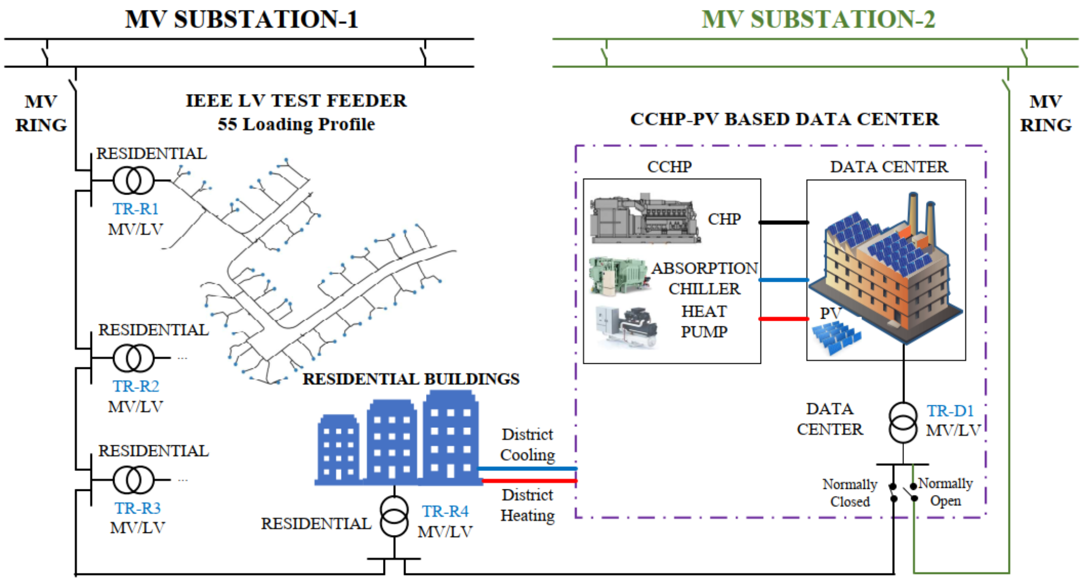


Figure 16. The Energy Connections of Residential Customers and CCHP-PV-based Data Center

$$E_{chp} = (V_{ng}\ x\ H_{ng}\ )\ /\ 3600 \tag{2}$$

CHP's mechanical energy (E_{m_chp}) is found by multiplying the mechanical efficiency (η_{m_chp}) with CHP's input energy in kWh (E_{chp}):

$$E_{m\_chp} = E_{chp}\ x\ \eta_{m\ chp} \tag{3}$$

CHP's mechanical efficiency (η_{m_chp}) varies based on the actual load in percentage.

CHP's electrical energy (E_{e_chp}) is found by multiplying the electrical efficiency (η_{e_chp}) with CHP's mechanical energy (E_{m_chp}):

$$E_{e\_chp} = E_{m\_chp}\ x\ \eta_{e\_chp} \tag{4}$$

CHP unit generates thermal energy as a side-product in terms of flue gas exhaust heat (H_{exh}), high-degree water heat (H_{hw}), and low-degree water heat (H_{lw}), while it is generating electricity. This heat can be recovered as useful heat to supply district heating, process heat, or steam. Dissipation heat from the engine (H_{diss}) is not a useful heat with a 3% share of the total energy input and it is dissipated to the ambient. Thus, CHP's total waste heat (H_{chp}) is found by the sum of the following:

$$H_{chp} = H_{exh} + H_{hw} + H_{lw} + H_{diss} \tag{5}$$

Without dissipation heat, total useful waste heat (H_{waste}) is calculated by the sum of all other useful energy sources:

$$H_{waste} = H_{exh} + H_{hw} + H_{lw} \tag{6}$$

CHP's useful waste heat recoveries vary based on the actual part load of the CHP unit. Each heat efficiency (η) determines the different sources of waste heat based on the CHP input energy (E_{chp}), and is calculated with the following formulas:

$$H_{exh} = E_{chp}\ x\ \eta_{exh} \tag{7}$$

$$H_{hw} = E_{chp}\ x\ \eta_{hw} \tag{8}$$

$$H_{lw} = E_{chp}\ x\ \eta_{lw} \tag{9}$$

On the other hand, H_{lw} usually is not recovered in CHP applications due to its low degree temperature, but this heat could be potentially recovered together with the data center's low degree excess heat (H_{dc}) by using a proper heat pump.

4.1.2 Data center cooling systems modeling. The absorption chiller can use CHP's exhaust heat and high-degree water to produce cooling for spaces or processes. There are different types of absorption chillers in the industry for different purposes. A multi-source absorption chiller is used to capture exhaust gas (375 °C) and high-degree (90 °C) water heat and convert them to chilled water (12 °C).

Absorption chiller's heat input (H_{abs}) is the sum of the CHP's exhaust heat and high-degree water heat:

$$H_{abs} = H_{exh} + H_{hw} \tag{10}$$

Absorption chiller's cooling output (Q_{abs}) varies on the actual load. It is calculated by multiplying the coefficient of performance (COP_{abs}) with heat input (H_{abs}):

$$Q_{abs} = H_{abs}\ x\ COP_{abs} \tag{11}$$

COP value varies based on the actual load. Absorption chiller has an internal electricity consumption (E_{abs}) during the operation. This value has been added to the total electricity consumption of the system's operation (E_{Demand}).

Water-cooled electric chillers are commonly used as cooling equipment in data centers. They produce chilled water that is supplied to CRAH units for providing cooling to IT racks in data halls. There are different types of electric chillers and COP values of these chillers also vary based on the actual load and type of the machine.

Electric chiller cooling output energy (Q_{ech}) is a function of the coefficient of performance (COP_{ech}) and electricity consumption of the chiller (E_{ech}).

$$E_{ech} = Q_{ech} / COP_{ech} \tag{12}$$

When the outside ambient temperature is low, the data center's excess heat can be dissipated to the environment without the need for an electric or absorption chiller by free cooling. The indirect evaporative cooling tower is used to dissipate the heat to the environment during the free cooling operation. In this operation, the cooling system uses only the water circulation pump and cooling tower fans, so it consumes relatively less energy than an electric chiller or absorption chiller operation. Free cooling operation electrical consumption (E_{frc}) is the total electricity consumption of the pumps (E_{pumps}), CRAH (E_{CRAH}), and cooling tower (E_{CT}).

$$E_{frc} = E_{pumps} + E_{CRAH} + E_{CT} \tag{13}$$

Besides the described main components in the system, water pumps, CRAH fans, and a cooling tower consume electricity for the cooling system's water circulation. Those vary based on the partial load in percentage. According to cooling operations (electric chiller, absorption chiller, or free cooling), these auxiliary components' consumption has been added to total electrical consumption. The effect of humidity is neglected due to simplicity of the model.

4.1.3 Data center heat pump modeling. An electric water-to-water heat pump is used to increase water temperature from low-degree to high-degree to be able to use low-degree waste heat for district heating. The heat pump consumes electricity for its operation and the efficiency of the heat pump varies based on the load with associated COP value.

Coefficient of performance value (COP_{hp}) is the ratio between heat pump heating output (H_{hp}) and heat pump's electricity consumption (E_{hp}). COP_{hp} value varies based on the actual load.

$$E_{hp} = H_{hp} \ / \ COP_{hp} \tag{14}$$

In our system, both the CCHP's low-degree water heat and the data center's excess heat were recovered and utilized. This low-degree water heat's temperature is increased to a higher degree by a heat pump to utilize this heat in the district heating network.

4.1.4 Photovoltaic (PV) system modeling. The PV system panels for the data center can be installed on the roof or at an adjacent plot. PV system's electricity generation (E_{pv}) model is calculated by using hourly solar radiation (G_{solar}), the PV panel's surface area (A_{pv}), the PV panel efficiency (η_{pv}), and other losses (η_{other}) (Kazem and Khatib, 2013). E_{pv} is found as follows:

$$E_{pv} = G_{solar} \ x \ A_{pv} \ x \ \ x \ \eta_{pv} \ x \ \eta_{other} \tag{15}$$

Other losses for inverter, connections, shading, wiring, degradation, etc. are accepted as a total of 14%, so η_{other} is equal to 0.86. The efficiency of the PV panels (η_{pv}) is influenced by ambient temperature and specific temperature coefficients of the PV panel, and η_{pv} is found as follows:

$$\eta_{pv} = \eta_{ref}\,[1 - \beta(T_{cell} - T_{cell\_ref})] \tag{16}$$

The temperature of the PV cell (T_{cell}) is determined by the ambient temperature ($T_{ambient}$), solar radiation (G_{solar}), and test temperature (T_{test}) of the cell at 800W/ m² irradiance. T_{cell} is calculated by the following formula:

$$T_{cell} = T_{ambient} + \left(G_{solar}\, x\, \frac{T_{test}}{800} \right) \tag{17}$$

4.1.5 Residential building modeling. For the residential building, a typical design for a multi-floor building with 5 floors and 10 dwellings (flats) has been chosen as the reference model as shown in Figure 17 and Figure 18. The structural details of this reference building are captured based on a report in Ref. (Schimsha et al., 2016) Schimsha et al. The total thermal transmittance of the building ($U_{building}$) is calculated as the sum of the heat transfer through the walls, floor, roof, and windows, according to the approach described in Ref. (Oktay and Dincer, 2009).

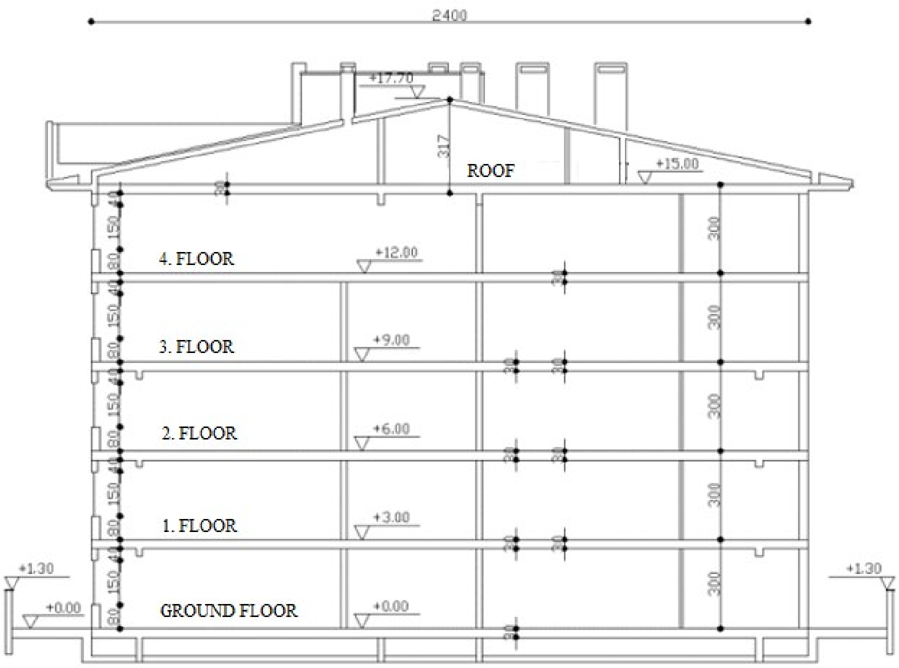


Figure 17. Reference Building Cross-sectional View-1 (Schimsha et al., 2016)

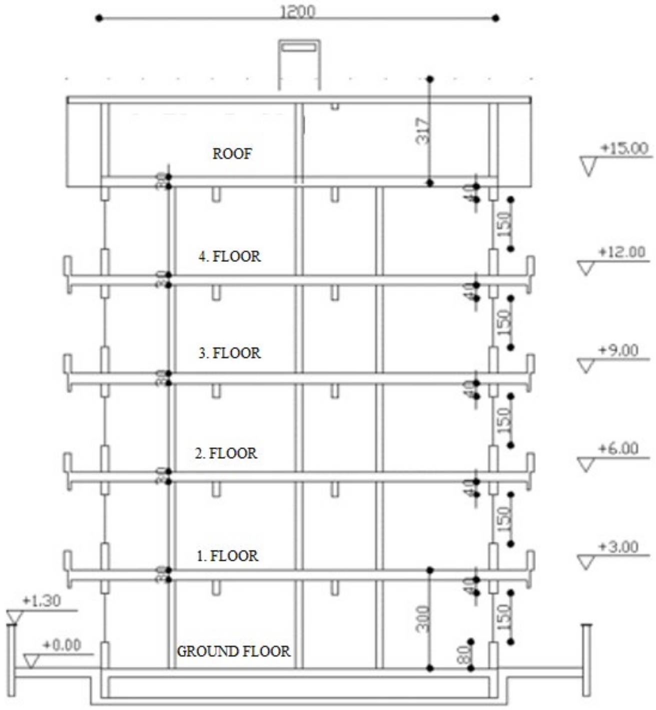


Figure 18. Reference Building Cross-sectional View-2 (Schimsha et al., 2016)

The structural specifications of the reference building are listed in Table 5.

Table 5

Reference Building's Specifications

Item	**Value**	**Unit**
Number of dwellings per floor	2	pcs.
Number of floors in the building	5	pcs.
The building's length	24	meters
The building's width	12	meters
the building's height	15	meters
The net floor height of the floors	3	meters
Ground floor areas of the building	288	m^2
Building roof area	288	m^2
Building total outside walls area	918	m^2
Building total windows area	162	m^2
Total shell area of the building (walls, windows, ground floor, and roof)	1656	m^2

The total thermal transmittance of the building ($U_{building}$) is calculated as the sum of the heat transfer through the walls, floor, roof, and windows, according to the approach described in Ref. (Oktay and Dincer, 2009):

$$U_{building} = U_{walls} + U_{floors} + U_{roofs} + U_{windows} \tag{18}$$

To estimate the heat transfers of the residential building, the specific thermal transmittance requirements (u-values) for the walls, floors, roofs, and windows are multiplied by their respective surface areas (in m^2). This yields simplified heat transfer values for each component, given by the following expressions in units of W/(m².K):

$$U_{walls} = A_{walls}\ x\ U_{walls\_req} \tag{19}$$

$$U_{floors} = A_{floors}\ x\ U_{floor\_req} \tag{20}$$

$$U_{roofs} = A_{roofs}\ x\ U_{roofs\_req} \tag{21}$$

$$U_{windows} = A_{windows}\ x\ U_{windows\_req} \tag{22}$$

4.1.6 Residential heat pump modeling. The air-to-water type central heat pump is selected to satisfy the space heating, domestic hot water, and cooling demand of all dwellings in the same building. The heat pump's electricity consumption in heating mode (E_{hp_heat}) is calculated by dividing the total heating demand (H_{b_total}) by the COP in heatingx mode (COP_{hp_heat}) (Nyers, 2017):

$$E_{hp\_heat} = H_{b\_total}\ /\ COP_{hp\_heat} \tag{23}$$

The heat pump's electricity consumption in cooling mode (E_{hp_cool}) is calculated by dividing the building cooling demand (Q_{b_cool}) by the COP in cooling mode (COP_{hp_cool}) (Nyers, 2017):

$$E_{hp\_cool} = Q_{b\_cool}\ /\ COP_{hp\_cool} \tag{24}$$

4.2 System Operational Modes

The possible modes of operations in the CCHP-PV-based data center are presented in Table 6. System results have been calculated for all operating conditions based on these operational modes.

Table 6

Mode Descriptions

Mode	CHP Operation	Cooling Supply System	District Heating Supply	District Cooling Supply
1	ON	Electric chiller	CHP exhaust, high-degree water, Low-degree water, data center's residual heat	Total absorption cooling
2	ON	Free cooling	CHP exhaust, high-degree water, Low-degree water, data center's residual heat	-
3	ON	Absorption chiller	CHP low-degree water, data center's residual heat	Surplus cooling
4	OFF	Electric chiller or free cooling	Data center's residual heat	-

4.3 Energy Demand and Supply Calculations

The overall system operation is the combination of multiple calculations related to one or multiple components in the previous chapter. In this chapter, firstly, energy demand calculations were presented. Secondly, energy supply calculations were presented.

4.3.1 Data center electrical energy demand. Data centers consume electricity mainly for IT racks' (E_{IT}), cooling generation ($E_{Cooling}$) and auxiliary equipment (E_{Aux}) such as lighting, small power and office use, etc. Total electricity consumption (E_{demand}) is the sum of these needs, heat pump's electricity consumption (E_{hp}) and electricity losses from power infrastructure (E_{Power_Losses}):

$$E_{demand} = E_{IT} + E_{Aux} + E_{Cooling} + E_{hp} + E_{Power\_Losses} \tag{25}$$

$E_{Cooling}$ represents the total electricity consumption of the cooling system under the different operational status. It varies hourly during the year, depending on the cooling demand of the data center and outdoor weather conditions:

$$E_{Cooling} = \begin{cases} E_{ech}, & \text{if electric} - \text{chiller is On} \\ E_{abs}, & \text{if absorption chiller is On} \\ E_{frc}, & \text{if free cooling is On} \end{cases} \tag{26}$$

4.3.2 Data center cooling energy demand. Data Center's total heat dissipation is calculated based on the IT devices' heat dissipation (H_{IT}) and other heat dissipations. Other heat dissipations are the sum of heat dissipations from CRAH fan coils (H_{CRAH_Fans}), lighting ($H_{Lighting}$), wiring (H_{Wiring}), and power infrastructure (H_{Power_Losses}) in whitespace [32]. Total dissipated heat (H_{dc}) is calculated as follows:

$$\mathrm{H_{dc}} = \mathrm{H_{IT}} + \mathrm{H_{CRAH\_Fans}} + \mathrm{H_{Lighting}} + \mathrm{H_{Wiring}} + \mathrm{H_{Power\_Losses}} \tag{27}$$

This total dissipated heat must be extracted from the data center whitespace by cooling supply with the different cooling systems by electric chiller, absorption chiller, or free cooling. Hence, the data center's cooling demand (Q_{demand}) is equal to the data center's dissipated heat to maintain the temperature of the room in the advised temperature range:

$$Q_{demand} = H_{dc} \tag{28}$$

4.3.3 Residential heating energy demand. Residential buildings' heating and cooling energy demand vary depending on the outside weather conditions, solar heat gain and building structural specifications. To calculate the thermal energy needs of a residential building over a period, degree–time method is one of the methods used in the literature.

In winter, thermal energy demand includes space heating and domestic hot water. The reference building's space heating demand is corresponding to the temperature gap between the dry-bulb outdoor temperature (T_{out}) and the system's heating set temperature (T_{set_h}) (Oktay and Dincer, 2009). The total residential space heating demand in the region is calculated by using the number of buildings (N_a), and total heat transmittance of the building ($U_{building}$) as follows:

$$H_{b_{heat}} = \sum_{t=1}^{8760} [(T_{set_h}(t) - T_{out}(t)) x\ N_a\ x\ U_{building}]$$
$$for\ T_{out} < T_{set\_h} \tag{29}$$

The hourly domestic hot water (DHW) load applies to all seasons. DHW load is calculated according to the number of dwellings (N_d), the average number of people in dwellings (N_p), the average hourly consumption of domestic hot water per dwelling (S_w), the temperature gap between the domestic hot water requirement (T_{hot}), and the water distribution network tap water (T_{tap}). Thus, domestic hot water (DHW) heating demand (H_{b_dhw}) can be calculated as follows (Oktay and Dincer, 2009):

$$H_{b\_dhw} = \sum_{t=1}^{8760} [\left(T_{hot}(t) - T_{tap}(t)\right) x\ N_d\ x\ S_w] \tag{30}$$

Daily domestic hot water demand is estimated with the average number of people in dwellings (N_p) according to the Building Research Establishment Domestic Energy Model (U.K. Department of Energy and Climate Change, 2008):

$$D_{demand\_dhw} = 38 + 25\ x\ N_p \tag{31}$$

The hourly fraction of the dwelling's domestic hot water consumption, f(h) is derived from the NREL's building protocol shown in Figure 19 (Wilson et al., 2014).

By considering the total daily consumption of a dwelling (D_{demand_dhw}), the average hourly consumption of domestic hot water per dwellings (S_w) as follows:

$$S_w = D_{demand\_dhw}\ x\ f(h) \tag{32}$$

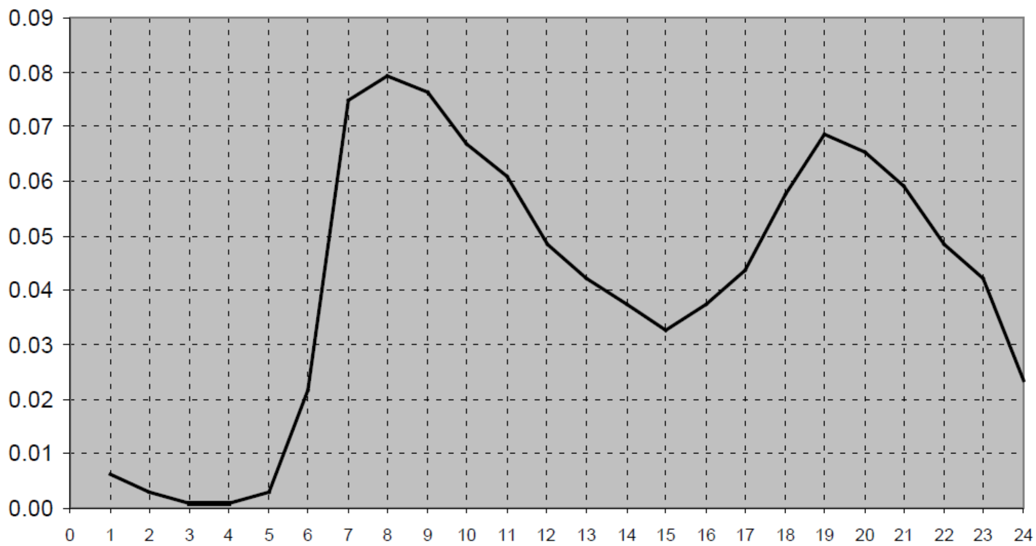


Figure 19. Fraction of total daily usage of domestic hot water (Wilson et al., 2014)

The solar heat gain of the building through its windows is the total amount of heat gained through all windows in all directions. This value is calculated using the Turkish Standard TS-825 (UCTEA Chamber of Mechanical Engineers) and requires hourly data on solar irradiation to windows in W/m² (I_i), window shading factor (r_i), glass total solar transmittance factor (g_i), and windows area ($A_{windows}$):

$$H_{shg} = I_i \; x \; r_i \; x \; g_i \; x \; A_{windows} \quad (33)$$

The total heating demand is calculated by subtracting the total solar heat gain (H_{shg}) from the sum of space heating demand (H_{b_heat}) and domestic hot water demand (H_{b_dhw}):

$$H_{b\_total} = H_{b\_heat} + H_{b\_dhw} - H_{shg} \quad (34)$$

4.3.4 Residential cooling energy demand. The building heat gain for cooling load of the reference building in summer is corresponding to the temperature gap between the dry bulb outdoor temperature (T_{out}) and the system's cooling set temperature (T_{set_c}).

$$H_{b\_cool} = \sum_{t=1}^{8760} [(T_{out}(t) - T_{set_c}(t))x\ N_a\ x\ U_{building}]$$

$$for\ T_{set\_c} < T_{out} \tag{35}$$

The total residential cooling energy demand is calculated as the sum of the building heat gain for cooling load (H_{b_cool}) and solar heat gain (H_{shg}) as follows:

$$Q_{b\_cool} = H_{b\_cool} + H_{shg} \tag{36}$$

Other heat gains and humidity are neglected for the simplicity of the model.

4.3.5 Residential total electricity demand. Residential power usage (E_{dwel_elc}) is derived from the IEEE European Low Voltage Test Feeder load profile and scaled (Schneider et al., 2017). This test feeder consists of 55 different load profiles for 24-hour data. However, the dwelling's electricity usage also changes during the week (weekday or weekend) or in different seasons. Thus, day and seasonal impact on the dwelling's electrical load profiles has been correlated based on electrical load profile factors for the daily and seasonal changes throughout the year shared by the Balancing Settlement Code (BSC) (Elexon). Finally, the residential power demand has been created for every hour during the year.

The total residential electricity demand, E_{res_elc}, is composed of the dwellings' hourly power demand, E_{dw_elc}, and the dwelling's heat pump electricity demand, either E_{hp_heat} in heating mode or E_{hp_cool} in cooling mode. The following equation represents E_{res_elc} :

$$E_{res\_elc} = E_{dw\_elc} + E_{hp\_heat} + E_{hp\_cool} \tag{37}$$

4.3.6 CHP electrical and heating energy supply. CHP provides electrical energy (E_{e_chp}) and thermal heat energy (H_{waste}) based on a partial load or full load. Electricity and heat energy outputs vary based on the actual load factor (LF) of the CHP:

$$E_{chp\_nominal}(t) \geq E_{e\_chp}(t) \geq E_{chp\_nominal} \ x \ LF(t) \tag{38}$$

$$E_{e\_chp}(t) = E_{chp\_nominal} \ x \ LF(t) \tag{39}$$

$$H_{waste}(t) = H_{waste\_nom} \ x \ LF(t) \tag{40}$$

4.3.7 Data center cooling energy supply. Data center's cooling demand (Q_{demand}) is supplied based on three different systems: electric chiller, absorption chiller or free cooling. Free cooling is possible when the outdoor temperature is relatively low and provides enough cooling without mechanical cooling. The free cooling operation has been determined by the outdoor wet-bulb temperature at a given data center's location.

If the electricity demand is fed from the power grid, the required cooling can be provided either from an electric chiller or free cooling. If the system operates with CHP, the absorption chiller can also provide cooling to the data center by converting CHP's heat output. In CHP operation, data center cooling demand (Q_{demand}) can be supplied from the electric chiller, absorption chiller, or free cooling.

$$Q_{demand} = \begin{cases} Q_{ech}, & \text{if electric} - \text{chiller is On} \\ Q_{abs}, & \text{if absorption chiller is On} \\ Q_{frc}, & \text{if free cooling is On} \end{cases} \tag{41}$$

4.3.8 Grid feed-in electrical energy supply. The data center's electrical energy demand depends on the electrical energy demand of IT racks and cooling systems. When CHP is turned-on, it can generate electrical energy as the maximum of its nominal electrical generation ($E_{chp\_nominal}$). If the data center's electrical demand is less than CHP's and PV's nominal electrical generation, the difference between actual generation and the data center's electrical demand could be sold back to the grid as a surplus electrical energy. Total possible electrical surplus (E_{feed}) is calculated by subtracting the electrical demand from the energy generations on-site:

$$E_{feed}(t) = E_{e\_cchp}(t) + E_{pv}(t) - E_{dc\_demand}(t) \tag{42}$$

4.3.9 Data center's residual heat energy supply. IT power consumption, lighting power, and CRAH's fan powers are almost converted to heat in a data center, and 100% of the heat could be recovered in theory. However, based on the studies and simulations in the literature, the results show that between 55% to 90% of the waste heat can be converted to useful heat (Taddeo, 2017; CE Delft and Buck Consultants International, 2020; Davies et al., 2016; Huang et al., 2020) created a simulation model in energy analysis software to determine the waste recovery potentials according to different heat recovery methods. Taddeo demonstrates that with the standard 18°C server air supply, the average 860kW heat of the 1200kW reference data center's electrical consumption can be recovered by the CRAH return-air waste heat recovery method. Hence, it is accepted as a mid-case scenario of the literature for a data center's residual heat recovery system calculation and 72% heat recovery ratio has been used in our model:

$$H_{rec} = 0.72 \; x \; H_{dc} \tag{43}$$

4.3.10 District heating energy supply. Heat cannot be transferred as efficiently as electricity over long distances. So, nearby heat demand is crucial for a data center heat recovery system. Although heat losses in modern networks usually range from 5% to 10% of the produced heat, average heat losses are accepted as 15% in the latest Europe district heating network report due to aging of the district heating systems and heat leakages during the pipe failures (Niessing and Rösler, 2015; Euroheat & Power Organization, 2012). Thus, in our calculations, the final consumer's useful heat recovery amount is decreased by 15% from the total district heating generation.

Surplus heating (H_{dist}) can be supplied to the district heating network. Mode-1 and Mode-2 are the same for the district heating calculation. The amount of district heating supply is calculated for all modes as follows:

Mode-1 / Mode-2 ($m1/m2$): When CHP is operating but the absorption chiller is not used, CHP's all waste heat can be supplied to district heating. This mode is usually used in winter when the outside temperature is low, and free cooling is possible. In this mode, the total district heat supply ($H_{dist\_m1/m2}$) is found by:

$$H_{dist\_m1/m2} = 0.85\ x\ \left(H_{exh} +\ H_{hw}\ +\ H_{lw} + H_{rec} + \frac{H_{hp}}{COP_{hp}}\right) \tag{44}$$

Mode-3 ($m3$): When CHP is operating and the absorption chiller is used, only CHP's low-degree water (H_{lw}) and the data center's residual heat (H_{dc}) can be supplied to district heating. This mode is usually used in summer when the outside temperature is high, free cooling is impossible, and mechanical cooling is needed. In this mode, the total district heat supply $\left(H_{dist\_m3}\right)$ is found by:

$$H_{dist\_m3} = 0.85\ x\ (H_{lw} + H_{rec} + \frac{H_{hp}}{COP_{hp}}) \tag{45}$$

Mode-4 ($m4$): When CHP is not operating, cooling generation can be supplied from an electric chiller or free cooling. In this mode, all IT and cooling systems are fed from grid power, so the district heating supply is only limited to the data center's residual heat recovery amount (H_{rec}). In this mode, the total district heat supply $\left(H_{dist\_m4}\right)$ is found by:

$$H_{dist\_m4} = 0.85\ x\ (H_{rec} + \frac{H_{hp}}{COP_{hp}}) \tag{46}$$

4.3.11 District cooling energy supply. The satisfaction of data center's cooling demand (Q_{demand}) is the first and unchangeable priority for cooling generation, so the only surplus cooling (Q_{dist}) can be supplied to the district cooling network according to in Mode-1 and Mode-3. Current district cooling networks are relatively newer than district heating networks in use. According to Ref. in (Calance, 2014), a maximum of 2% losses is observed in the district cooling network. According to Ref. (International Energy Agency, 2019), system losses shall not exceed 5% of the total distributed cooling energy in sustainable district cooling systems. Thus, the final consumer's useful cooling utilization is calculated by a 5% reduction from the CCHP's surplus cooling supply. The amount of district cooling supply is calculated as:

Mode-1 ($m1$): CHP is in operation and an electric chiller is used, the data center's cooling demand is supplied by the electric chiller. Thus, the absorption chiller's total cooling generation can be supplied to the district cooling network. In this mode, the entire district's cooling supply $\left(Q_{dist\_m1}\right)$ is found by:

$$Q_{dist\_m1} = 0.95 \; x \; Q_{abs} \tag{47}$$

Mode-3 ($m3$): When CHP is in operation and an absorption chiller is used, only the surplus cooling generation from the absorption chiller can be supplied to the district cooling network. In this mode, the surplus district cooling supply $\left(Q_{dist\_m3}\right)$ is found by:

$$Q_{dist\_m3} = 0.95 \; x \; (Q_{abs} - \; Q_{demand}) \tag{48}$$

4.4 Optimization Model for Data Center Energy Scheduling

The optimization model finds optimal operational modes of the power and cooling systems for yearly energy cost minimization of the data center. In the literature, Mixed Integer Linear Programming (MILP) is the preferred model to find the optimal scheduling for energy plant operations (Lahdelma, 2017).

4.4.1 Objective function. The objective of the model is to minimize the overall hourly energy costs of the operation.

$$\min \sum_{t=1}^{8760} \left(C_{ops}\,(t)\right) \tag{49}$$

If the system such as grid or CCHP is on, the decision variables become a=1, or b=1, respectively. Otherwise, they become a=0, or b=0 (Lahdelma, 2017). Therefore, the objective function, $C_{ops}\,(t)$, can be extended by incorporating the decision variables of a and b, the operational modes of the cooling system m, n, and p, and the grid electricity purchasing price (C_{grid}), natural gas purchasing price (C_{ng}), district heating energy selling price (C_{dist_h}), district cooling energy selling price (C_{dist_q}), the electricity consumption from the grid (E_{grid}), the natural gas consumption for CCHP (V_{ng}), feed-in surplus electricity to the power grid at different cooling modes (E_{feed}), surplus heating energy for district heating (H_{dist}), surplus cooling energy for district cooling (Q_{dist}) :

$$\min \sum_{t=1}^{8760} \left(a\ x\ C_{ops\_grid}\,(t)\ + b\ x\ C_{ops\_cchp}\,(t)\,\right) \tag{50}$$

where,

$$C_{ops\_grid}(t) = C_{grid}(t)x\ E_{grid}(t) \tag{51}$$

$$\begin{aligned} C_{ops\_cchp}(t) = \ & C_{ng}(t)\ x\ V_{ng}(t) - C_{dist\_h}(t)x\ H_{dist}(t) - \\ & C_{dist\_q}(t)x\ Q_{dist}(t) - \\ & C_{feed}(t)x\ E_{feed\_ech}\,(t)x\ m - \\ & C_{feed}(t)x\ E_{feed\_abs}(t)x\ n\ - \\ & C_{feed}(t)x\ E_{feed\_frc}(t)\ x\ p \end{aligned} \tag{52}$$

4.4.2 Problem constraints. The overall power operation has mainly two-power modes: a = grid-fed, and b = CHP-fed. The following equation constraints the data center to select one of the power modes:

$$a + b = 1 \tag{53}$$

The cooling operation of the data center comprises three cooling systems: m = absorption chiller (Q_{abs}), n = electric chiller (Q_{elc}), and p = free cooling (Q_{frc}). To meet the cooling demand, one of these cooling systems must be selected, and the free cooling mode can only be used if the outdoor temperature is appropriate. The following equation represents the constraint on the data center to choose one of the cooling modes:

$$m = n = 0 \quad if\ free\ cooling\ is\ suitable \tag{54}$$

$$m + n = 1 \quad if\ free\ cooling\ is\ not\ suitable \tag{55}$$

The electricity demand of the data center is supplied by the power grid or CCHP generation. The maximum electricity generation output ($E_{e\_cchp\_max}$) of CCHP is limited by its nominal output.

$$E_{e\_cchp\,max}\,(t) = \; E_{e\_cchp\_nominal} \tag{56}$$

The electricity demand of the overall systems in the data center (E_{dc_demand}) needs to be satisfied by the combined electricity generation of CCHP (E_{e_cchp}) and PV (E_{pv}). Any surplus electricity (E_{feed}) could be supplied to the power grid:

$$E_{e\_cchp}\,(t) \; \geq E_{dc\_demand}\,(t) - \; E_{pv}\;\;(t) \tag{57}$$

$$E_{feed}(t) = E_{e\_cchp}\;\;(t\,) + \; E_{pv}\,(t)\;\; - E_{dc\_demand}\;\;(t) \tag{58}$$

The total electricity demand of the data center in grid-fed operation is satisfied by the electricity supply from the grid. The PV electricity generation is deducted from the total electricity demand to obtain the net grid electricity consumption:

$$E_{grid}\,(t) = \; E_{dc\_demand}\,(t) \; - \; E_{pv}\,(t) \tag{59}$$

The cooling energy demand of a data center (Q_{dc_demand}) must be satisfied by cooling energy generation (Q_{gen}). Q_{gen} can be greater than the data center's demand in absorption chiller mode. In this case, only the surplus cooling energy is provided to the district cooling network:

$$Q_{gen}\,(t) \; \geq Q_{dc\_demand}\,(t) \;\; \geq 0 \tag{60}$$

The following equation constraints the data center to select one of the cooling modes:

$$Q_{gen}(t) \;\; = \;\; Q_{elc}\,(t)\,x\,m + Q_{abs}\,(t)\,x\;\;n + Q_{frc}\,(t)\,x\;\;p \tag{61}$$

The maximum cooling generation output of cooling systems is limited by the manufacturer's nominal output values in the datasheets:

$$Q_{elc\_nominal}\,(t)\;\geq\;Q_{elc}\,(t)\;\;\geq 0 \tag{62}$$

$$Q_{abs\_nominal}\,(t)\;\geq\;Q_{abs}\,(t)\;\;\geq 0 \tag{63}$$

$$Q_{CT\_nominal}\,(t)\;\geq\;Q_{frc}\,(t)\;\;\geq 0 \tag{64}$$

4.5 Power Grid Electricity Demand Reductions

Main contributions to the power grid by the CCHP-PV-based data center occur in three ways: (a) operating the data center off-grid thanks to on-site electricity generation and eliminating the data center's electricity demand on the power grid, (b) supplying surplus electricity to meet a portion of electricity demand required in the MV power grid, (c) supplying surplus heating and cooling to the district energy networks, meeting the thermal energy demand of the dwellings and indirectly decreasing the electricity demand on the power grid. As a result, power grid electricity demand can be reduced considerably during the year thanks to these surplus energies.

In the grid-fed data center, the electricity demand on the MV distribution ring, ($E_{mv\_ring\_wo\_cchp}$), is the electricity demand of the data center (E_{dc_demand}) and the electricity demand of the residential buildings without district energy network connection ($E_{res\_elc\_wo\_dhc}$) :

$$E_{mv\_ring\_wo\_cchp}(t) = E_{dc\_demand}(t) + E_{res\_elc\_wo\_dhc}(t) \tag{65}$$

In the CCHP-PV-operated data center, the electricity surplus to the power grid (E_{feed}) is found by subtracting the total electricity demand of the data center (E_{dc_demand}) from on-site electricity generation by CCHP and PV panels, which is given with Eqn. 66. In this operation, the data center's electricity demand is eliminated. Moreover, residential electricity demand is decreased with the district energy network ($E_{res\_elc\_w\_dhc}$). Hence, the electricity demand of the MV distribution ring with CCHP

($E_{mv\_ring\_w\_cchp}$) can be calculated by subtracting E_{feed} from the residential electricity demand with district energy connection:

$$E_{mv\_ring\_w\_cchp}(t) = E_{res\_elc\_w\_dhc}\,(t) - E_{feed}(t) \tag{66}$$

4.6 Carbon Emission Reductions

A grid-fed data center's carbon dioxide (CO_2) equivalent emission is proportional to its electricity consumption from the power grid. These indirect emissions are defined as Scope 2 emissions in GHG Protocol. Carbon dioxide equivalent emissions associated with energy consumption are calculated using the emission factors in Table 7 (Dino and Akgul, 2019; Republic of Türkiye Ministry of Energy and Natural Resources, 2021).

Table 7

Carbon Dioxide Equivalent Emission Factors for Energy Sources in Turkiye (Dino and Akgul, 2019; Republic of Türkiye Ministry of Energy and Natural Resources, 2021).

Power Grid Cf_{grid}	**Natural Gas** Cf_{ng}	**District heating** Cf_{dist_h}	**District cooling** Cf_{dist_q}	**Grid feed-in** Cf_{feed}
0.570 kg CO2-eq /kWh	1.920 kg CO2-eq /Sm^3	0.226 kg CO2-eq /kWh	0.114 kg CO2-eq /kWh	0.570 kg CO2-eq /kWh

The emission of a grid-fed data center can be calculated by multiplying the electricity carbon emission factor of the power grid (Cf_{grid}) by the total electricity consumption of the data center (E_{grid}) measured in kWh:

$$CE_{ops\_grid}(t) = \sum_{t=1}^{8760} Cf_{grid}(t) x\, E_{grid}(t) \tag{67}$$

In the CCHP-PV-operated data center, the final carbon emission is calculated by subtracting the carbon emissions contributions of all types of surplus energy from the carbon emissions by the consumed natural gas:

$$CE_{ops\_chp}(t) = \sum_{t=1}^{8760} Cf_{ng}(t)\ x\ V_{ng}(t) - Cf_{dist\_h}(t) x\ H_{dist}(t) - Cf_{dist\_q}(t) x\ Q_{dist}(t) - Cf_{feed}(t) x\ E_{feed} \quad (68)$$

To calculate the carbon emission factor of district heating, it is assumed that the natural gas boiler has an efficiency of 80% (Dino and Akgul, 2019). The carbon emission factor of district heating is found as follows:

$$Cf_{dist\_h} = \frac{Cf_{ng}(\mathrm{kWh})}{0.80} \mathrm{kg\ CO2-eq/kWh} \quad (69)$$

For district cooling, it is assumed that the residential air-conditioners are used and the grid electricity is consumed with an average cooling COP of 5. The carbon emission factor of district cooling is calculated by dividing the power grid's electricity carbon emission factor by a COP of 5:

$$Cf_{dist\_q} = \frac{Cf_{grid}(\mathrm{kWh})}{5} \mathrm{kg\ CO2-eq/kWh} \quad (70)$$

The carbon emission factor of surplus electricity feed-in is assumed to be equal to the carbon emission factor of the power grid. Any emission savings that result from the elimination of electricity transmission and distribution losses due to on-site generation are neglected.

$$Cf_{feed} = Cf_{grid} \quad (71)$$

Residential customers' carbon dioxide (CO_2) equivalent emission without a multi-energy hub connection is proportional to their total electricity consumption from the power grid.

$$CE_{residential}(t) = \sum_{t=1}^{8760} Cf_{grid}(t)xE_{res\_elc\_wo\_dhc}\,(t) \tag{72}$$

Residential customers' carbon dioxide (CO_2) equivalent emission with a multi-energy hub connection is decreased due to energy contributions from the CCHP-PV-based data center. Final emissions of the residential customers as follows:

$$CE_{residential}(t) = \sum_{t=1}^{8760} Cf_{grid}(t)x\,E_{res\_elc\_w\_dhc}\,(t) \tag{73}$$

Chapter 5

Simulation And Results

The proposed system was examined in the sample data center with a 1 MW IT power demand. The main components and their nominal values were given for CCHP-PV-based data center and residential customers in Table 8.

Table 8

Main Components and Characteristics of CCHP-PV-based 1MW IT Data Center and Residential Buildings

Main Components	**Nominal Values**
CHP (natural gas engine)	Electrical output: 1487kWe, Input energy: 3569kWt, Total CHP efficiency: 92% Electricity efficiency: 41.7%, Thermal efficiency (incl. intercooler): 50.3%,
Absorption chiller (multi-source, double effect)	Cooling output: 1758kW, Input energy-1: 940kWt, Input energy-2: 590kWt, COP (thermal): 1.15 (full load)
Electric chiller (screw chiller)	Cooling capacity: 1200kW, COP (electrical): 5.36 (full load)
Data center heat pump (water to water)	Heating capacity: 1355kW, COP (electrical): 4.2 (full load)
Cooling tower	Cooling capacity: 1914kW, Fan power: 11kW
CRAH	Cooling capacity: 145.7kW cooling per unit, Total: 8 units, Fan power: 4.05kW per unit
PV Panels	PV panel power output (Pmax): 450W per panel, PV panel efficiency: 20.4%, Temperature coefficient of Pmax: -0.36%, Number of panels: 656 pcs (W+E), T_{test}: 20°C T_{cell_ref}: 25°C, PV panel surface area: 978mm x 2100mm, Cell Type: Monocrystalline Roof:560 pcs, Total Installed Capacity: 250kWp, Roof and Plot:2240 pcs, Total Installed Capacity: 1000kWp,
Residential heat pump (air to water)	Max. heating capacity:2x12.3kW, COP (heating): 4.0 @45°C supply, COP (cooling): 3.15 @18°C supply
Reference building specifications	Areas for Floor: 288 m^2 ; Roof: 288 m^2 ; Walls: 918 m^2 ; Windows: 162 m^2 ; r_i: 0.4 ; g_i : 0.6
Residential room set temperatures	T_{set_h}= 21°C ; T_{set_c}= 23.5°

The numerical study was simulated for 8760 hours. It is important to mention that there is no study with comparable topology in the literature, and some studies do not take seasonal changes into account.

We assumed that the sample data center is situated in Izmir, a city located on the Mediterranean Sea coast in western Turkiye. The monthly changes in dry-bulb and wet-bulb temperature were illustrated in Figure 20.

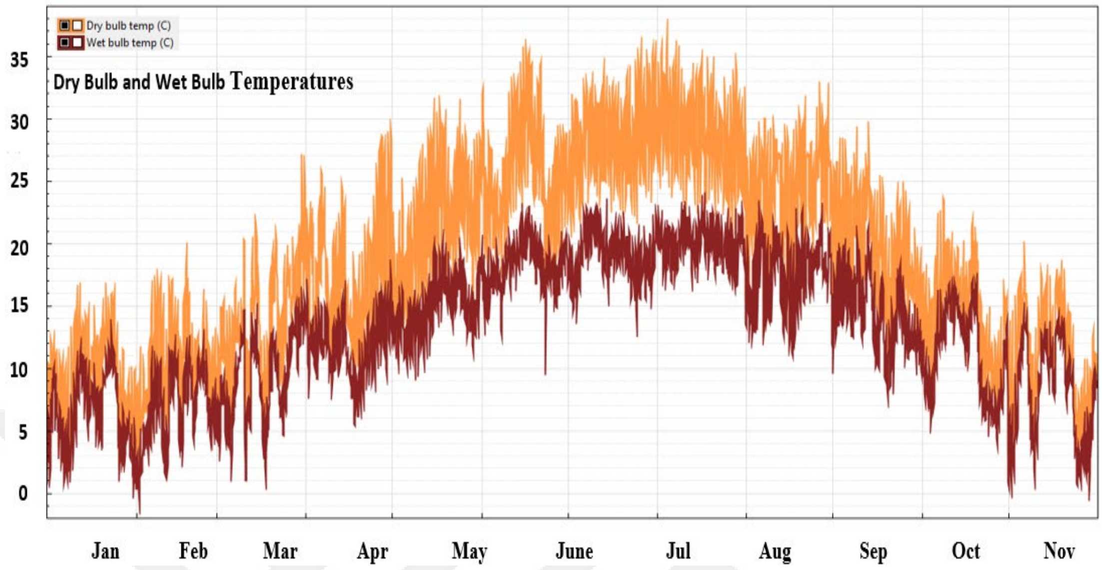


Figure 20. Monthly Dry-bulb and Wet-bulb Temperature Changes in Izmir, Turkiye (National Renewable Energy Laboratory)

The data center and residential customers are connected to the power grid in a shared MV distribution ring as shown in Figure 17. To achieve the peak demand of 5MW in the ring for the data center and residential customers, a total of 220 buildings are required. Assuming each building contains 10 dwellings, the total number of dwellings becomes 2,220. These buildings are evenly distributed across four transformers in the MV ring, with 55 buildings assigned to each transformer.

For PV installations, if only the data center's 1290 m^2 available roof area is used, then a total of 250kWp can be installed. If an additional plot of 3670 m^2 area adjacent to the data center is allocated for PV installations, then a total power of 1MWp can be installed according to the PV panel surface calculator tool (IBC Solar).

Tap water temperature varies during the year and is captured from the literature of the case study location. Figure 21 shows the monthly tap water temperature changes for the case study location. Besides, the average number of people in dwellings (N_p) is taken as 3.3 for a case study derived from the Ref (Turkish Statistical Institute, 2020).

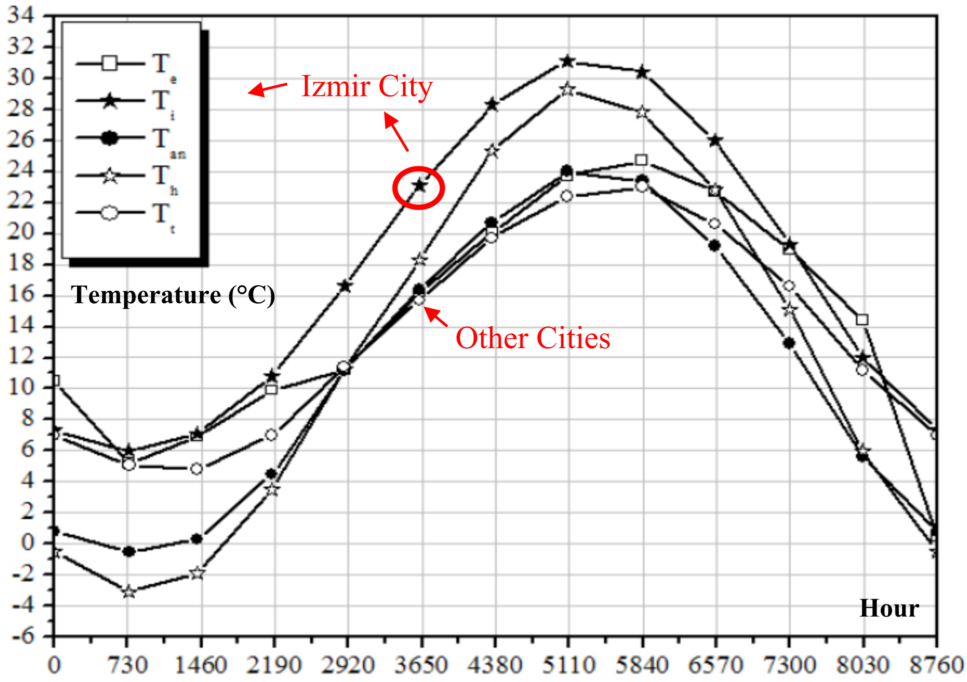


Figure 21. Monthly Tap Water Temperature Changes for the Case Study Location (Karacavus, 2017)

According to Turkish Standard TS – 825, different zones were created for the building thermal insulation requirements as in Figure 22.

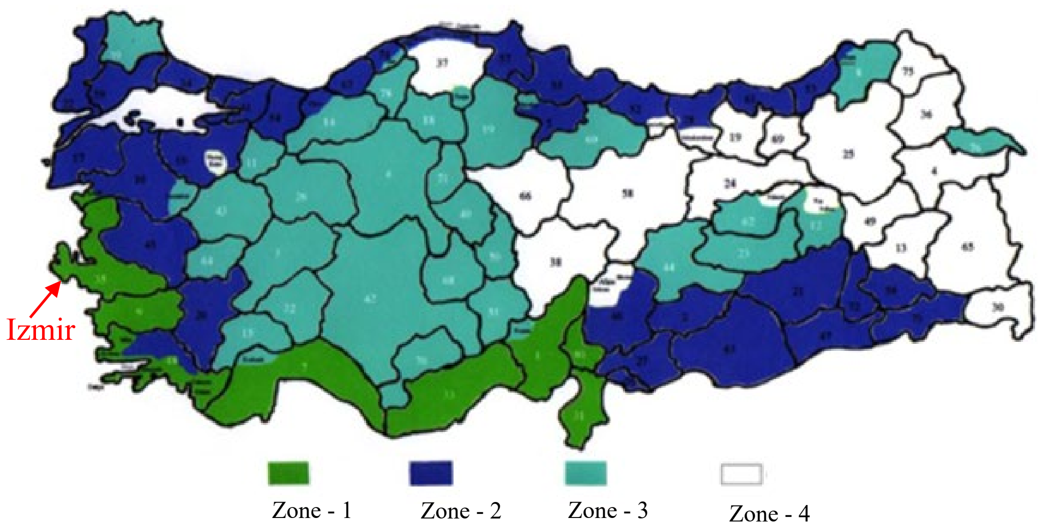


Figure 22. Climate zones according to Turkish Standard TS825 (UCTEA Chamber of Mechanical Engineers)

The u-value requirements for the case study location in Zone-1 were determined based on Table 9.

Table 9

U-value Requirements for Buildings according to Turkish Standard TS825

Climate Zones	**Wall [W/ m^2.K]**	**Floor [W/ m^2.K]**	**Roof [W/ m^2.K]**	**Window [W/ m^2.K]**
Zone -1	0.7	0.7	0.45	2.4
Zone -2	0.6	0.6	0.4	2.4
Zone -3	0.5	0.45	0.3	2.4
Zone -4	0.4	0.4	0.25	2.4

Residential energy demand varies depending on the day and season. Figure 23 and Figure 24 shows the residential heating, cooling, and electrical power demand for a sample day from each season.

The sum of the electricity demand of the heat pump (heating or cooling mode) and residential electrical power determines the total residential electricity demand. Figure 25 shows the aggregated residential electricity demand for a sample day from each season.

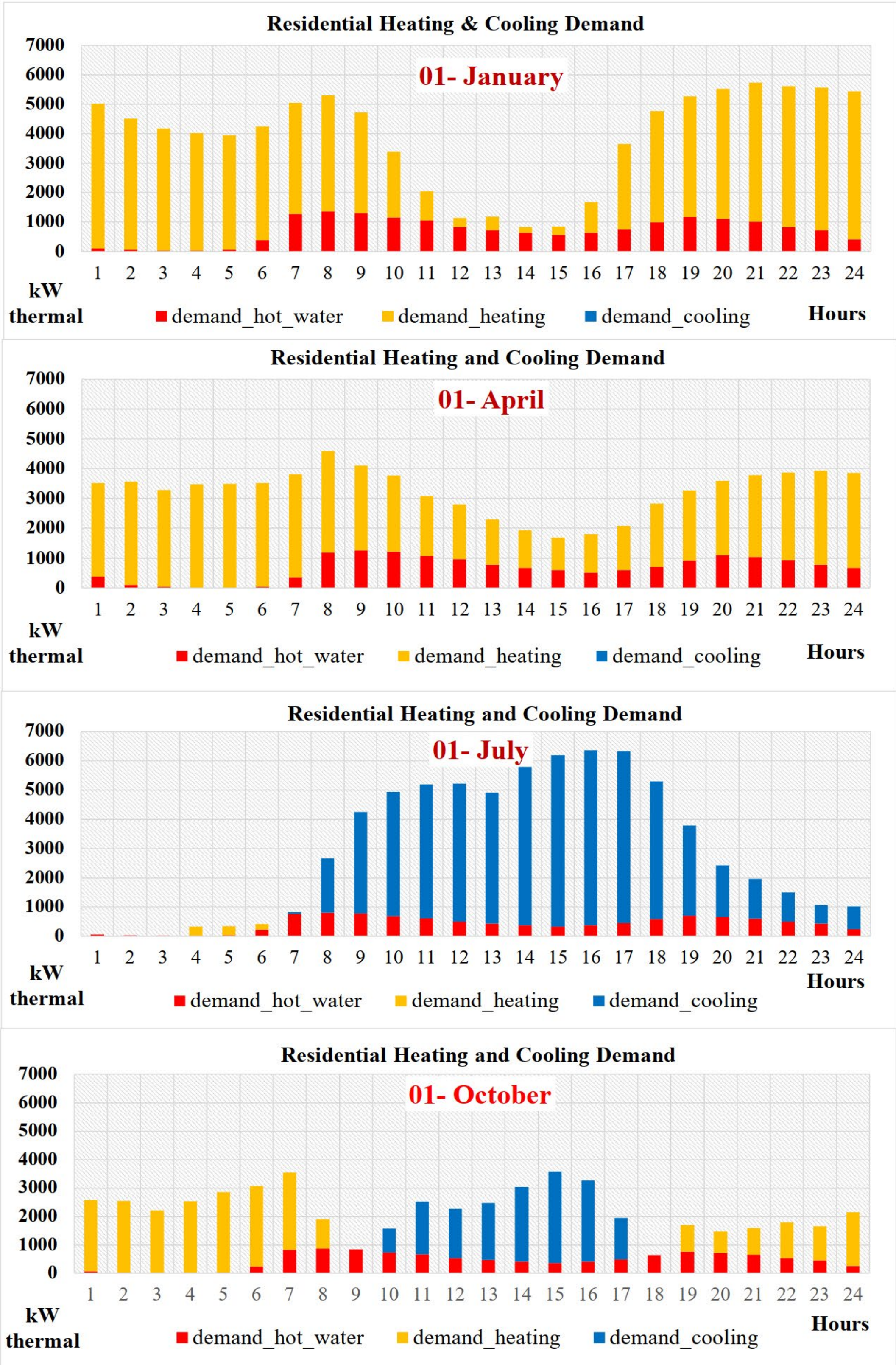


Figure 23. Seasonal Change in Hourly Residential Heating and Cooling Thermal Demand

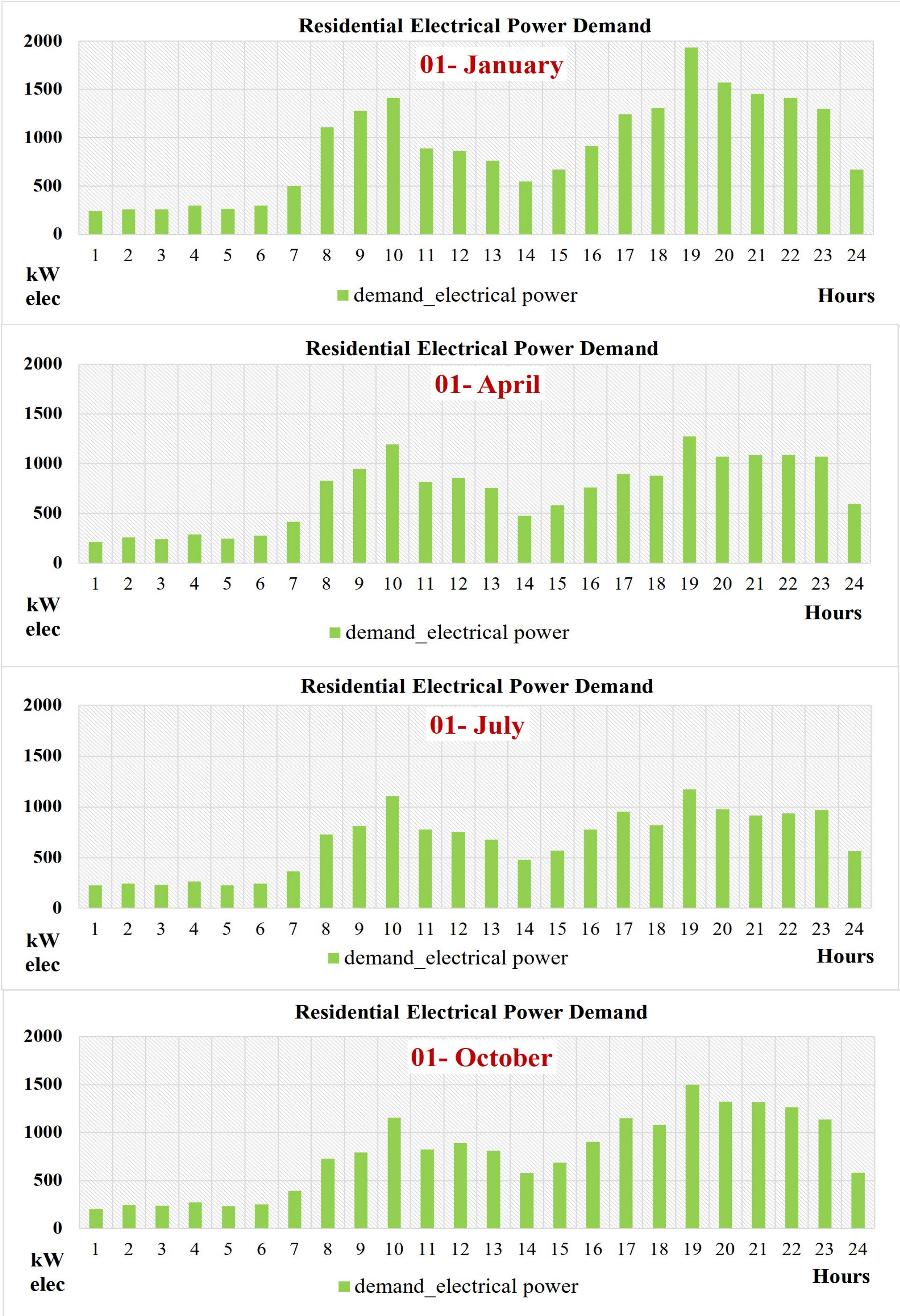


Figure 24. Seasonal Change in Hourly Residential Electrical Power Demand

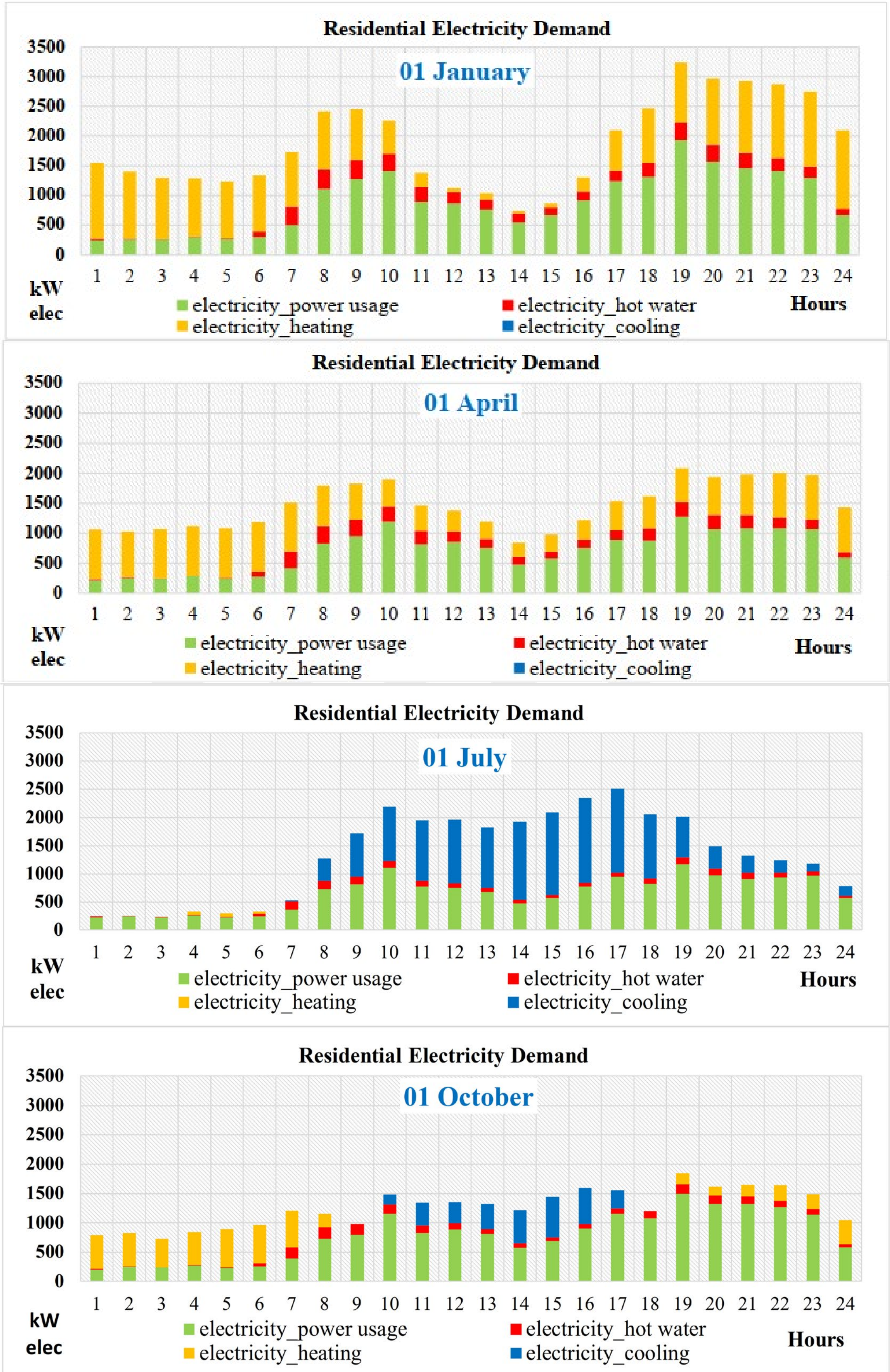


Figure 25. Seasonal Changes in Hourly Aggregated Residential Electricity Demand for Heating, Cooling, Hot Water, and Power Usage

5.1 Description of Simulation Cases

Six cases are defined in Table 10 for the simulations. Case-1 represents the reference case for the grid-based data center. The other five cases utilize a cost-optimized operation for the data center. All cases are simulated for 8760 hours. The case study location's hourly weather data and energy prices are used as input.

Table 10

Case Descriptions

Cases	Data Center Configuration	District Energy Connection
Case 1	Grid-fed (No-PV)	No
Case 2	CCHP (No-PV)	No
Case 3	CCHP-PV (Roof PV)	No
Case 4	CCHP (No-PV)	Yes
Case 5	CCHP-PV (Roof PV)	Yes
Case 6	CCHP-PV (Roof+Plot PV)	Yes

5.2 Electricity Demand and Energy Consumption Reductions

At first, the total electricity demand from the MV ring is found for the grid-fed data center and residential customers. Figure 26 shows the total electricity demand reduction on the grid by utilizing CCHP, PV, and district energy connections. As shown, CCHP-PV systems and district energy connections in multi-energy-hub reduced the total electricity demand from the grid. The figure is drawn for the peak demand day throughout the year in Case-5 to present the significance of the contribution of the proposed systems.

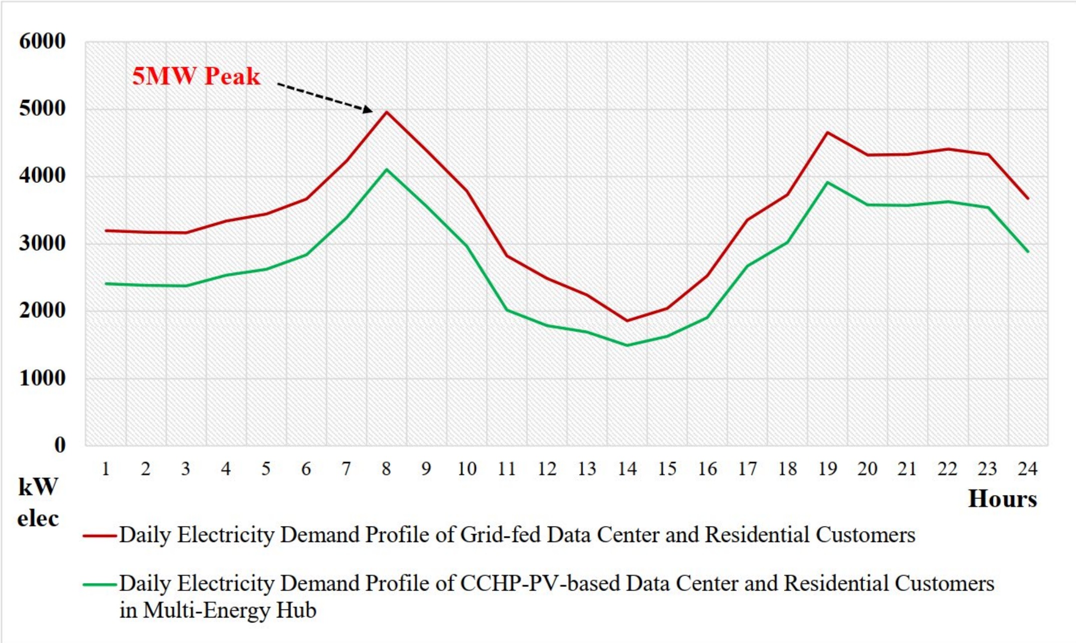


Figure 26. Electricity Demand Profiles on MV Ring at 5MW Peak Demand Day

The elimination of the data center's grid electricity consumption, provision of surplus heating and cooling to residential customers, and supply of excess electricity to the electricity grid from the CCHP-PV-based data center have resulted in a reduction in annual electricity consumption. Annual electricity consumption reduction on the MV grid and thermal energy demand reductions on residential customers are presented in Table 11.

5.3 Grid Electrical Performances

To evaluate the changes in grid electrical performances, the electrical topology, Figure 27 was created on one of the power system simulation software.

The load flow and short-circuit analysis were run on the software to investigate the MV distribution power losses, voltage, and short circuit levels of the specific connection points at the MV grid. Analysis was done for the 5MW peak hour as it is the most severe condition for the overall MV ring. Data center and residential electricity demand, CCHP and PV electricity generation, electricity demand reduction, and MV distribution power losses for each case have been summarized in Table 12.

Table 11

Annual Electricity Consumption Reduction on the MV Grid and Annual Thermal Reduction on the Residential Customers

Cases	Electricity reduction on the MV grid (%) Including: • Feed-in (Surplus electricity) • Surplus Heating&Cooling • Data Center's self elec. consumption	Electricity reduction on the residential customers (%) Including: • Feed-in (Surplus electricity) • Surplus Heating&Cooling • -	Thermal reduction on the residential customers (%) Reduction on: Residential Heating	 Reduction on: Residential Cooling
Case 1	Reference	Reference	Reference	Reference
Case 2	48%	5%	-	-
Case 3	51%	10%	-	-
Case 4	64%	34%	68%	39%
Case 5	66%	37%	68%	39%
Case 6	70%	45%	68%	39%

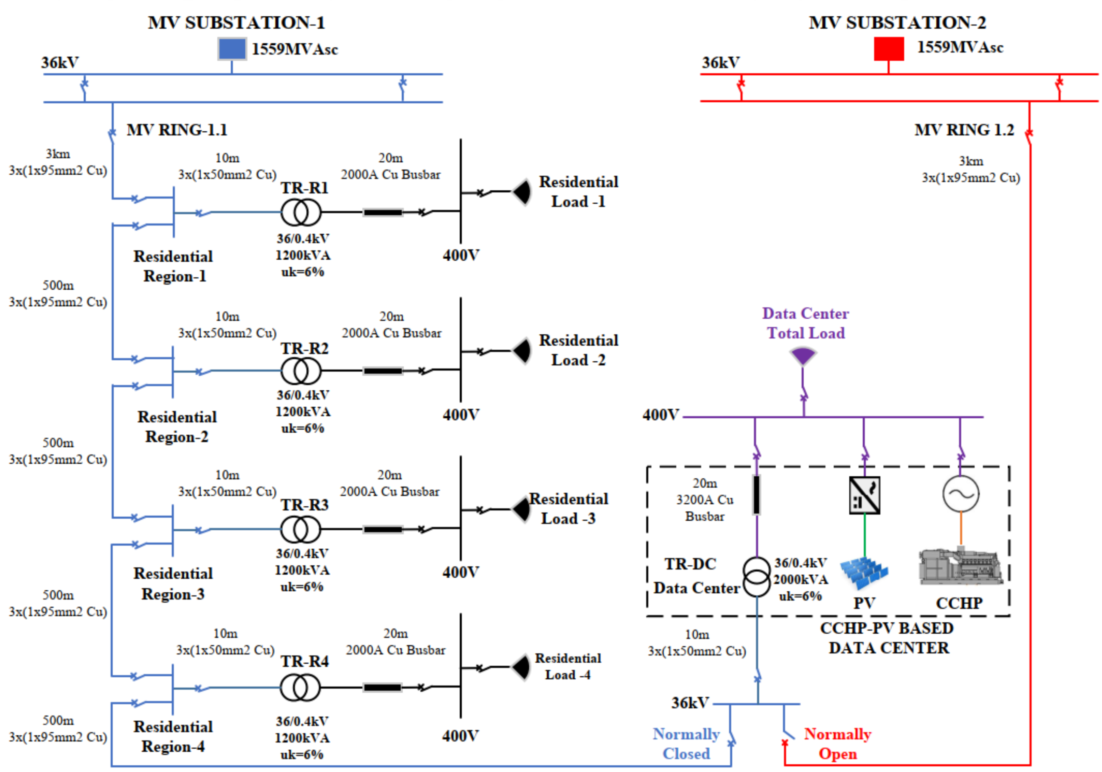


Figure 27. The Simulated Topology with Electrical Parameters

Table 12

Electricity Demand Reduction and Power Losses on the MV Distribution Grid (at 5MW peak demand hour throughout the year)

Cases	Residential electricity demand (TR - R1/R2/R3/R4)	Data center electricity demand (TR-DC)	CCHP electricity generation (100%)	PV electricity generation (Max. Actual)	Electricity demand on the grid (inc. losses)	Electricity demand reduction on the grid	Power losses on the grid (%)
Case 1	3942kWe (no-thermal reduction)	1112kWe (no-heat pump)	-	-	5150kWe	Reference	1.890 %
Case 2	3942kWe (no-thermal reduction)	1112kWe (no-heat pump)	1487kWe	-	3640kWe	29 %	1.458 %
Case 3	3942kWe (no-thermal reduction)	1112kWe (no-heat pump)	1487kWe	86kWe	3554kWe	31 %	1.462 %
Case 4	3257kWe (with thermal reduction)	1390kWe (with heat pump)	1487kWe	-	3210kWe	38 %	1.069 %
Case 5	3257kWe (with thermal reduction)	1390kWe (with heat pump)	1487kWe	86kWe	3124kWe	39 %	1.078 %
Case 6	3257kWe (with thermal reduction)	1390kWe (with heat pump)	1487kWe	454kWe	2757kWe	46 %	1.089 %

CCHP-PV electricity generation is directly connected to the data center's LV bus. LV bus voltage levels and short-circuit levels for both data center and residential buses are presented in Table 13.

5.4 Energy Cost Reductions

Cost optimization is utilized in the model for the data center's energy resource scheduling. The yearly energy cost saving of data center operation is presented for six cases in Figure 28. According to the findings, a CCHP-PV-based data center with a district energy connection can reduce the data center's operation energy cost.

Table 13

Voltage Deviation and Short-circuit Level Impacts at the Residential and CCHP-PV-based Data Center (at 5MW peak demand hour throughout the year)

Cases	**LV bus voltage at TR-R1 (p.u)**	**LV bus voltage drop at TR-R1 (%)**	**LV bus voltage at TR-DC (p.u)**	**LV bus voltage drop at TR-DC (%)**	**LV bus short-circuit level at TR-R1**	**LV bus short-circuit level at TR-DC**
Case 1	0.9655	3.45 %	0.9725	2.75 %	30.919kA	50.417kA
Case 2	0.9665	3.35 %	1.0	0 %	30.919kA	63.016kA
Case 3	0.9665	3.35 %	1.0	0 %	30.921kA	63.204kA
Case 4	0.9726	2.74 %	1.0	0 %	30.919kA	63.016kA
Case 5	0.9726	2.74 %	1.0	0 %	30.921kA	63.204kA
Case 6	0.9728	2.72 %	1.0	0 %	30.925kA	63.416kA

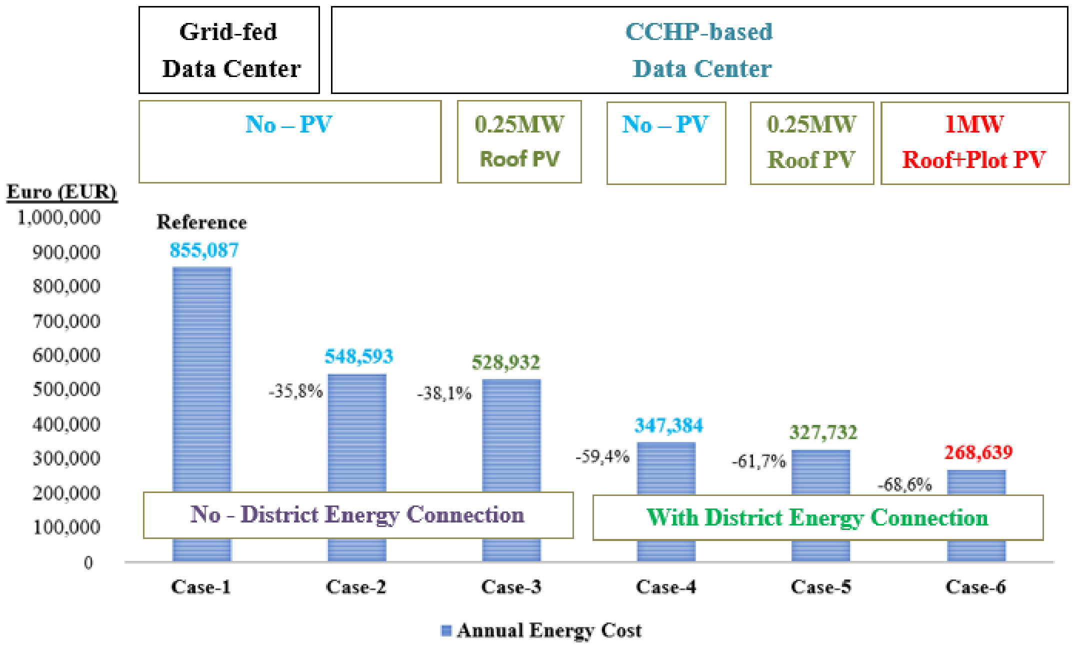


Figure 28. Annual Energy Cost for Six Cases

5.5 Emission Reductions

Carbon dioxide equivalent emission reduction is another benefit of the proposed systems. Results show that emissions could be decreased significantly. Emission reductions on the power grid and residential customers are demonstrated in Table 14 for Case-5. Thanks to cleaner production, waste heat utilization, and energy exchanges, emissions associated with energy consumption for the data center and residential customers are reduced.

Table 14

Comparison of Carbon Dioxide Equivalent Emissions associated with Data center and Residential Customers

Compared systems	**Emission Amount**
Emissions associated with the data center's energy consumption for Case-1	5,900,000 kg $CO_2 - \mathrm{eq}$
Emissions associated with the data center's energy consumption for Case-5	1,314,000 kg $CO_2 - \mathrm{eq}$
Emissions associated with the residential customers' energy consumption for Case-1	7, 256,000 kg $CO_2 - \mathrm{eq}$
Emissions associated with the residential customers' energy consumption for Case-5	4,646,000 kg $CO_2 - \mathrm{eq}$

5.6 Investment Analysis

CCHP and PV systems are major investments with a typical 20 years of operation. Hence, the investment analysis for the given systems must be studied for a longer period. The investment analysis can be evaluated with return on investment (ROI) and net present value (NPV) indicators. Table 15 lists the total system costs for the conventional data center in terms of equipment and installation expenditures for proposed systems (U.K. Department for Business, Energy and Industrial Strategy, 2021; U.S. Department of Energy, 2017; U.S. Environmental Protection Agency, 2007). Installation cost is estimated at 15% of the equipment cost. Additionally, yearly operation and maintenance cost (O&M) is assumed at 4% of the total system costs.

Table 15

Total System Cost for the Proposed Systems for Conventional Data Center

Equipment	**Equipment Cost**	**Installation Cost**	**Total System Cost**
CHP	1,350,000	202,500	1,552,500
PV Panels – 0.25MW Installed (roof only)	155,000	23,250	178,250
PV Panels – 1MW Installed (roof and land plot)	590,000	88,500	678,500
Absorption chiller – for data center only	305,000	45,750	350,750
Absorption chiller – for data center and surplus	385,000	57,750	442,750
Heat pump – for data center residual heat	210,000	31,500	241,500
Heat pump – for data center residual heat and CCHP's low-temp. heat	260,000	39,000	299,000
Heat exchangers – for CCHP only	30,000	4,500	34,500
Heat exchangers – for CCHP and data center residual h	45,000	6,750	51,750

Prices are in Euro (EUR).

ROI is known as simple payback analysis and is calculated as follows (Świerzewski et al., 2021).

$$\text{ROI (years)} = \frac{\text{Total Investment Cost}}{\text{Energy Saving (annual)} - \text{O\&M Costs (annual)}} \tag{74}$$

The costs, energy saving, and ROI values are shown in Table 16. A CCHP system (No-PV) with a district energy network connection (Case-4) is found to have the lowest ROI since the PV installations increase the total investment costs. However, CCHP-PV (roof), Case-5, is also found promising, where the return on investment is in 5.9 years. This result supports CCHP-PV use and district energy network integration for data centers.

Table 16

Return on Investment (ROI) for Different Cases based on Conventional Data Center

Cases	Total Investment	Annual O&M Cost	Annual Energy Cost Saving	ROI (Years)
Case 1	Reference	Reference	Reference	Reference
Case 2	1,937,750	77,510	306,493	8.5
Case 3	2,116,000	84,640	326,155	8.8
Case 4	2,346,000	93,840	507,703	5.7
Case 5	2,524,250	100,970	527,354	5.9
Case 6	3,024,500	120,980	586,448	6.5

Prices are in Euro (EUR).

NPV is the most frequently used indicator to evaluate a project and considers cash flows considering the time factor (Pärssinen et al., 2019). NPV incorporates the present discounted value of all yearly operational costs and yearly savings together with total investment cost. In NPV calculation, we assumed that operational costs are equally distributed in years and yearly saving is not changed by years.

Cumulative NPV is calculated for the CCHP-PV(roof) Case-5 with the following formula (Świerzewski et al., 2021). The discount rate is shown with an r-value in the formula.

$$\text{NPV (EUR)} = \sum_{t=1}^{T} \frac{\text{Annual Saving (EUR)}}{(1+r)^t} - \text{Total Investment Cost (EUR)} \quad (75)$$

We also calculated the internal rate of return (IRR) to estimate the profitability of the investment. The following formula shows that IRR is an r-value (discount rate) that equals the NPV to zero. A project is accepted as profitable if the IRR result is bigger than the used discount rate.

$$0 = \sum_{t=1}^{T} \frac{\text{Annual Saving (EUR)}}{(1+\text{IRR})^t} - \text{Total Investment Cost (EUR)} \quad (76)$$

The discount rate has a big impact on the cumulative NPV to be able to turn positive in years (Taylan, 2019). Therefore, different discount rates have been calculated. In different projects, locations, and for different investors, discount rates may change. For the case study's country, the discount ratio of 8% is advised to be used (Gugul et al., 2018). It locates at mid-scenario between 4% and 12%, and it is in accordance with the current policy rates of the central bank (The Central Bank Republic of Turkey).

Figure 29 presents the cash flow projection for NPV calculation and IRR of the additional systems with a discount ratio of 4%, 8%, and 12%. According to the mid-scenario, NPV turns positive in 9 years in Case-5.

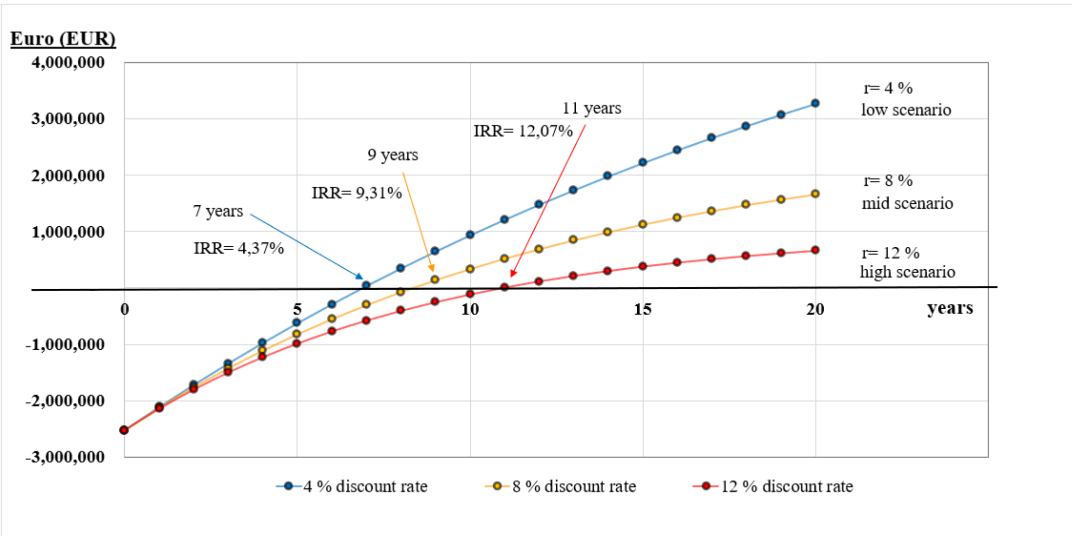


Figure 29. NPV cash flow in years and IRR comparison of Case-5

Furthermore, energy prices are volatile and change in different countries. For that reason, the financial benefit of CCHP-PV and the ROI of additional system investments are sensitive to energy purchase prices. The CCHP use in data centers was found beneficial where the natural gas to electricity ratio is around 0.19 to 0.30 (Xu and Qu, 2013; Ahn et al., 2019). This ratio fluctuates in a similar range in the case study location of this study. Natural gas and electricity price deviation between 2011 and 2023 are shown in Figure 30 for Turkiye (Republic of Türkiye Energy Market Regulatory Authority; Izgaz; Energy Markets A.S.). The ratio tends to decrease over the years in Turkiye but it peaked in 2020 temporarily due to uncertainties in the global natural gas prices. Turkiye recently discovered new natural gas reserves and already started to use its local reserves in its national gas distribution system. Hence, it is expected that this ratio could decrease in the near future.

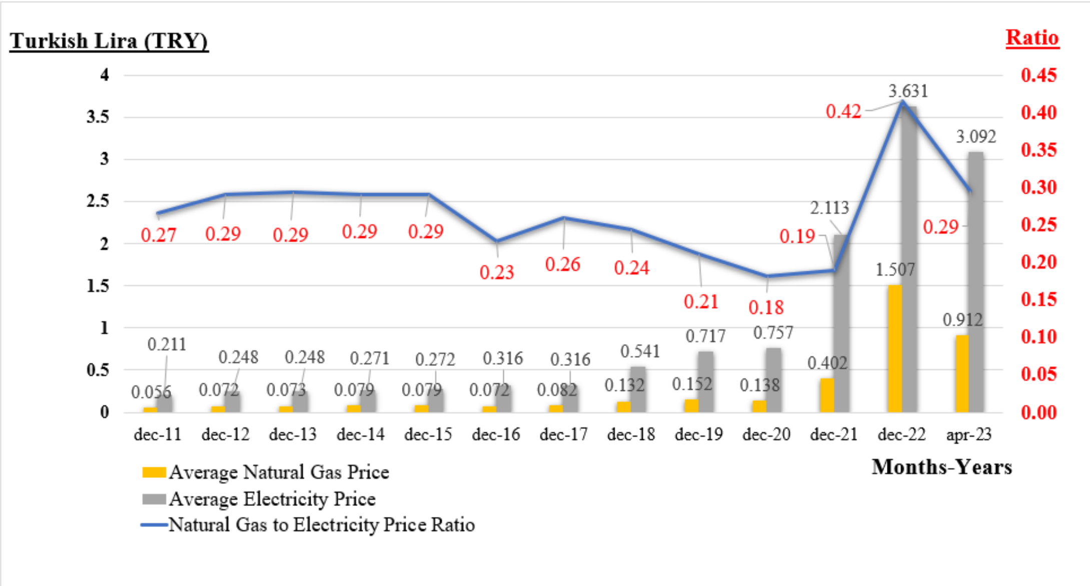


Figure 30. Natural Gas and Electricity Price Ratio Changes for Case Study Location (Republic of Türkiye Energy Market Regulatory Authority; Izgaz; Energy Markets A.S.)

5.7 Discussions

- The CCHP-PV systems can provide the data center's energy demand while providing their surpluses for regional energy demands. Since we executed hourly simulation, we have explored that the energy usage benefit varies based on the outdoor weather conditions throughout the day and the year. This further shows the importance of our study executed for a complete year simulation to capture the seasonal impact on the results. Considering the results of Case-5, the annual residential heating, and cooling energy consumption reductions were found 68% and 39%, respectively. In Case-5, the CCHP-PV-based data center's electricity surplus can cut the annual grid electricity consumption by 66%. Reduction in residential heating and cooling's electricity consumption was found 37%. It has been found that district energy integration utilized the CCHP-PV system better, increased energy usage efficiency, and provided more responsible energy consumption.

- Literature emphasized that the power grid is challenged by peak demands. On-site generation helped with this issue by matching the generation at the consumption point and decreasing the power losses in the power grid. Considering the results of Case-5, the proposed system decreased the grid electricity demand by 39% on the 5MW peak hour. By reducing electricity demand, grid power distribution losses were also decreased from 1.890% to 1.078%, which represents a 43% reduction. This reduction is beneficial for grid operators by reducing economic losses. According to different case studies, it has been found that increased on-site generation with extended PV capacity does not mean a further reduction in power losses due to increased circulation currents in the grid power lines. For the lowest power losses, on-site generation is advised to be matched with local demands. This result provides a good clarification for the data center literature in this research area.
- In the unidirectional electrical distribution grid, the voltage drop on the load side is a known electrical phenomenon. However, on-site generation eliminated the 2.75 % voltage drop at the data center's LV bus. On the negative side, short-circuit level on the data center's LV bus is increased from 50.4 kA to 63.2 kA due to the parallel operation of the CCHP-PV with the grid. Hence, electrical materials must be selected properly during the design stage. The impacts on the residential LV buses are very little due to long cable distances in the MV ring.
- CCHP and district energy connections are advised for data centers. According to case studies, it has been found that data center with district energy connections always performed better in terms of energy cost savings. Compared to the reference case, Case-1, CCHP-PV(roof)-based data center's residual heat recovery and district energy network connection (Case-5) reduced the annual energy costs by 61.7%.
- Carbon dioxide equivalent emissions associated with grid electricity consumption were decreased. CCHP-PV-based data center's (Case-5) carbon dioxide equivalent emission is 77% lower than the only grid-fed data center. Also, residential customers' emissions were decreased by 36% thanks to electricity and thermal energy surpluses by CCHP-PV. This is a significant

emission reduction, and it helps for cleaner and more sustainable consumption for the region.

- PV systems are environmentally attractive for data centers, but the capacity of the PV system is also critical. Although extended PV capacity (Case-6) additionally reduces the operational costs, it will come with additional investment costs. The return on investment shall be reviewed before the decision on the PV capacities.

Chapter 6

Reliability and Availability of CCHP-integrated Data Centers

6.1 Reliability and Availability in Data Centers

A data center is a facility designed to support essential operations for its intended purposes, such as serving a bank, military base, hospital, or global telecommunications traffic. Thus, the importance of data centers is increasing day by day. As an illustration, during the Covid-19 pandemic, the UK government classified data centers as essential infrastructure, allowing operational staff to receive exemptions to keep the facilities running (Judge, 2020). Similarly, the US also deemed data center construction to be essential critical infrastructure and exempt from Covid-19 restrictions (Eversheds Sutherland, 2020). These examples demonstrate the significance of data centers for countries and society as a whole.

Given the vital nature of data centers, the reliability and availability of these mission-critical facilities are also crucial and reliability and availability analyses are the common approaches used in data centers to understand the level of safety of operations. As a result of increased redundancy levels in systems in data centers, an achieved availability of 0.99999, also known as 5-nines, is commonly considered a highly available data center benchmark in the industry and the literature (Arno et al., 2012).

Although the industry tends to describe a highly available data center with availability parameters, reliability also has an important role in defining the safety of the operation in data centers. In other words, availability does not necessarily indicate the same level of reliability when comparing two different data centers (Arno et al., 2012). Hence, both availability and reliability should be assessed for evaluating the safety level of data center operation.

Reliability and availability analysis is an important aspect of data centers but there is limited research in the literature. Few studies focus on the electrical or cooling topologies in data centers. Arno et al. (Arno et al., 2012) investigated the reliability and availability of data centers from Tier-1 to Tier-4 using IEEE (The Institute of Electrical and Electronics Engineers) standard reliability data. However, they did not investigate the cooling supplies in their studies. Bodi (Bodi, 2007) presented a reliability analysis of UPS systems in data centers based on multiple topologies. He highlighted the trade-off concerns between excessive demand for redundancy and additional UPS costs in data center designs. Wiboonrat (Wiboonrat, 2008, 2008, 2012) published multiple studies on electrical reliability analysis, and he used simulation software to analyze a Tier-4 data center using IEEE reliability data. Wiboonrat utilized Monte Carlo and RBD methods in different studies but presented similar results. The author's studies did not cover the main cooling systems such as chillers, crah units, cooling distribution, and electrical power impact on these main cooling systems. Sithimolada and Sauer (Sithimolada and Sauer, 2010) conducted a comparative reliability analysis of a DC power distribution system and an AC distribution system in a data center. According to the findings, a configuration with multiple units of uninterruptible power supply and loads but without redundancy suggests that the DC system may be more reliable than the AC system, up to a certain extent. Marwah et al. (Marwah et al., 2010) introduced an approach to evaluate the sustainability impact of various data center topologies, in which availability is considered as one of the essential performance parameters, in addition to energy and sustainability factors. The authors utilized SPN (stochastic petri network) method for the analysis. They also computed the results with RBD and the results were found to be similar to SPN. Muller and Strunz (Muller and Strunz, 2012) utilized the RBD together with the Boolean algebra method to calculate the reliability of a data center based on IEEE reliability data. They compared a complex design topology to a simple design topology with 40% fewer components and found that a simple design topology achieved only 3% lower reliability in one-year results. In this study, availability was not analyzed. Ahmed et al. (Ahmed et al., 2021) performed quantitative studies to show the impacts of power losses on service availability and the overall availability of two different data centers. They found out that service availability cannot be assured by increasing the rated power of power distribution units, while the optimal number of servers per power distribution unit can reduce the possible server outages. However, the study did not consider the emergency generators and grid connections.

There is a need to allocate more research efforts toward evaluating the reliability of data center cooling systems, and the current literature is very limited (Ahmed et al., 2021). Callou et al. (Callou et al., 2012) proposed a set of cooling topologies for the integrated assessment of data center cooling availability, sustainability impact, and cost. Their findings showed that hot-standby redundant units increased the availability slightly without any additional investment cost or exergy consumption. Cheung and Wang (Cheung and Wang, 2019) performed reliability and availability assessments specifically for a specific type of chiller in data centers. They found that it is crucial to install a redundant system to meet the requirements of higher Tier levels. Gomes et al. (Gomes et al., 2017) utilized SPN to model the availability of cooling systems in data centers. However, the study focuses on entry-level Tier redundancies which are not commonly used in today's data centers and it does not consider the electrical systems in the overall availability. Nishida et al. (Nishida et al., 2008) examined the system reliability specifically considering the power source reliability of an air-conditioning system. Wang et al. (Wang et al., 2019) provided a reliability and availability analysis for the operational modes of cooling systems in a data center considering N+1 redundant units.

CCHP use in data centers was investigated in some studies for utilizing or replacing one of the power grid connections and emergency generators. Keskin and Soykan (Keskin and Soykan, 2023) examined the electrical impact and emission reduction on the power distribution grid by utilizing a CCHP system in parallel with grid connection in a data center. Angelis and Grasselli (Angelis and Grasselli, 2015) suggested a reference schematic where one of the emergency generators is replaced with CCHP in a Tier-3 data center. The study emphasized that replacing emergency generators with a CCHP system could affect the current industry-accepted Tier classifications. However, both studies did not investigate the reliability and availability. Keskin and Soykan (Keskin and Soykan, 2019) examined the reliability and availability impact of swapping one of the grid connections with CCHP. The study consders only electricity supply and they found a positive contribution to reliability, availability, and energy cost saving.

Research on the reliability of CHP and CCHP systems has primarily centered on component-level analysis and optimal operational strategies. Haghifam and Manbachi (Haghifam and Manbachi, 2011) determined the reliability of the system from the generation point to the consumer and found that a higher failure rate of the CHP system greatly impacts the overall integrated system's reliability. Jiang et al. (Jiang et al., 2019) studied the reliability of a CCHP system and the effect of redundant devices on overall reliability. They found that implementing redundant devices can enhance the availability of a CCHP system. Wang et al. (Wang et al., 2013) compared the reliability and availability of a CHP system to separate energy production systems and found that the redundant CHP system showed improvement in reliability and a decrease in failure rates for all energy supplies. Lei et al. (Lei et al., 2018) utilized a new approach for analyzing the reliability of integrated energy systems that includes a CHP unit and found that the type and capacity of energy hubs greatly impact reliability. Talebjedi and Behbahaninia (Talebjedi and Behbahaninia, 2021) proposed a thermo-economic analysis that incorporates reliability assessment and found that this approach reduces energy and operational costs. Santos et al. (Santos et al., 2021) developed a method to examine the interconnection between electricity and gas systems and found that using CHP support increases flexibility and decreases failure rates in the electrical network. Gbadamosi and Nwulu (Gbadamosi and Nwulu, 2020) optimized the operation of a CHP-PV-Wind-Energy storage coupled system while considering different reliability performance indexes and found that hybrid systems provide more reliable performance. Ahmed et al. (Ahmed et al., 2021) published a recent review article to identify the research gaps in the reliability modeling of data centers. The authors noted that the number of published articles on data center reliability is lower compared to those on data center energy efficiency while there has been a growing interest in achieving energy efficiency and reliability in data centers over the past few decades. They highlighted research gaps in the literature concerning investigations into the reliability of cooling systems and alternative energy systems for data centers.

6.2 Data Center Failures and Cost of Downtime

The continuous operation of data centers is crucial for public services, and the cost of service interruption is also a major consideration. To prevent possible downtime, reliable power, cooling, and infrastructure are essential to data center operations. Compared to 20-30 years ago, data centers today are more reliable, thanks to redundant infrastructures, automation, distributed architectures, data traffic management, and replication, which help prevent many IT service failures. However, despite these significant improvements, new research shows that failures and downtime are still common problems. When downtime does occur, recovery times can be lengthy and complicated, resulting in high costs due to the heavy reliance on IT technologies in society and business. Based on a survey, the human factor was responsible for 8% of the total failures, while data center design-related issues accounted for 13% of data center failures. Nevertheless, most of the failures could have been prevented (Lawrence, 2021).

According to the Uptime Institute's database, which has collected data for over 25 years, electrical failures accounted for 80% of all IT load losses in data centers (Uptime Institute, 2023). The combined percentage of power and cooling failure causes is 50%, which highlights the need for more reliable power and cooling infrastructure solutions for data centers. It is also important to evaluate the reliability and availability impacts of these solutions before implementing them.

The reliability and availability of an industrial or commercial facility are crucial due to the high costs associated with downtime (IEEE, 2007). When designing a new data center, downtime cost is an important consideration. Unfortunately, there has been limited research into the causes and effects of data center downtime, and it can be difficult to measure due to indirect impacts at the macro level. Apart from physical damages, reputational losses are also critical for most organizations and companies. For example, in 2018, a stock exchange was closed for almost an entire day due to a problem in a data center, and the incident was widely reported in the news (Tanwen, 2018). Furthermore, when a company's web services experience an outage, its stock price can trade 0.1% lower at the opening (Tripathi, 2021). In another instance, a top executive in a company resigned after a data center failure disrupted services to its 53 million users (Lee, 2022).

The damage caused by an outage can vary significantly depending on when it occurs, to whom it affects, and how long it lasts. According to a data center outage report published in 2016 (Emerson, 2016), the average cost of a data center downtime increased to 740,357 USD, representing a 38% increase since the first study in 2010. Furthermore, the maximum downtime cost increased by 81% to $2,409,991 in 2016. Uptime Institute also conducted a global survey in 2022 amongst the 778 data center operators. The survey indicates that 45% of the participants reported an incident with a total cost of downtime ranging from 100,000 USD to 1,000,000 USD (Uptime Institute, 2023).

6.3 Reliability and Availability Analysis

Reliability (R) is defined as the ability of a component or system to perform required functions under stated conditions for a stated period. It is the function of time and failure rate (λ) (IEEE, 2007).

$$R(t) = e^{-(\lambda \times t)} \tag{77}$$

Availability (A) is defined as the ability of an item to perform its required function at a stated instant of time or over a stated period. A is a more comprehensive form of another availability term, A_i, so-called inherent availability. In the previous research in the literature, generally inherent availability was used in the calculations since A_i does not count the time duration of failures that are human dependent such as logistics time and preventative maintenance time (IEEE, 2007). Hence, it provides more subjective and inherent data for system and topology comparisons as used similarly in the literature.

Ai is calculated by MTBF and MTTR as follows:

$$A_i = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \tag{78}$$

6.4 Reliability Calculation Methods and Reliability Block Diagram (RBD)

There are multiple methods for reliability calculations in the literature. These are as follows:

- Fault Tree Analysis
- Event Tree Analysis
- Binary Decision Diagram
- Markov Processes
- Common Cause Failures
- Monte Carlo simulation

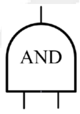
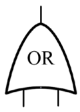
Amongst these reliability analysis methods, fault tree analysis is commonly used for evaluating and enhancing the reliability and safety of operations.

Fault treee analysis has been implemented across a range of industries including nuclear, aerospace, electrical, chemical, railway, transportation, software, and insurance (Čepin, 2011).

A fault tree model can be transformed into an inductive method known as RBD for analyzing reliability. RBD is a schematic representation with blocks arranged in series and parallel, representing individual components or groups of them. This method is commonly used in data center-related studies and also in commercial software in Ref. (ReliSoft Bloksim). By using the reliability index of each component, the overall reliability of the system can be calculated (Čepin, 2011). In RBD, each component is identified by reliability indexes with a series or parallel configuration, and they are represented with ``AND`` or ``OR`` gates. Table 17 lists the typical gates and their corresponding RBD equivalents (Menčík, 2016).

Table 17

Gate Descriptions and RBD Equivalents

Name of Gate	**Gate Symbol**	**Description**	**RBD Equivalent**
AND		The output event occurs if all input events occur	Series configuration
OR		The output event occurs if at least one of the input events occur	Parallel configuration

When the components are in series, any component failure causes the failure of the entire system. Figure 31 shows a reliability block diagram with n number of components connected in series.

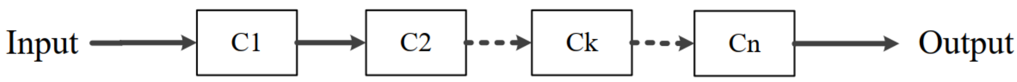


Figure 31. Reliability block diagram in series configuration (Cepin, 2011)

The reliability of the system, R, is calculated as:

$$R = \prod_{k=1}^{n} R_k \tag{79}$$

The availability of the system, A, is calculated as:

$$A = \prod_{k=1}^{n} A_k \tag{80}$$

When the components are in a parallel configuration, the system's reliability improves rapidly. This is because the presence of alternative paths in the path allows for continued function even if one of the parallel components fails. Figure 32 shows a reliability block diagram with n number of components connected in parallel.

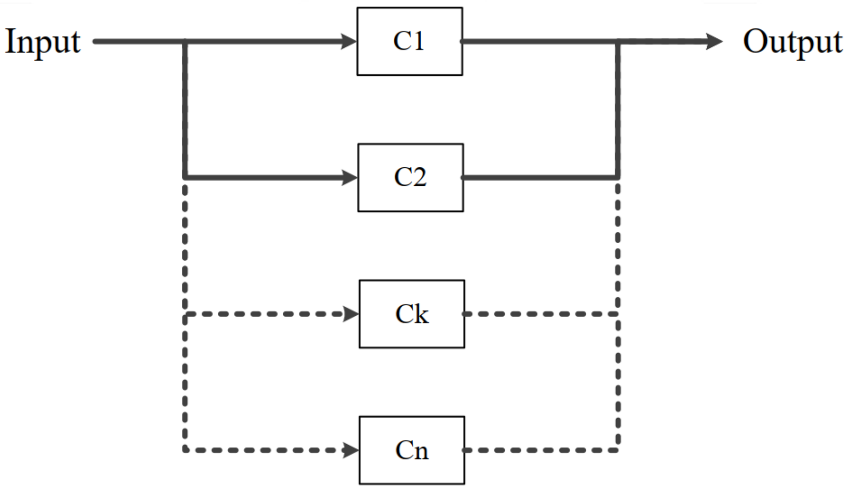


Figure 32. Reliability block diagram in parallel configuration (Čepin, 2011)

The reliability of the system, R, is calculated as:

$$R = 1 - \prod_{k=1}^{n} (1 - R_k) \tag{81}$$

The availability of the system, A, is calculated as:

$$A = 1 - \prod_{k=1}^{n} (1 - A_k) \tag{82}$$

6.5 CCHP Integration to Data Centers

From an energy standpoint, data centers are energy-intensive, and their energy consumption is much higher than a typical building (Darrow and Hedman, 2009). In 2020, the global electricity demand for data centers accounted for about 1% of the global final electricity demand and it is expected to increase (International Energy Agency, 2022). With the growing need for new data centers, the global energy demand is also increasing. Therefore, it is essential to develop more energy-efficient solutions for data centers to support future energy networks and society. CCHP systems can provide continuity of power generation and cooling for data centers. CCHP-integrated data centers can continue to operate during catastrophic events such as hurricanes and prolonged blackouts (Keskin and Soykan, 2019).

To increase the level of safety, data centers are usually designed with an increased level of redundancy such as N+1, N+2, or 2N. N defines the minimum required number or capacity of a system for its functioning properly (IEEE, 2007). Data center redundancy performances are classified and nominated with different Tier levels from 1 to 4, and Tier 4 represents the safest data center due to its high resilience against failures. Full redundancy with a dual path (2N) is a well-known and highly reliable topology in the data center industry (Heslin, 2017). However, it doesn't mean that every 2N redundant system data center qualifies for the Tier-4 class since each organization has its definition of Tier-4 based on different physical or technical criteria. A data center with 2N redundancy can be used as a reference topology to study the impact of alternative energy systems on the reliability and availability. The success of an alternative energy system in a data center with a 2N redundant system, which already has high availability and reliability performance, can be determined if the final results exceed the performance of a standard data center with a 2N redundant system. For this reason, we analyzed the impact of CCHP in a 2N redundant system data center.

The proposed energy connections and flows within a CCHP-integrated data center with 2N redundancy are illustrated in Figure 33.

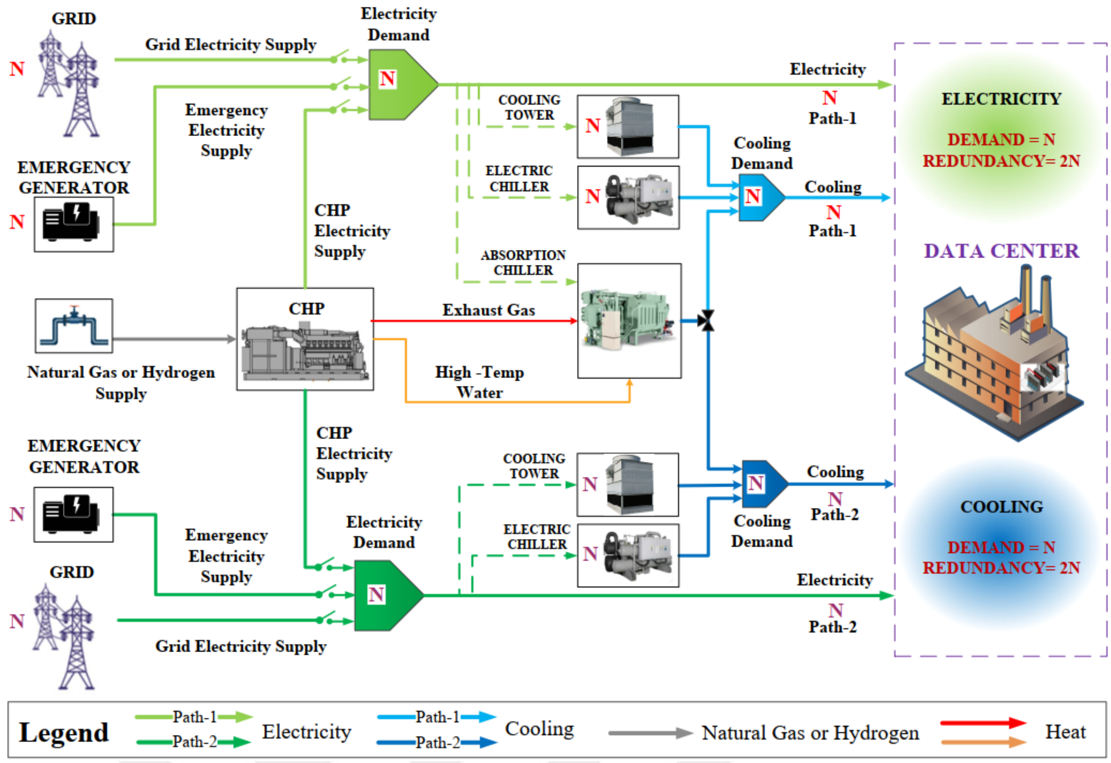


Figure 33. Energy Flow and Connection Topology of CCHP-integrated Data Center with 2N Redundancy

In this design, both the power grid and emergency generators are maintained to meet the Tier and strict data center end-client requirements. The Tier classification should not be impacted by replacing a grid connection with a CCHP system, as grid connections are not considered a reliable source of electricity (U.S. Environmental Protection Agency Combined Heat and Power Partnership, 2007). 2N redundancy data center design involves two N-sources and paths that work in active-active mode. If one N system or path fails, the redundant system or path can provide sufficient electricity and cooling. This ensures the safety of the operation.

For the energy flow, the CHP system provides electricity to meet the electricity demand of the data center. When the CHP system generates electricity from natural gas or hydrogen supply, it produces heat energy as a byproduct via exhaust gas and engine jacket water. This waste heat energy can be utilized by the absorption chiller and converted to a cooling supply. Furthermore, the addition of alternative energy systems as redundant operating systems increases the reliability and availability of the overall system.

6.6 System Modelling and Calculations

Single-line diagram (SLD) is a common method of representing both electrical and mechanical systems. This diagram provides a straightforward symbol-integrated representation of the infrastructure, highlighting the quantity, capacity, path, and connection sequence of the subsystems. To understand the impact of a CCHP integration on a data center, both grid-fed data center with 2N redundancy and CCHP-integrated data center are created separately. Figure 34 illustrates the single-line diagram of a grid-fed (typical) data center with 2N redundancy considering electricity and cooling systems. Electrical and mechanical components and utility connections were shown with different color coding.

To analyze these impacts on reliability and availability, the following block diagram of the methodology used in this study is shown in Figure 35. This diagram is repeated for both standard and CCHP integrated data center design. Firstly, an up-to-date grid-fed data center design is created with a single-line diagram. Secondly, single-line diagrams are converted to reliability block diagrams. Data sources from IEEE and the literature are used for capturing failure rates, mean time between failures (MTBF), and mean time to repair (MTTR) data. The reliability and availability values are calculated from the data sources to use in the reliability block diagram for each component. By doing the necessary calculations for series and parallel configurations, reliability and availability results are found. Thirdly, the grid-fed and CCHP-integrated data centers are compared and evaluated in terms of failure rate, reliability, and availability.

The life-cycle cost analysis is conducted with a sensitivity analysis based on investment cost, operation & maintenance cost, energy saving cost, cost of downtime, and failure rate improvements to demonstrate the financial viability of the proposed CCHP integration to data centers.

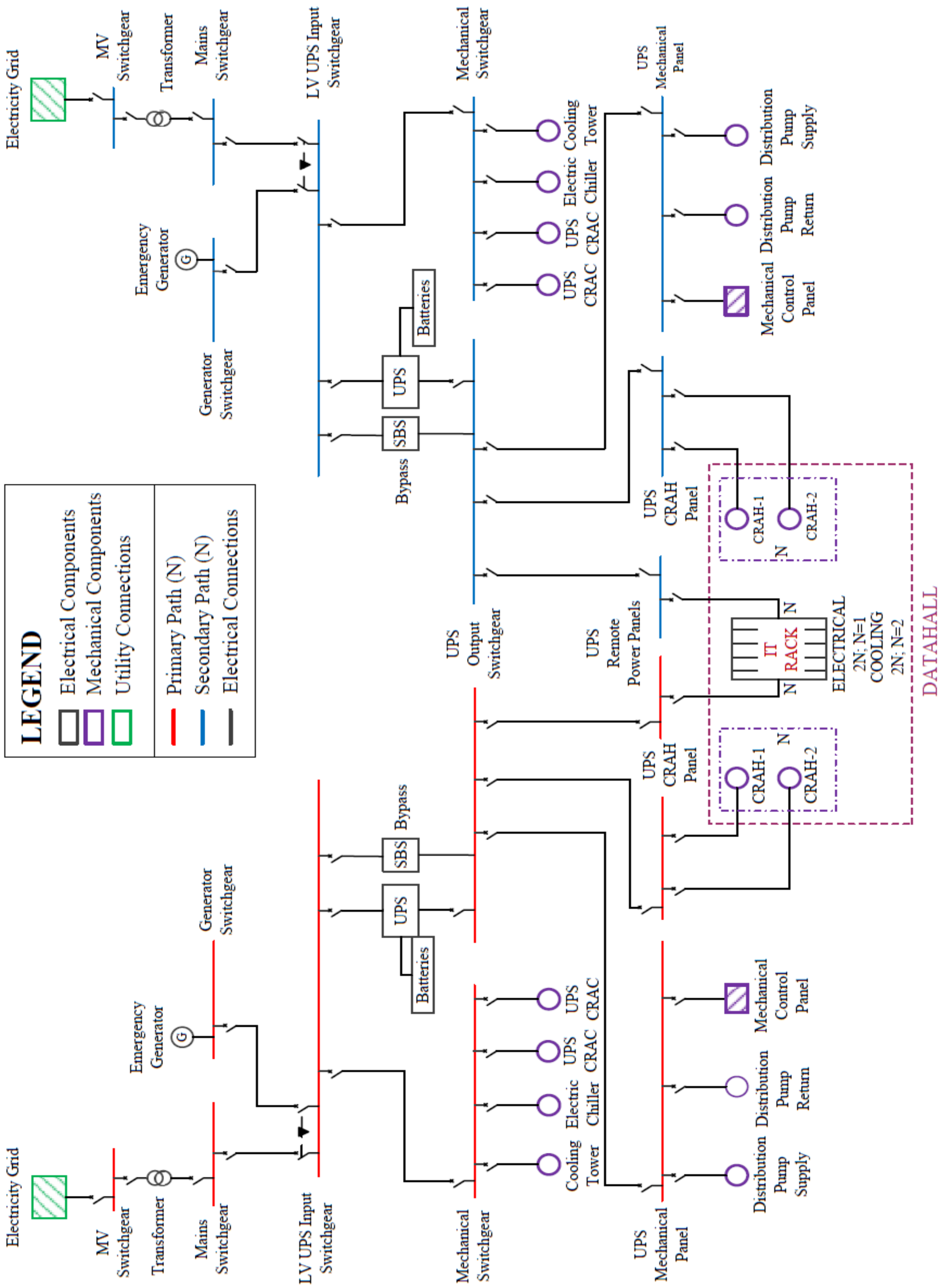


Figure 34. Single Line Diagram of the Grid-fed Data Center with 2N Redundancy considering Electricity and Cooling Systems

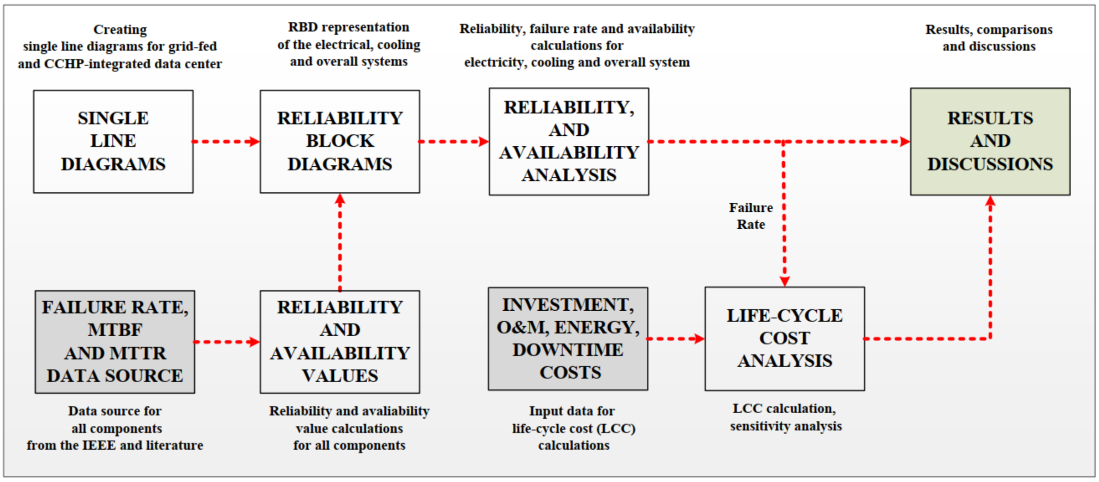


Figure 35. Block Diagram of the Methodology

6.7 Input Data for Reliability and Availability Analysis

An accurate and reliable source of equipment data is crucial for conducting accurate reliability and availability analysis. However, collecting data can often be the most challenging aspect of performing a reliability analysis (Borges). It may not even be possible due to the operator's lack of willingness to share (Ahmed et al., 2021). The IEEE Standard-493 (Gold Book) provides source data based on extensive surveys conducted over many years as per reference (IEEE, 2007). This standard establishes a common foundation for comparing different topologies in electrical and mechanical systems. It allows for judging different network topologies equally under the same conditions and using the same equipment reliability data. Due to its independence and standardization, IEEE Standard-493 can serve as a generic data source and is widely used in literature. Additionally, for CCHP-related components such as CHP units, power generation and heat recovery units, electric chillers, absorption chillers, and natural gas network supplies, the literature can be used as a recent data source for these specific components as in Ref. (Jiang et al., 2019). Failure rates, MTBF, and MTTR data are captured from these sources and the list of reliability and availability is given in the Appendix.

6.8 Analysis of a Grid-fed and CCHP-integrated Data center with 2N Redundancy

Electricity and cooling supplies are vital for the safe operation of a data center. The combination of these systems creates the overall system for the critical operation of a data center. To calculate the impact of CCHP integration on the overall system, both grid-fed and CCHP-integrated data center with 2N redundancy is created. Figure 36 illustrates the single-line diagram of a CCHP-integrated data center with 2N redundancy for the electricity and cooling systems. In a CCHP-integrated data center, a CHP and absorption chiller are additional to the grid-fed data center. Each electrical and cooling component in the single-line diagram is represented with an index such as a1, b11, k3, etc. The descriptions of the components and their indexes are given in the List of Abbreviations and Symbols. The reliability and availability values are given in the Appendices together with indexes and descriptions of the components.

Electricity and cooling single-line diagrams can be transformed into reliability block diagrams by using ``AND`` and ``OR`` gates to represent series connections or parallel connections. The reliability blog diagram is shown in Figure 37. Each node in the reliability block diagram represents a component of a CCHP-integrated data center. Each node is assigned with reliability and availability indexes captured from source data.

Reliability and availability calculations are done separately with the same method. The results of the reliability and availability of the system are obtained using reliability and availability indexes for all components configured in both series or parallel. These results have been calculated for both a grid-fed data center and the CCHP-integrated 2N redundant data center.

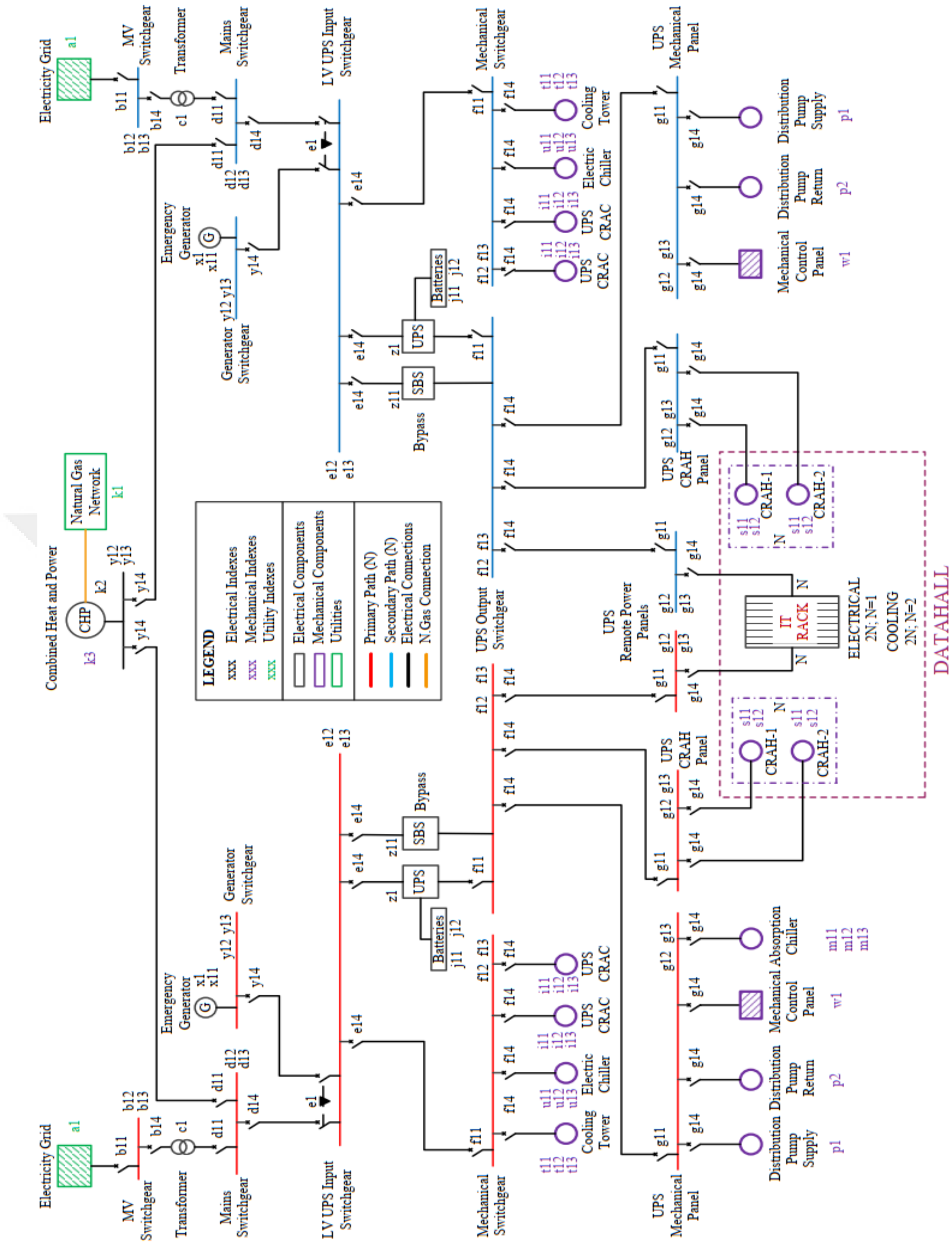


Figure 36. Single Line Diagram of the CCHP-Integrated Data Center with 2N Redundant Electricity and Cooling Systems

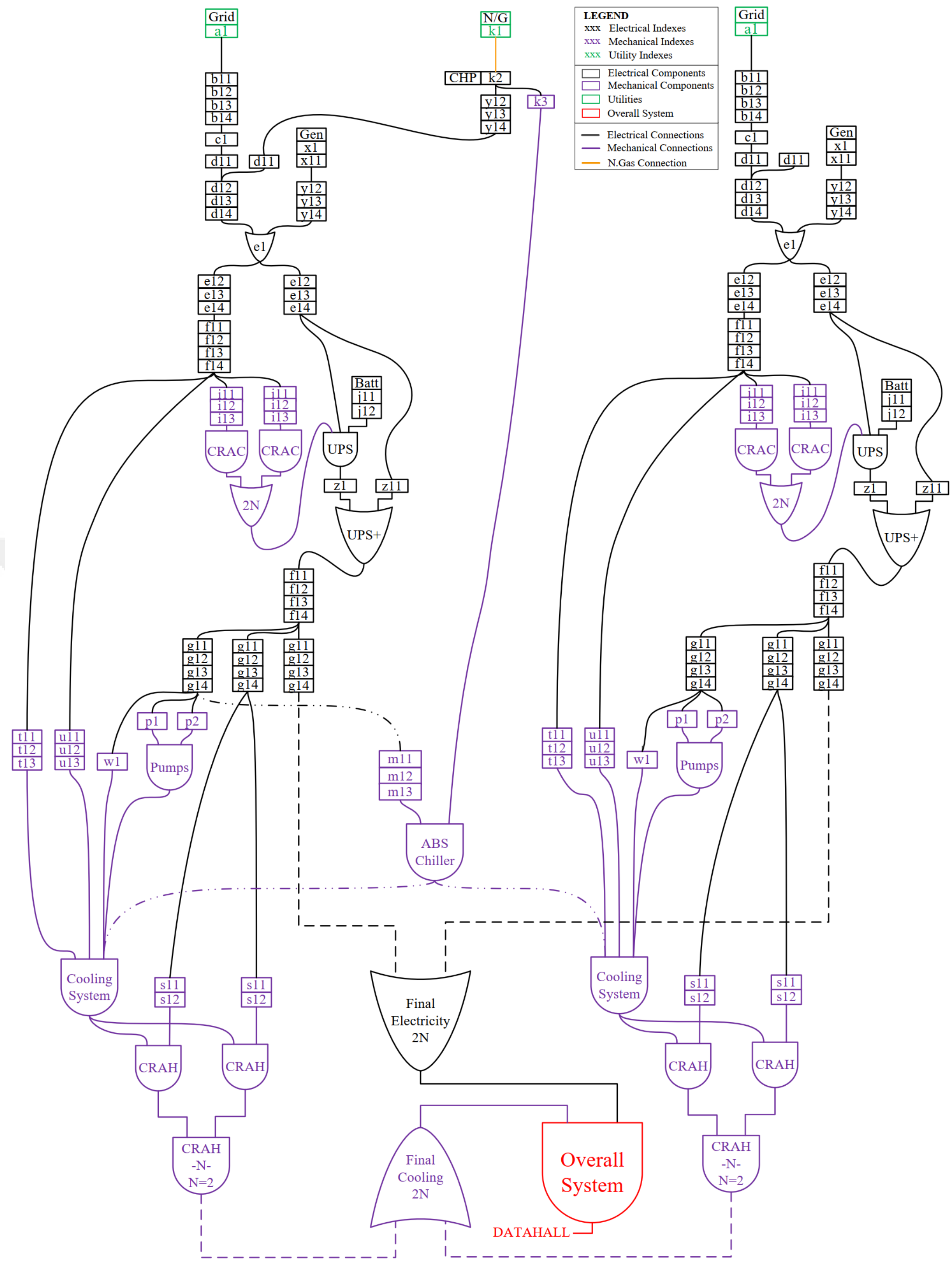


Figure 37. Reliability Block Diagram of CCHP-Integrated Data Center with 2N Redundancy for Electricity and Cooling Supply

6.9 Results

In the data center-related literature, the number of nines is recognized as an important metric for the availability performance of a data center. Failure rates and reliability analysis are given for a 1-year duration to compare with findings in the literature and to use in LCC calculation. Results of the reliability, failure rate, availability, and number of nines are summarized in the following tables. Table 18 shows the electricity, cooling, and overall supply results of a grid-fed data center with 2N redundancy. The electricity, cooling, and overall supply results of a CCHP-integrated data center with 2N redundancy are presented in Table 19.

Table 18

Reliability, Failure Rate, Availability, and Number of Nines of the Grid-fed Data Center with 2N Redundancy

System	Reliability (%) (t=year)	Failure Rate /year	Availability (%)	Number of Nines
Electricity Supply	98.86	0.011	**99.9999999**8	9-Nines
Cooling Supply	49.80	0.697	**99.999**56752	5-Nines
Overall Supply	49.23	0.709	**99.999**56751	5-Nines

Table 19

Electricity, Cooling, and Overall Supply Results of a CCHP-integrated Data Center with 2N Redundancy

System	Reliability (%) (t=1 year)	Failure Rate /year	Availability (%)	Number of Nines
Electricity Supply	99.63	0.004	**99.9999999**8	9-Nines
Cooling Supply	74.89	0.289	**99.99999**140	7-Nines
Overall Supply	74.62	0.293	**99.99999**139	7-Nines

By using the results given in Table 19 and Table 20, the comparison and improvements in failure rate and the number of nines for the electricity, cooling, and overall supply are presented in Table 20.

Table 20

Comparison of the Grid-fed Data Center and the CCHP-integrated Data Center with 2N Redundancy

System	Grid-fed Data Center Failure Rate/year	CCHP integrated Data Center Failure Rate/year	Improvement in Failure Rate (%)	Improvement in Number of Nines
Electricity Supply	0.011	0.004	63.6	Same
Cooling Supply	0.697	0.289	58.5	From 5 to 7
Overall Supply	0.709	0.293	58.7	From 5 to 7

6.10 Validation for Results

We utilized one of the most widely used analytical methods in the data center literature, referred to as RBD, employing a non-state-space approach. RBD is a frequently used benchmark for data centers. By utilizing mathematical equations for the components in series or parallel, RBD assumes statistical independence to carry out reliability and availability analysis (Trivedi, 2017). The accurate data source for the components is the most critical part of the validation of the analytical reliability and availability analysis.

Based on our literature review, some previous studies have investigated the reliability and availability of data center topologies; however, these studies had some deficiencies. Therefore, we listed the findings of these studies, their limitations, and our results in Table 21. Due to variations in configuration, the number of components in different models, differences in data sources, separate consideration of electricity and cooling supply, and other limitations in previous research, it is not possible to compare our results directly with those in the literature. However, for the grid-fed typical data center with 2N redundancy, IEEE Standard Ref. (IEEE, 2007) presents 99% reliability in electricity supply similar to our findings. Furthermore, a recent research Ref. (Cheung and Wang) found a 44% reliability for 2N data center cooling systems, which is closer to our findings. Also, our overall availability results fulfilled the availability attributes for 2N data center design (Turner et al., 2019). The results show that there is a good agreement between the results of our study and previous research.

6.11 Financial Risk

Risk refers to the combination of the probability of an accident occurrence and potential negative outcomes that may result. Risk is often reserved for random events with negative consequences for human life and the environment (Čepin, 2011). The probability of failure defines the level of risk, while the probability of success indicates reliability. Hence, risk and reliability are two complementary concepts (NASA).

Many data center projects tend to overlook the evaluation of risks in terms of financial impacts, as this factor is often assumed to be covered by insurance premiums or the selection of higher Tier level data center design topologies (Wiboonrat, 2012). However, the concept of reliability and failure rate can be applied in the financial risk context, practically.

Financial risk is determined by both the severity of the failure (measured in terms of financial losses caused by the failure) and the probability of the failure occurring within a given time frame (Arno et al., 2012). Downtime is defined as the loss of function for a period and the disruption of business activities is seen as occasional costs. In the data center world, the cost of downtime can vary based on the purpose and service of a data center.

$$\text{Financial Risk}\left(\frac{\text{EUR}}{\text{year}}\right) = \text{Failure Rate}\left(\frac{\text{failure}}{\text{year}}\right) \text{x Severity}\left(\frac{\text{EUR}}{\text{failure}}\right) \tag{83}$$

The total cost of downtime for a data center typically includes the sum of various factors, such as the direct loss of revenue, cost of lost data, payments for SLA (service level agreement) penalties, recovery and repair costs, lost employee productivity, and loss of reputation (Bauer et al, 2011; Wiboonrat, 2011).

Table 21

Comparison of the Previous Research in Literature for Data Center Reliability and Availability Results (ordered by year)

References	Pub. Year	Parameter	Reliability (1 year)	Availability	Methodology/ System Topology	Model Deficiencies
Bodi	2007	Electricity Supply	0.999990	-	Monte Carlo 2N	No cooling, Only a single grid and a generator exist
IEEE	2007	Electricity Supply	0.992761	0.99999130	RBD 2N	No cooling
Wiboonrat	2008	Electricity Supply	0.999996	-	RBD 2N	No cooling
Wiboonrat	2008	Electricity Supply	0.999997	-	Monte Carlo 2N	No cooling
Sithimolada and Sauer	2010	Electricity Supply	0.967152	0.99999993	RBD 2N	No cooling, Only a single generator exists (N)
Marwah et al.	2010	Electricity Supply	-	0.99999997	SPN 2N	No cooling, and electrical topology was not presented
Müller and Strunz	2012	Overall Supply	0.908351	-	RBD+Boolean 2N	Outdated design with multiple transfer switches, no detailed cooling, 56 comp.
		Overall Supply (*)	0.879329	-		(*) results with 32 components-design
Arno et al.	2012	Electricity Supply	0.998778	0.99999760	RBD 2N	No cooling
Wiboonrat	2012	Electricity Supply	0.995623	-	RBD 2N	No cooling
Callou et al.	2012	Cooling Supply	-	0.99998850	RBD +SPN 2N	No electricity, and final cooling devices are not 2N
Keskin and Soykan	2019	Electricity Supply	0.996747	0.99999757	RBD 2N	No cooling
Cheung and Wang	2019	Cooling Supply	0.442218	0.99883000	RBD 2N	No electricity
Ahmed et al.	2021	Electricity Supply	-	0.99999510	RBD 2N	No cooling, and electrical topology was partially developed
Keskin and Soykan	2023	Electricity Supply	0.988588	0.99999999	RBD 2N	-
		Cooling Supply	0.498007	0.99999567		
		Overall Supply	0.492324	0.99999567		

6.12 Life-Cycle Cost (LCC) Analysis

Life-cycle cost (LCC) analysis is a widely used technique for estimating the total cost of ownership, and it is commonly applied to evaluate the costs of whole buildings, alternative systems, building components, and environmental considerations. Typically, LCC involves obtaining multiple cost inputs to calculate costs for different phases of a project's life cycle (Davis Langdon Management Consulting, 2006). LCC analysis considers all high and relevant costs incurred over the life of a system to achieve defined levels of performance, including reliability, safety, and availability (Risi et al., 2018). Consequently, LCC is comprised of the net present value (NPV) of all expected costs from the installation to the end of a system's lifespan, including investment costs (IC), operation and maintenance costs (O&M), and other costs. Other costs include annual energy-saving costs (ENE) and reliability-related exposure costs (REL). The downtime cost is related to financial risk and it is covered under reliability-related exposure costs (REL). This cost is similar to yearly occurring O&M costs in LCC analysis and the improvements in reliability should also be deducted from the annual costs (Dang et al., 2015). Based on these, a comprehensive LCC for the alternative energy systems integration to data centers can be calculated as in Eqn. 84 (Davis Langdon Management Consulting, 2006; Fatemi et al., 2023). In Eqn. 84, *r* represents the discount rate and *T* represents the total years of the calculation such as 20 years.

$$\mathrm{LCC} = \mathrm{IC} + \sum_{t=1}^{T} \frac{\mathrm{O\&M} - \mathrm{ENE} - \mathrm{REL}}{(1+r)^{t}} \tag{84}$$

The combination of risk assessment and life-cycle cost analysis has been used in previous research, particularly in risk-related projects such as earthquake or flood mitigation projects. It helps to quantify the impact and design outcomes of mitigation strategies (Risi et al., 2018). In this study, the combination of reliability assessment and life-cycle cost analysis was provided as an ideal method for quantifying the cost and reliability effectiveness of the alternative energy system integration to data centers. It is also a powerful way to present the investment results to the industry and investors.

Annual energy saving cost (ENE) for locally operated CCHP integrated data center is extracted from the Table 16, as 306,493 EUR. Initial cost (ICE) and the annual O&M costs are captured from the Table 16, as 1,937,750 EUR and 77,510 EUR, respectively. In addition to cost components of CCHP, we are additionally considering the reliability-related exposure cost (REL) as an outcome of the reliability study in Chapter 3. Reliability-related exposure cost (REL) is the function of failure rate improvement and the cost of downtime (severity of failure). The failure rate for the CCHP-integrated data center is reduced from 0.709 to 0.293 in the overall system and the improvement becomes 0.416. The cost of downtime is accepted at the industry average level of 650,000 EUR per failure and obtained from the published data center outage report (Emerson, 2016). The value of REL is found by multiplying the improvement in failure rate with the cost of downtime, resulting in a yearly sum of 270,400 EUR. CCHP systems are major investments, and as such, a 20-year operation period has been adopted as the basis for the life-cycle cost (LCC) analysis.

Discount rates also change in different projects, locations, and for different investors. For the reference study location, a discount ratio of 8% is recommended in previous research in Ref. used (Gugul et al., 2018) and it is in accordance with the current policy rates of the central bank (The Central Bank Republic of Turkey). In our analysis, we did not consider yearly fluctuations in the O&M and energy costs, as well as other costs like residual costs, due to the simplicity of the calculations. The reliability-related exposure costs were accepted evenly over the 20 years, following the principle in the IEEE Standard (IEEE, 2007). The LCC calculations for the CCHP system integration have been calculated for each year from t=0 to T=20 year, and the results are presented in Table 22.

The LCC results show that, with an industry-average cost of downtime, the results turn to below zero after 5 years of operation. However, it's important to note that the reliability-related exposure cost may vary depending on the cost of downtime per failure and it is related to the service type and end-clients of the data center. Therefore, performing a sensitivity analysis is crucial to address the impact of the cost of downtime in the LCC analysis.

Table 22

LCC Calculation by Years for the CCHP Systems Integration to Data Centers for Each Year for a Duration of 20 Years

Years	IC	O&M	REL	ENE	Annual Cash Flow	Discounted Cash Flow	LCC by years
0	1,937,750	0		0	1,937,750	1,937,750	1,937,750
1		77,510	-270,400	-306,493	-499,383	-462,392	1,475,358
2		77,510	-270,400	-306,493	-499,383	-428,140	1,047,218
3		77,510	-270,400	-306,493	-499,383	-396,426	650,792
4		77,510	-270,400	-306,493	-499,383	-367,061	283,730
5		77,510	-270,400	-306,493	-499,383	-339,872	-56,142
6		77,510	-270,400	-306,493	-499,383	-314,696	-370,838
7		77,510	-270,400	-306,493	-499,383	-291,385	-662,223
8		77,510	-270,400	-306,493	-499,383	-269,801	-932,024
9		77,510	-270,400	-306,493	-499,383	-249,816	-1,181,840
10		77,510	-270,400	-306,493	-499,383	-231,311	-1,413,151
11		77,510	-270,400	-306,493	-499,383	-214,177	-1,627,327
12		77,510	-270,400	-306,493	-499,383	-198,312	-1,825,639
13		77,510	-270,400	-306,493	-499,383	-183,622	-2,009,261
14		77,510	-270,400	-306,493	-499,383	-170,020	-2,179,282
15		77,510	-270,400	-306,493	-499,383	-157,426	-2,336,708
16		77,510	-270,400	-306,493	-499,383	-145,765	-2,482,473
17		77,510	-270,400	-306,493	-499,383	-134,968	-2,617,441
18		77,510	-270,400	-306,493	-499,383	-124,970	-2,742,411
19		77,510	-270,400	-306,493	-499,383	-115,713	-2,858,124
20		77,510	-270,400	-306,493	-499,383	-107,142	-2,965,266

Prices are in EUR

6.13 Sensitivity Analysis

Sensitivity analysis involves the behavior of model variables to determine their relative effect on the model outcome (Davis Langdon Management Consulting). One approach to sensitivity analysis is a local sensitivity analysis. Local sensitivity analysis assesses the impact of a single variable at a time while all other variables are kept fixed (Matworks). In this section, a local sensitivity analysis is conducted to examine how variations in the cost of downtime affect the presented LCC analysis of integrating CCHP systems into a data center. The results of the total LCC calculation for 20 years are shown in Figure 38 for different costs of downtime. Figure 39 summarizes the LCC change by years for different cost of downtime scenarios which represents high, average, low, and zero cost. The cost of downtime is found critical for the LCC results and a data center investor or operator should determine the LCC as per the specific cost of downtime that can occur during the operation. LCC can be negative within 3.5 years to 14 years depending on the high or zero downtime cost while the other costs were kept fixed.

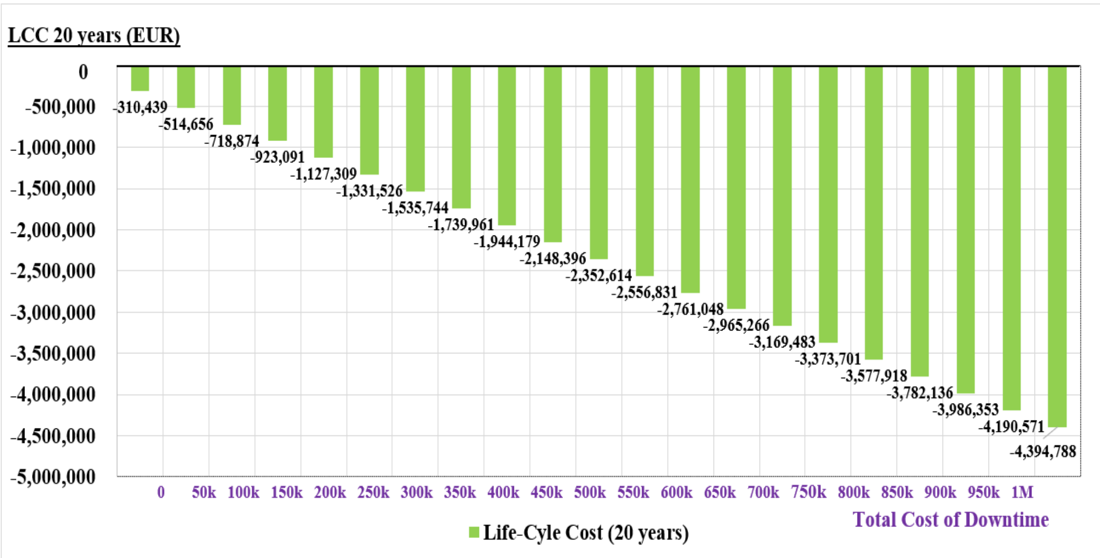


Figure 38. LCC Calculation Results for CCHP Systems integration to the data center for 20 years of duration

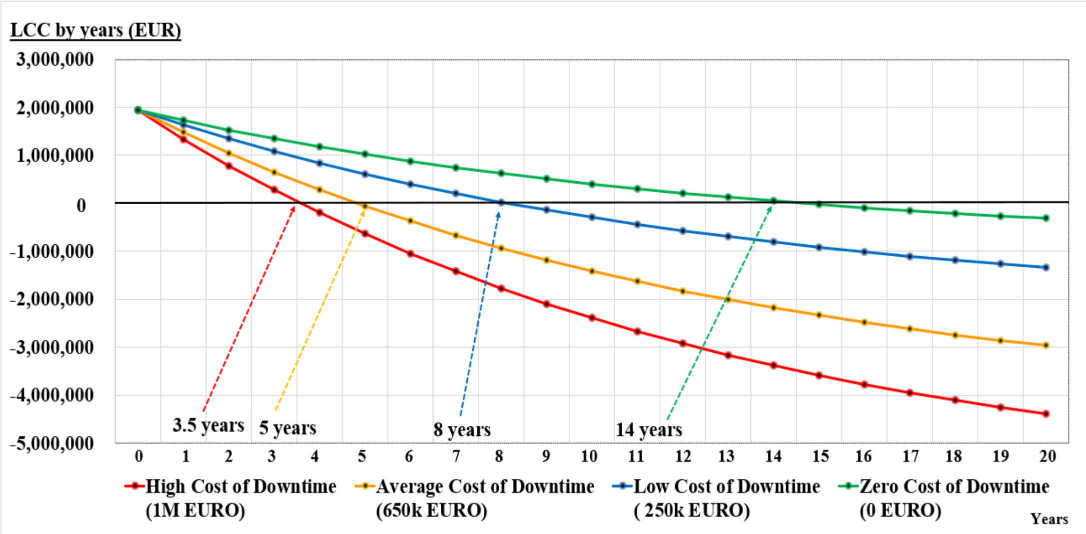


Figure 39. LCC changes by years for different cost of downtime scenarios

6.14 Discussions

- The reliability and availability results of the electrical systems were found to be higher compared to those of the cooling system. This is due to the fact that cooling systems are generally more prone to failure than electrical systems. It is worth noting that the reliability of the electrical systems also has an impact on the operation of the cooling system. Most of the studies in the literature have neglected to evaluate the overall supply topology. However, it is crucial to consider the overall supply to provide a more realistic analysis for the industry.
- The integration of CCHP increases the reliability of a grid-fed data center. The overall system's reliability (t =1 year) improved from 49.23% to 74.62%.
- The failure rate (λ/year) of a grid-fed data center is significantly reduced by CCHP integration. The improvement in the failure rate for the electricity supply, cooling supply, and overall supply is 63.6%, 58.5%, and 58.7%, respectively.
- The study's results indicate that the failure rate of the electricity supply is significantly lower when compared to that of the cooling supply. However, the overall system's failure rate is closer to that of cooling systems. This implies that there is a need to improve the failure rates in cooling systems to enhance the overall system's performance.

- According to the given comparative list of previous research, each study found different results for the 2N design. Our study results fulfilled the Uptime Institute's availability specifications for 2N data center design. There is a good agreement between the results of our study and previous research, but they are not identical. These differences can be attributed to the variations in the number of components, different SLDs, partially completed designs, and some deficiencies in similar studies. Therefore, there is a need for typical, up-to-date, and commonly accepted topologies that can serve as a reference for future investigations in the data center literature and industry.
- A data center A grid-fed data center with 2N redundant topology achieves an industry-accepted availability level of 5-nines for both electricity and cooling supply similar to previous research in the literature.
- A CCHP-integrated data center with 2N redundant topology can increase the number of nines in availability from 5-nines to 7-nines for the overall system.
- The availability contribution of the CCHP integration in the electricity supply is almost negligible (both 9 nines), while its contribution to the cooling supplies is significant from 5-nines to 7-nines.
- Although the availability contribution of CCHP is limited, its reliability contribution for both electricity and cooling supplies is remarkable. This highlights the importance of reliability analysis over data centers with similar availability while determining the risk to the safety of operations.
- Considering the LCC calculation based on 20 years, integrating CCHP systems into data centers has a promising outcome, as it provides energy cost savings for data center operations, as previously shown in the literature. The decrease in reliability-related exposure cost has a positive impact on the LCC calculations, which is an additional benefit of CCHP integration to data centers by mitigating the overall system's risk of failure.
- The sensitivity analysis revealed that the cost of downtime played a crucial role in the LCC results. The LCC could be negative in 3.5 years to 14 years, depending on the zero or high downtime costs while keeping other costs constant. Therefore, data center investors and operators should accurately consider the cost of downtime when evaluating the use of alternative energy systems.

Chapter 7

Conclusions

The utilization of digital technology is increasing rapidly, causing a growth in the number of data centers around the world. Data centers provide essential services, making them known as mission-critical. Reliable electricity and cooling supplies are vital for the data center's operation, and almost all data centers rely on the power grid to feed their electrical and cooling systems. However, the power grid is considered an unreliable source in the data center industry. An alternative to the power grid is a sustainable Combined Cooling, Heating, and Power (CCHP) system, which can supply continuous electricity and cooling to a data center while also providing on-site energy generation, reduction on power distribution losses, peak demand decrease, energy cost saving, and emission benefits.

Grid-connected data centers are one of the major customers for power distribution operators in terms of their huge electricity demand. This demand affects the capacity and electrical performance of the power grid with various factors. Hence, CCHP-PV-based energy generation systems and district energy network connections for data centers need to be investigated as sustainable option for the distribution grid. To understand the impact of alternative energy systems on data centers and the power grid, we modeled the energy demands of the residential customers and energy flows of the CCHP-PV-based data center in a multi-energy hub.

Energy surpluses occurring in the CCHP-PV-based data center can be utilized by residential customers in the neighborhood with a multi-energy hub. Thus, such a surplus can meet the thermal demand of a region and it helps to reduce the power grid electricity demand of residential customers indirectly. According to the analysis, total electricity demand on the MV distribution ring is reduced by 39% at the 5MW peak demand hour. This demand reduction also decreases the MV distribution losses from 1.890% to 1.078%. According to case comparison, district energy network connection or increased PV capacity provides more reduction on total power grid demand. This further reduces the MV distribution losses. Besides, the CCHP-PV-based data center reduced the annual residential heating consumption by 63% and the annual residential cooling consumption by 65% in the region. The annual grid electricity consumption was reduced by 66% with the elimination of the data center electricity demand, electricity back feeding into the power grid and reduction in residential final electricity consumption.

Thanks to surplus energies and efficient use of primary energy sources, the CCHP-PV-based data center operation's carbon dioxide equivalent emission is 77% lower than the conventional grid-fed data center. When only residential customers' electricity consumption is evaluated, residential customers' emissions decrease by 37%. This is a large amount of emission reduction which helps to sustainable consumption for regions.

Furthermore, the CCHP-PV-based data center reduces the yearly energy cost by 61.7%. However, the benefit of the CCHP system is highly dependent on regional energy prices. It has been proven that CCHP integration for a data center is more feasible and beneficial for a region where the natural gas price to electricity price ratio is relatively low, such as Turkiye. This ratio tends to continue in Turkey today in a similar range as in the last decade, which positively promotes and supports the use of CCHP in data centers.

On the other hand, given the vital nature of data centers, the reliability and availability of these mission-critical facilities are also crucial, and reliability and availability analyses are the common approaches used in data centers to understand the level of safety of operations. CCHP-integrated data centers can continue to operate during catastrophic events such as hurricanes and prolonged blackouts. The results showed that the overall system reliability of a grid-fed data center increased from 49.23% to 74.62% with a CCHP integration. The use of CCHP at the grid-fed data center increased the availability from 5-nines to 7-nines for the availability of the overall system. Thus, CCHP integration to a grid-fed data center provided higher reliability and availability for the overall system for even 2N redundant topology data centers.

Financially, CCHP and other additional system investments require long-term evaluation. When the data center's residual heat is recovered and the CCHP-PV-based data center is integrated into the regional energy network with optimized scheduling, the return on investment (ROI) could be in 5.9 years. As a new approach for data center-related literature, we combined reliability assessment and LCC analysis to provide an effective method for quantifying the cost and reliability benefits of alternative energy system integration in data centers. Based on the life-cycle cost (LCC) analysis, integrating CCHP systems into data centers has a promising outcome. However, when conducting an LCC analysis, we recommend considering the realistic cost of downtime along with the reliability-related exposure to properly assess the viability of alternative energy systems by data center investors and operators.

In addition to the above, this study enables a detailed assessment of the alternative energy system use in the data centers. It provides a technical, environmental, and economic analysis as it is stated in Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. The proposed system reduces Greenhouse Gas Protocols (GHG) Scope-2 emissions associated with the grid electricity consumption of data center and residential buildings. The study also serves the Sustainable Development Goals determined by United Nations such as sustainable cities and communities, affordable and clean energy, and responsible consumption and production.

Chapter 8

Future Work

Due to environmental concerns, it is important for the future to be able to meet the energy needs of data centers with on-site carbon-neutral energy sources. In this way, the power demanded from the electricity grid will be reduced, and the operating conditions of the grid will be improved. In addition, making data centers work together with district heating and cooling networks as thermal energy is also very valuable in terms of energy efficiency. With these applications, carbon emission values will be reduced both on the data center and the grid side. Because of the gains that can be achieved, the use of alternative energy systems based on hydrogen and data center energy management with multi-objective optimization are areas that need to be studied for the future.

Data center-related reliability and availability studies mainly focus on design topologies or component performance. However, some operational strategies such as load shedding can be evaluated. While ensuring the service level agreements (SLA) of different loads, load shedding can be utilized for less critical loads. In that way, operational reliability and availability performances can be improved for more critical loads in the data center. In addition, the changes that will occur on the distribution grid side with this load shedding study should also be investigated. These topics can be handled in future research.

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