MODELING THE TRENDS OF EUROPEAN SECONDARY RESOURCE AND REVENUE FLOWS FOR SOLAR E-WASTE, 2030-2050

GÜNEŞ PANELİ E-ATIKLARI İÇİN AVRUPA İKİNCİL KAYNAK VE GELİR AKIŞLARI EĞİLİMLERİNİN MODELLENMESİ, 2030-2050

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ABSTRACT

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Circular economy is a comprehensive strategy for minimizing waste in the long run for developing the economy that aims to benefit the industry, society and the environment. Effective management of solar panel waste is becoming an increasingly important part of the transition to green energy, due to importance of recycling for circularity.

This study was designed to examine the recycling potential of solar panels in terms of the effective management of the revenue obtained from recycling, to observe the changes that will occur with the effect of the price, and to offer economical and environmentally friendly options on the way to the green transition. The study focuses specifically on Europe to observe the projection between 2030 and 2050. The study was divided into two main branches according to management of revenue obtained from the recycling of solar panels as directed to solar industry & other industries. Key sectors for directing revenue were determined and the study was carried out within these sectors. These key sectors are; Construction Industry, Packaging Industry, Health and Medical Industry and Automotive Industry. Within the scope of the study, Vensim PLE, a system dynamics software, was used to create the models and SimaPro, an LCA software, was used to evaluate environmental impacts.

In the analyses, it was determined that solar panel recycling would yield 1.04E+06 dollars in 2030 and 1.53E+09 dollars in 2050 in the minimum scenario which is potentially feasible, and 2.08E+06 dollars in 2030 and 2.10E+13 dollars in 2050 in the maximum scenario which is the most profitable one. Accordingly, it has been determined that the revenue to be obtained in 2030 in the most profitable scenario is 2 times more than the potentially feasible scenario. Using the potentially feasible average price in the analysis of cost avoidance by using secondary resources in lieu of primary resources will provide a total avoided cost of $11.05 million in 2030 and $5.82E+03 million in 2050 for all key sectors. Using the more profitable higher price would avoid total costs of $66.46 million in 2030 and $3.50E+04 million in 2050 for all key sectors. Accordingly, it was determined that the cost avoided in 2030 in the most profitable scenario was approximately 6 times higher than in the potentially feasible scenario.

In LCA analyses, it has been determined that the recycling process generates less emissions than the landfill option, and similarly, organic solar panels generate less emissions than c-Si solar panels, so they are more environmentally friendly for all impact categories.

The data show that the revenue of recycling solar panels is quite high and should be evaluated in line with circular economy practices. Although it is economically favorable to produce monocrystalline solar panels in directing revenue to the solar industry, it would be better to invest in organic solar panels in terms of environment. Other industries can avoid cost by using secondary resources in lieu of primary resources. In this way, the expenses of the industries will be restricted, economic gain will be maximized and a greener approach will be adopted. However, it was determined that there may be fluctuations in prices in the secondary material market due to reasons such as competition. Based on this result it is recommended that states adopt sanctions such as price fixation policy to prevent this. It was determined that the amount of use in secondary resources will also increase when the prices are reduced and fixed after the state intervenes. Accordingly, it is expected that there will be a total increase of approximately 13% in secondary resource use in all key sectors as a result of price fixation.

As a result, the thesis showed the complexity of secondary market. Although this complexity does not make it possible to achieve circularity, circularity can be achieved with more effort in secondary material management.

Keywords: Solar Panel Waste, Circular Economy, System Dynamic, Solar-Panel Recycling, Green Transition, Life Cycle Assessment, Secondary Resource

ÖZET

GÜNEŞ PANELİ E-ATIKLARI İÇİN AVRUPA İKİNCİL KAYNAK VE GELİR AKIŞLARI EĞİLİMLERİNİN MODELLENMESİ, 2030-2050

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Döngüsel ekonomi, endüstriye, topluma ve çevreye fayda sağlamayı amaçlayan ekonomiyi geliştirmek için uzun vadede israfı en aza indirmeye yönelik kapsamlı bir stratejidir. Güneş paneli atıklarının etkin yönetimi, çevresellik için geri dönüşümün önemi nedeniyle yeşil enerjiye geçişin giderek daha önemli bir parçası haline gelmektedir.

Bu çalışma, güneş panellerinin geri dönüşümünden elde edilen gelirin etkin yönetimi açısından geri dönüşüm potansiyelini incelemek, fiyatın etkisiyle oluşacak değişimleri gözlemlemek ve yeşile geçiş yolunda ekonomik ve çevre dostu seçenekler sunmak amacıyla tasarlanmıştır. Çalışma, 2030 ve 2050 yılları arasındaki projeksiyonu gözlemlemek için özellikle Avrupa'ya odaklanmaktadır. Çalışma, güneş enerjisi endüstrisine ve diğer endüstrilere yönelik olarak güneş panellerinin geri dönüşümünden elde edilen gelir yönetimine göre iki ana kola ayrılmıştır. Geliri yönlendirmeye yönelik kilit sektörler belirlenmiş ve bu sektörler içinde çalışma gerçekleştirilmiştir. Bu kilit sektörler; İnşaat Endüstrisi, Ambalaj Endüstrisi, Sağlık ve Medikal Endüstrisi ve Otomotiv Endüstrisidir. Çalışma kapsamında modellerin oluşturulmasında bir sistem dinamiği yazılımı olan Vensim PLE, çevresel etkilerin değerlendirilmesinde ise bir YDA yazılımı olan SimaPro kullanılmıştır.

Yapılan analizlerde potansiyel olarak uygulanabilir olan minimum senaryoda güneş paneli geri dönüşümünün 2030 yılında 1,04E+06 dolar, 2050 yılında ise 1,53E+09 dolar getirisi olacağı, en karlı senaryo olan maksimum senaryoda 2030'da 2,08E+06 dolar ve 2050'de 2,10E+13 dolar getirisi olacağı belirlendi. Buna göre, 2030 yılında en karlı senaryoda elde edilecek gelirin, potansiyel olarak uygulanabilir senaryodan 2 kat fazla olduğu belirlenmiştir. Birincil kaynaklar yerine ikincil kaynaklar kullanılarak maliyetten kaçınma analizinde potansiyel olarak uygulanabilir ortalama fiyatın kullanılması, tüm kilit sektörler için 2030'da 11,05 milyon dolar ve 2050'de 5,82E+03 milyon dolarlık toplam kaçınılmış maliyet sağlayacaktır. Daha karlı olan daha yüksek fiyatı kullanmak, tüm kilit sektörler için 2030'da 66,46 milyon dolar ve 2050'de 3,50E+04 milyon dolarlık toplam maliyetten kaçınılmasını sağlayacaktır. Buna göre, 2030 yılında en karlı senaryoda kaçınılan maliyetin, potansiyel olarak uygulanabilir senaryoya göre yaklaşık 6 kat daha yüksek olduğu belirlenmiştir.

LCA analizlerinde, geri dönüşüm sürecinin çöp depolama seçeneğinden daha az emisyon ürettiği ve benzer şekilde organik güneş panellerinin c-Si güneş panellerinden daha az emisyon ürettiği, dolayısıyla tüm etki kategorileri için daha çevre dostu oldukları belirlenmiştir.

Veriler, güneş panellerinin geri dönüşüm gelirinin oldukça yüksek olduğunu ve döngüsel ekonomi uygulamaları doğrultusunda değerlendirilmesi gerektiğini göstermektedir. Geliri güneş enerjisi endüstrisine yönlendirmede monokristal güneş panelleri üretmek ekonomik olarak uygun olsa da çevre açısından organik güneş panellerine yatırım yapmak daha iyi olacaktır. Diğer endüstriler, birincil kaynaklar yerine ikincil kaynakları kullanarak maliyetten kaçınabilir. Bu sayede sanayilerin giderleri kısıtlanacak, ekonomik kazanç maksimize edilecek ve daha yeşil bir yaklaşım benimsenecektir. Ancak rekabet gibi nedenlerle ikincil malzeme piyasasında fiyatlarda dalgalanmalar olabileceği tespit edilmiştir. Bu sonuca dayanarak, devletlerin bunu önlemek için fiyat sabitleme politikası gibi yaptırımlar benimsemeleri önerilmektedir. Devletin müdahalesi sonrasında fiyatların düşürülüp sabitlenmesiyle ikincil kaynaklardaki kullanım miktarının da artacağı belirlenmiştir. Buna göre, fiyat sabitlemesinin bir sonucu olarak tüm kilit sektörlerde ikincil kaynak kullanımında toplam yaklaşık %13'lük bir artış olması beklenmektedir.

Sonuç olarak, tez ikincil malzeme piyasasının karmaşıklığını ortaya çıkarmıştır. Bu karmaşıklık, döngüselliğin sağlanmasını mümkün kılmasa da, ikincil malzeme yönetiminde daha fazla çabayla döngüsellik sağlanabilir.

Anahtar Kelimeler: Güneş Paneli Atıkları, Döngüsel Ekonomi, Sistem Dinamiği, Güneş Paneli Geri Dönüşümü, Yeşil Geçiş, Yaşam Döngüsü Analizi, İkincil Kaynak

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LIST OF ABBREVIATIONS AND SYMBOLS

ABMs	Agent-Based Models
AC	Alternative Current
ADP	Abiotic Depletion Potential
Ag	Silver
Al	Aluminum
AP	Acidification Potential
CIGS	Copper Indium Gallium Selenide
CLD	Causal Loop Diagramming
CPV	Concentrator Photovoltaics
Cu	Copper
DC	Direct Current
DES	Discrete Event Simulation
EIA	Environmental Impact Assessment
EoL	End-of-Life
EoU	End-of-Use
EP	Eutrophication Potential
EU	European Union
EVA	Ethylene/Vinyl Acetate Copolymer
FRELP	Full Recovery of EoL Photovoltaics
GW	Giga Watt
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IMF	International Monetary Fund

IOTs	Input-Output Tables
IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LGRF	Laminated Glass Recycling Facility
LNG	Liquefied Natural Gas
MJ	Mega Joules
MWh	Mega Watt hour
ODP	Ozone Depletion Potential
OECD	Organization for Economic Co-operation and Development
OPV	Organic Photovoltaic Cells
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
QDSC	Quantum Dot Solar Cell
R&D	Research and Development
SAGE	Semi-Automatic Ground Environment
Sb	Antimony
SD	System Dynamics
TPT	Topotecan Hydrochloride
UNEP	United Nations Environment Programme
V	Volt

1. INTRODUCTION

This section provides a brief overview of the worldwide solar PV installation projection, the importance of solar panels and their recycling, and the correct management of the revenue obtained from recycling. Additionally, the purpose, importance and scope of the study are presented.

1.1. General Overview

A renewable energy source that is generated from the sun is solar energy. Solar energy is converted into electricity using solar panel devices. Solar panels usually consist of photovoltaic (PV) cells and use sunlight to generate electricity. According to IRENA statistics, solar photovoltaic panels are the most promising energy source, able to meet around 60% of the world's existing electricity consumption. As shown in Figure 1, projections indicate that the production of solar PV is expected to rise significantly on a global scale, 1630 GW by 2030 and an enormous 4500 GW by 2050 (IRENA, 2023).

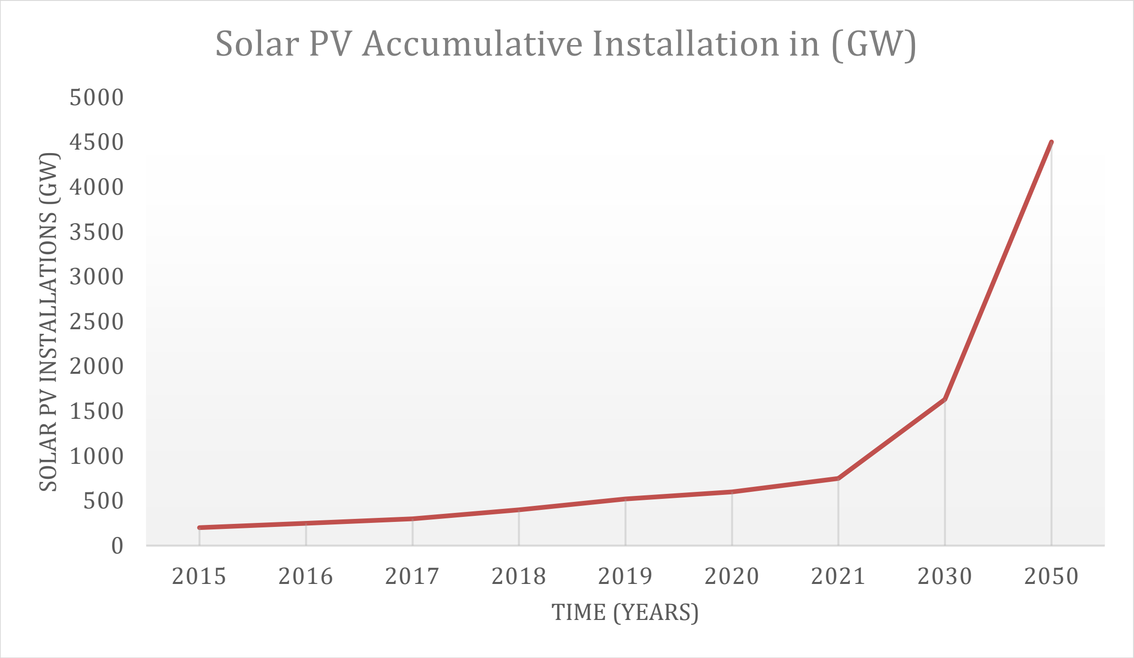

Figure 1. Global solar PV installation projection in 2015 - 2050 (IRENA, 2023)

There are three types of solar panels: 1.generation (crystalline silicon), 2.generation (thin film), and 3.generation (emerging technologies) solar cells.

For many years, silicon solar cells have served as the mainstay of the photovoltaics industry. Monocrystalline silicon panels, which have high durability and efficiency, also have disadvantages such as high initial cost and fragility (Okil et al., 2022). Organic solar cells, which are an important development in solar energy technology, stand out with their use of carbon-based materials. The special properties of these batteries, including their translucency, flexibility, and capacity for low operating temperatures, make them extremely versatile for a wide variety of uses (Machín & Márquez, 2024). Also, its environmental impact is quite low. However, the performance of organic solar cells is lower than the silicon solar cells. The operating life of organic solar cells is also shorter than silicon solar cells. The best organic solar panels last 10 years. This is encouraging but less than the 25-30 year lifetime that has become the norm for conventional solar cells (Du et al., 2019).

1.2. Problem Statement

With the rapidly growing solar energy sector, the correct management of solar panel waste is becoming increasingly important. Solar panels are usually made of a variety of materials, for example, they may contain glass, silicon, aluminum and some rare earth elements. Recycling of these materials requires the right management strategies. Circular economy principles play an important role in recycling solar panel waste and reusing sources. Unfortunately, there is still a gap in the application of these principles. It is necessary to determine and implement correct management strategies. With the correct management of the revenue obtained from recycling solar panels, the right steps will be taken for both the environment and the economy.

Using the revenue obtained from recycling solar panels to produce solar panels again or using secondary resources derived from recycling in other sectors provides significant benefits both economically and environmentally. This approach contributes to reducing costs, preserving natural resources, saving energy and reducing carbon emissions. Additionally, it encourages technological innovations by increasing R&D investments and supports the transition to a circular economy model. Therefore, directing recycling revenues to the solar cell sector or secondary resources to other sectors is of great importance for both the sector and the environment.

The reason why recycling was preferred in the thesis study is that it is assumed that solar panel wastes have completely expired. While methods such as reuse and repair may be effective in some cases, these approaches remain limited due to the technical characteristics and long-lasting structures of solar panels. Recycling reduces the amount of waste produced and the requirement for raw resources by allowing valuable materials to be recovered from waste solar panels and used again in production. In addition, secondary materials obtained during the recycling process can be used as raw materials in other sectors, increasing resource efficiency and contributing to the circular economy. For these reasons, since this thesis aims to examine the management of secondary resources, the recycling option is taken into account.

1.3. Objectives of the Study

This study aims to outline a method for assessing the recycling potential of solar panel waste and to guide the establishment of a waste management strategy aligned with circular economy principles.

The approach in this study took into account the potential revenue from recycling solar panels and reinvesting it in R&D to improve solar panel technology. Additionally, it anticipated the amounts of secondary resources that could be acquired through recycling and projected their total availability in Europe between 2030 and 2050, assessing their potential for use as raw materials in other industries.

1.4. Scope of the Study

The study focuses specifically on Europe to observe the projection between 2030 and 2050. The reason for choosing Europe is related to this region's high emphasis on interest in renewable energy sources and its leadership in this field. The European Union is taking major steps towards its carbon neutrality goals. In line with these goals, investments in clean energy sources such as solar energy are increasing rapidly. However, since the lifetime of solar panels is generally 25-30 years, a huge amount of waste will be generated as a result of these investments. Europe's advanced recycling infrastructure and commitment to environmental sustainability are crucial in ensuring that this waste is recycled effectively. Therefore, examining Europe in this thesis was an ideal choice to obtain meaningful results both economically and environmentally.

The study was divided into two main branches according to management of revenue obtained from the recycling of solar panels as directed to solar industry & other industries. Within the scope of the study, Vensim PLE, a system dynamics software, was used to create the models and SimaPro, an LCA software, was applied to assess the effects on the environment. The reason why system dynamics was preferred in the thesis is that system dynamics has the ability to better model complex and dynamic processes. The recycling process of solar panel waste involves many factors that change over time, such as the growth rate in the amount of waste, the profit from recycling and the potential for use of these materials in different sectors. System dynamics allows analyzing the behavior and interactions of such dynamic systems over time, thus allowing to more accurately predict future scenarios and the effects of policies. In this study, using Vensim PLE software, the changes of different components over time and the effects of these changes on the system were modeled in detail.

In the first scenario, the effect of using the revenue directed to solar energy industries to produce monocrystalline solar panels and organic solar panels was examined. In the second scenario, the economic and environmental impact of supplying and using recycled solar panel waste to various sectors was examined.

A modeling study was conducted as part of the thesis, and the model allowed for the presentation of the analyzed values considering various factors. The results of different effects were evaluated through the model and a comparative analysis was provided. According to the model results, the fact that economic data provided sufficient gains and that environmental data provided values on the way to a green transition for the environment was sufficient to approach the desired circularity and ensure the model.

Although studies such as recycling of solar panels and environmental and economic evaluation of panel types are available in the literature, studies are lacking both in terms of waste management and secondary resource use analysis. This study has carried out an economic and environmental analysis of the recycling of solar panels in the context of circularity and then directing revenue to R&D studies, the solar industries or other industries as secondary resource use.

1.5. Structure of the Study

There are six chapters in total for this thesis. Chapter 1, provides an introduction by presenting a comprehensive review of the research. Chapter 2 gives background information on solar panels, solar energy in Europe, the importance of recycling, circular economy, system dynamics and LCA. In Chapter 3, previous studies in the literature on modeling the circularity of end-of-life (EoL) waste materials in solar photovoltaic (PV) modules are given. Chapter 4 describes collecting and analyzing data to create a model, creating scenarios and performing analyses. Chapter 5 contains the results and discussion, and Chapter 6 presents the final outcomes and recommendations from the research.

2. BACKGROUND INFORMATION

In this section, after giving brief information about solar panels and their recycling, information is given about the solar energy installed capacity in Europe and the expected developments in the solar energy sector in the next years. The impacts of recycling solar panels to the environment, its contribution to the circular economy and green transition, information on primary and secondary resource markets, and the impact of price are detailed. Additionally, the system dynamics and LCA methods used in the study are explained.

2.1. Solar Panels

A solar panel is a device that uses photovoltaic (PV) cells to turn sunlight into electricity. Direct current (DC) electricity is produced when PV cells are exposed to light and flows through the circuit to supply power to various devices or to be stored in batteries.

Conventional solar energy systems consist of a solar panel, a solar controller, and a battery or group of batteries. The arrangement additionally requires an inverter if the output power is 110 V or 220 V (Fig. 2).

The solar panel, which consists of many solar cells connected in series, is the main component of the system. The battery group's job is to store the energy that the solar panel emits so that it is always available to power the load. It is the controller's responsibility to prevent the battery from being overcharged automatically. Converting direct current to alternating current is the function of an inverter (Xu et al., 2018).

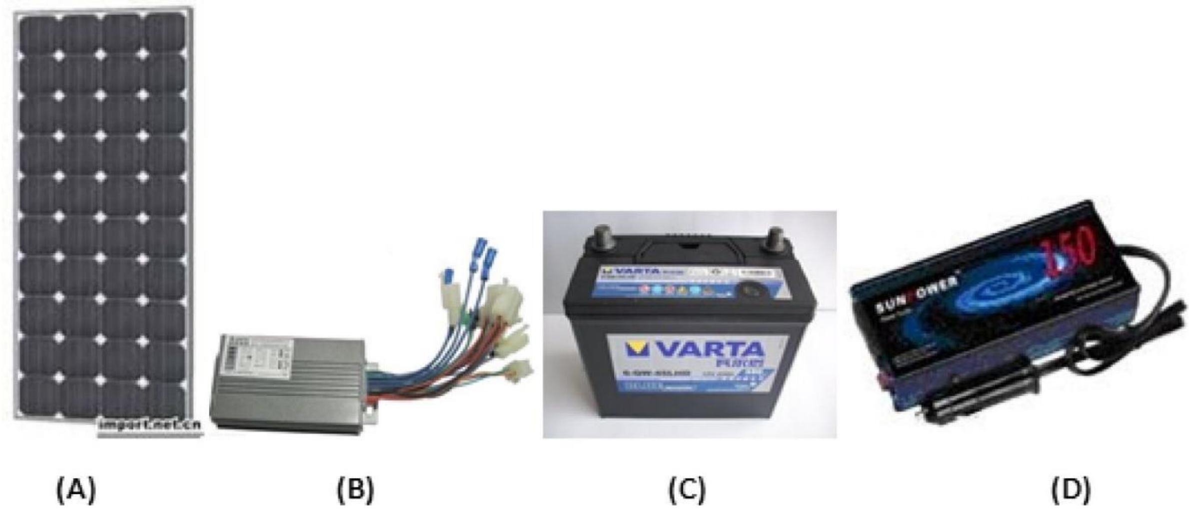

Figure 2. Components of a solar energy system: (A) solar panel, (B) solar controller, (C) battery and (D) inverter (Xu et al., 2018).

There are three types of solar panels: 1.generation (crystalline silicon), 2.generation (thin film), and 3.generation (emerging technologies) solar cells (Figure 3).

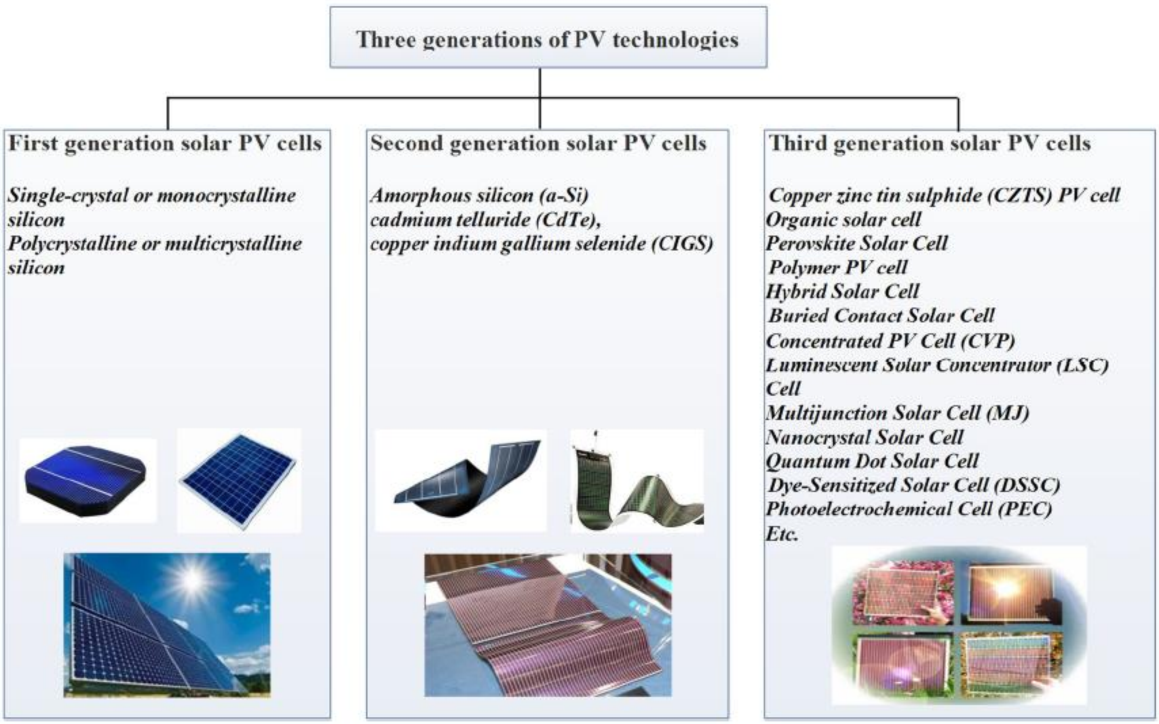

Figure 3. Types of solar panels (Zhang et al., 2018)

A typical panel has a frame made of aluminum (Al), tempered glass, a backsheet made of topotecan hydrochloride (TPT), an EVA (ethylene/vinyl acetate copolymer), and a battery piece made of photovoltaic solar cells. A silicon-based PVM's main components are shown in Figure 4.

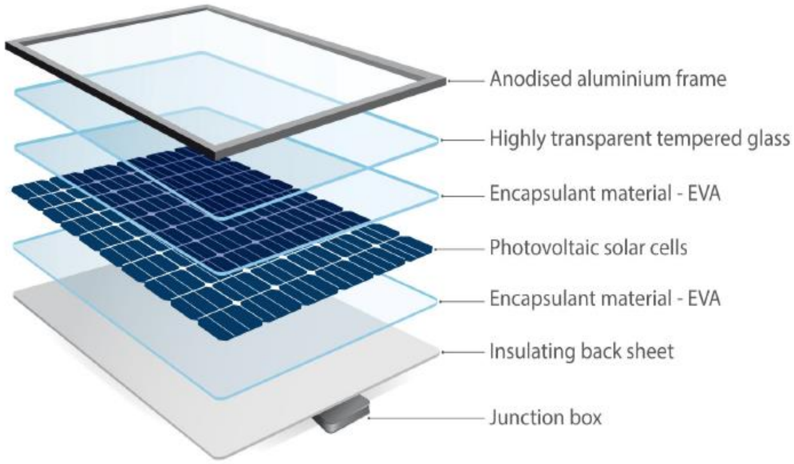

Figure 4. Composition of a photovoltaic module (Tan et al., 2022)

Solar panels offer a guaranteed lifespan of 25-30 years (Sodhi et al., 2022). Recycling of panels at the end of their useful life occurs in the following stages: The physical deconstruction of the solar panel—during which the aluminum frame, junction box, and copper cables are removed—is the first step in the majority of methods for recycling solar panels. The recovery of silicon and metals comes next, followed by the removal or separation of the EVA encapsulant that covers the silicon cell (El-Khawad et al., 2022).

The components of PV panels and content of PV panels after the recycling are described in Table 1 and 2. A range of components are produced by recycling solar panels at the end of their life cycle, including 67% recycled glass, 18% aluminum, 11% plastic, 3% silicon and 1% metals (Ag, Cu) (Máčalová et al., 2021).

Table 1. Composition of a solar-energy system (Xu et al., 2018)

Units	Main Components
Tempered glass	Glass
Battery piece	Silicon, cadmium, selenium, tellerium, gallium, molybdenum, indium, etc.
EVA (ethylene/vinyl-acetate copolymer)	$(C_2H_4)_x$. $(C_4H_6O_2)_y$: chemical properties: general polymer
Backboard	TPT, TPE, etc.
Al alloy frame	97% Al
Junction box	Box body (including copper or plastic terminal), lid, diode, cables, connectors
Silica gel	Highly active adsorption materials, and amorphous material with chemical formula SiO_2. nH_20

Table 2. Composition of crystalline silicon solar panels (Máčalová et al., 2021).

Recyclable material	%
Recycled Glass	67
Aluminum	18
Plastic	11
Silicon	3
Metals (Ag, Cu)	1

After the PV panels have been recycled, the parts that make up the Al frame, the silver grid line, the tin copper wire, and the glass can be processed again to produce new items.

In this thesis, only materials derived from the recycling of solar panel components were examined, and the recycling of other components (e.g. junction boxes, batteries, and inverters) was not taken into account. Materials such as 67% glass, 18% aluminum, 11% plastic, 3% silicon and 1% metal (Ag, Cu) gained from the recycling process are obtained from the solar panel itself. Recycling of other components has not been analyzed within the scope of this thesis.

In the study, the focus is on recycling monocrystalline silicon panels using basic recycling techniques. These methods are expected to yield materials consisting of 67% glass, 18% aluminum, 11% plastic, 3% silicon, and 1% metal (Ag, Cu) (Máčalová et al., 2021). Although more advanced and efficient techniques are available, a basic recycling method was chosen to minimize environmental impacts.

For many years, silicon-based solar cells have served as the mainstay of the photovoltaics sector. The market dominance of silicon in photovoltaics can be traced to multiple important aspects. First off, silicon is easily utilized for the creation of solar cells because it is the second most prevalent material in the Earth's crust. This abundance has played a major role in silicon-based solar cells' broad adoption and scalability. Second, silicon is a perfect material for turning sunlight into electricity because of its semiconductor qualities. The band gap maximizes energy conversion efficiency by absorbing a broad range of the solar spectrum. Monocrystalline silicon cells, which have a uniform crystal structure and are known for their excellent efficiency, are becoming increasingly more common in high-performance applications. However, although they have a marginally lower efficiency, polycrystalline silicon cells, which are composed of many silicon crystals, provide a more affordable option. Monocrystalline silicon panels, which have high durability and efficiency, also have disadvantages such as high initial cost and brittleness (Okil et al., 2022).

A significant advancement in solar energy technology, organic photovoltaic cells (OPVs) are distinguished by their use of carbon-based materials. OPVs are different from conventional inorganic solar cells in that these materials, which include polymers and tiny molecules, are essentially organic semiconductors. These materials' special qualities, which include their translucency, flexibility, and capacity for low processing temperatures, make them extremely versatile for a wide range of uses (Machín & Márquez, 2024). Because transparent devices can be made with efficiency and absorbers accessible in any color, OPV may be very appealing to the building-integrated PV market.

The roll-to-roll manufacturing method is essential for maximizing the possibility of producing OPVs at a reasonable cost. Compared to conventional silicon cell production processes, this technique—which prints photovoltaic components onto flexible substrates—uses less energy and is more economical. Although roll-to-roll production reduces costs, production costs for organic solar cells can still be high because the technology is not fully mature and large-scale production is limited. This production technique enables continuous and highly efficient production of PV modules and diversifies the number of applications due to their flexibility.

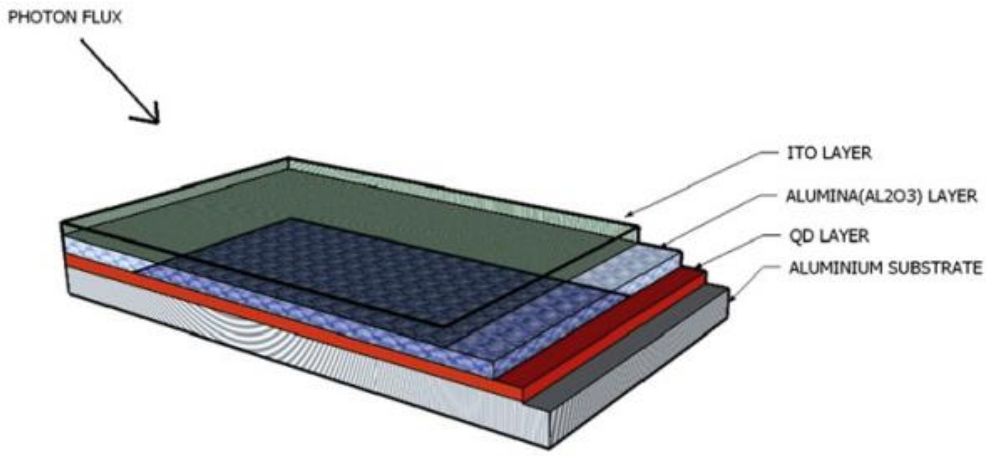

Figure 5. An example of a QDSC design configuration adapted to roll-to-roll production using an aluminum substrate (Şengül & Theis, 2011)

Figure 5 shows an example of a quantum dot solar cell design configuration optimized for roll-to-roll manufacturing on an aluminum substrate. Other flexible substrates can be used in place of aluminum foil as the substrate, lowering the GWP (Şengül & Theis, 2011).

Organic solar panels have many advantages. These are the low weight and flexibility of PV modules, ease of integration into other products, offering new market opportunities due to design features such as flexible solar modules, low environmental impact and short energy payback periods. However, the performance of organic solar cells is lower than the performance of silicon-based solar cells. The operating life of organic solar cells is also shorter than silicon-based solar cells. The best organic solar panels last 10 years, which is encouraging but less than the 25-30 year lifetimes that have become the norm for conventional solar cells. This is an important area of research and development needed (Du et al., 2019).

2.2. Techniques for Solar-Panel Recycling

Solar panels can be recycled in a number of ways. The majority of them entail some or all of the procedures mentioned below (Chowdhury et al., 2020) (Radziemska et al., 2008) (Rahman et al., 2021) (Punathil et al., 2021):

- Removing the frame and junction box from the module;
- Separating the laminated construction from the encapsulant;
- Glass panel and c-Si cells being separated by mechanical, chemical, or thermal methods;
- Essential metals (such as silver, copper, tin, aluminum, and lead) and c-Si cells are extracted and purified using chemical and electrical methods (Bošnjakovic et al., 2023) .

2.3. Solar Power in Europe

Solar energy distribution entered a new growth phase in 2022 as a result of rising energy costs, stable supply chains, and post-epidemic recovery initiatives. 239 GW of new solar energy capacity were successfully added to the grid in 2022 (SolarPower Europe, 2023).

By 2030, Europe's need for solar energy is predicted to increase significantly. According to SolarPower Europe, the amount of solar installations in Europe is increasing quickly; in 2023 alone, a record 56 GW of additional capacity will be added. By the end of 2023, Europe's installed solar capacity amounted to 263 GW, a 27% increase from 2022. It is necessary to install 70 GW of annual average solar energy capacity by 2030 in order to satisfy the renewable energy targets set by the European Union (SolarPower Europe, 2023).

In reaction to the challenges posed by Russia's invasion of Ukraine and the disruptions in the global energy market, the European Commission is implementing its REPowerEU Plan. REPowerEU, which was established in May 2022, supports the EU's efforts to reduce energy consumption, produce renewable energy, and diversify its energy supply. According to the Medium Scenario and the High Scenario, the total solar fleet in the EU is expected to be 920 GW and 1,184 GW, respectively. Both scenarios far exceed the 750 GW of solar energy goal established by the EU Commission's REPowerEU initiative for the year 2030 (SolarPower Europe, 2022).

In 2022, the European Union added 41.4 GW of solar energy, at the top of all previous records. The increased capacity replaces 102 LNG tankers and is equal to the energy requirements of 12.4 million homes in Europe. From 28.1 GW in 2021, the EU's yearly solar growth climbed by 47%.

The EU's total solar generation fleet expanded from 167.5 GW in 2021 to 208.9 GW in one year, a 25% increase. Other types, such as rooftop solar for parking lots that now allow direct EV charging, building-integrated systems, and floating solar, are gaining traction.

The total solar fleet in the EU will grow from the 209 GW deployed at the end of 2022 to roughly 400 GW in 2025 and 920 GW in 2030, according to the medium scenario's long-term perspective. (Figure 6)

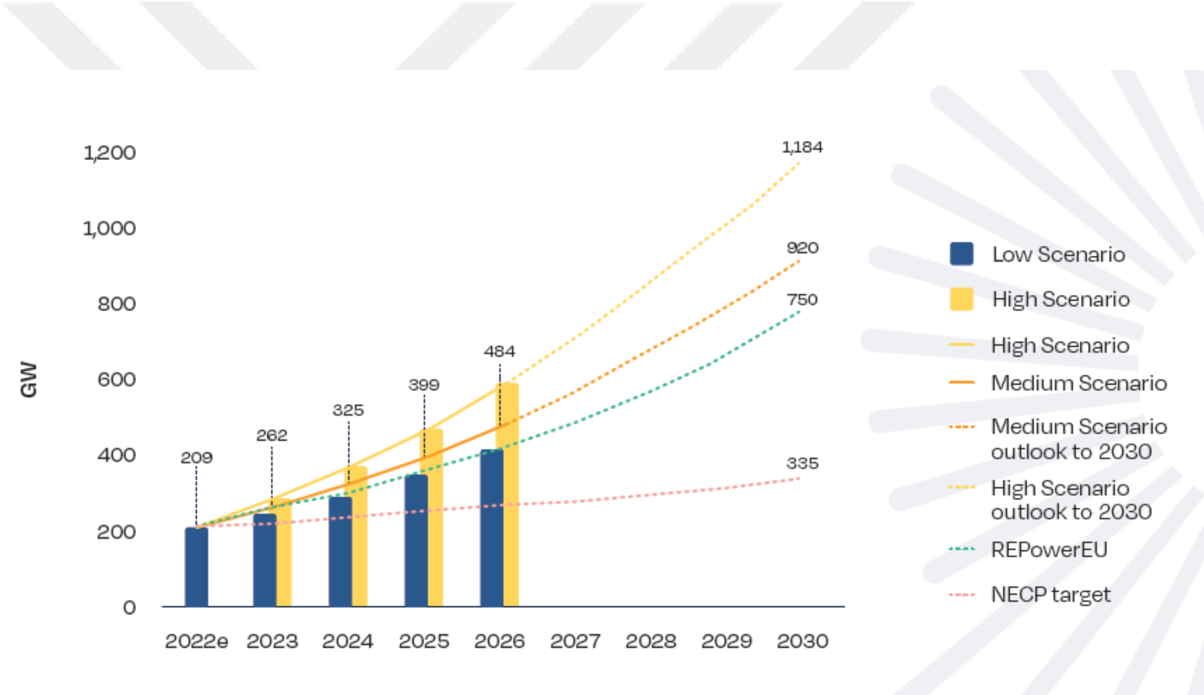

Figure 6. EU27 total solar PV market scenarios 2022 – 2030 (SolarPower Europe, 2022).

The levelized cost of electricity for solar energy increased in 2022 for the first time in more than ten years as a result of substantial supply chain interruptions brought on by the war in Ukraine, ongoing COVID-19 effects, and inflationary pressure. This does not, however, pose a problem for cost competitiveness because solar PV is still far less expensive than new fossil fuels and nuclear.

IRENA's report states that global average solar energy costs in 2020 are approximately $48/MWh, and by 2030 these costs may drop to $20/MWh or lower (IRENA, 2021).

The SolarPower Europe report predicts that the levelized cost of electricity of solar power in Europe will fall to the range of €14-€24/MWh (approximately $15-$26/MWh) by 2030 (SolarPower Europe, 2022).

Turkey's Share in European Solar Energy

Electrical energy consumption in Turkey decreased by 0.2% in 2023 compared to the previous year, reaching 330.3 billion kWh, and electricity production decreased by 0.6% compared to the previous year, reaching 326.3 billion kWh (T.R. Energy and Natural Resources Ministry, 2024).

In 2023, 36.3% of electricity production will come from coal, 21.4% from natural gas, 19.6% from hydraulic energy, 10.4% from wind, 5.7% from solar, 3% from solar energy. 4% was obtained from geothermal energy and 3.2% from other sources (T.R. Energy Market Regulatory Authority, 2024). Solar energy capacity in Turkey from 2008 to 2023 is given in Figure 7.

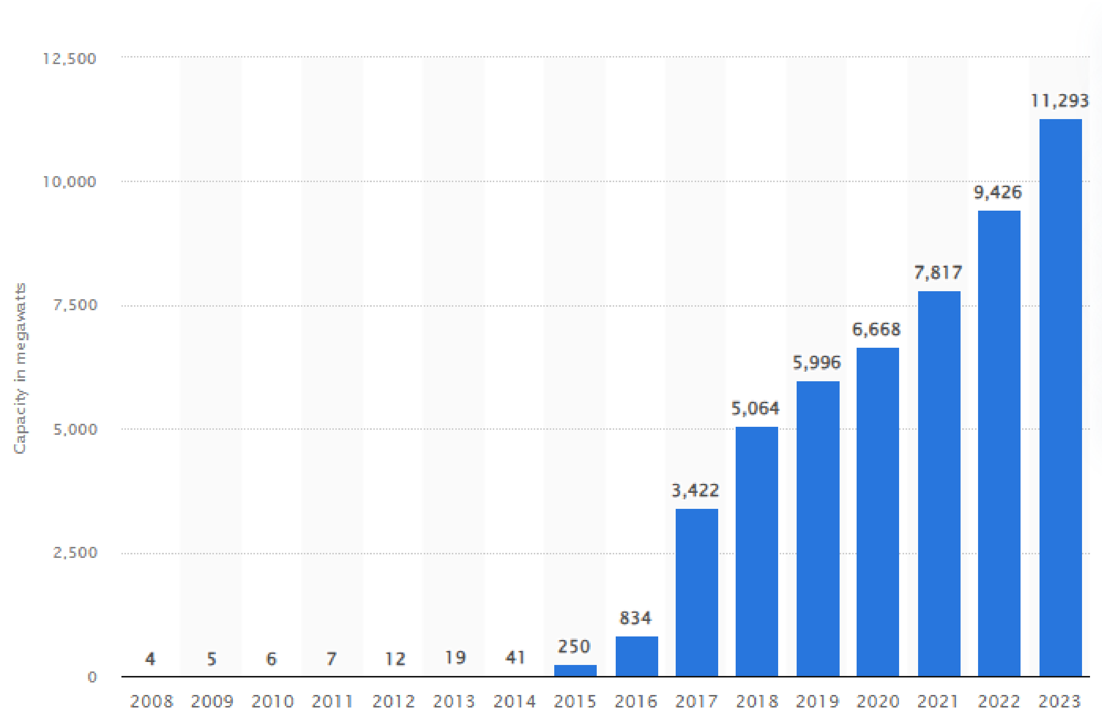

Figure 7. Solar energy capacity in Turkey from 2008 to 2023 (Statista, 2024)

Turkey's solar energy installed power exceeded 12 thousand MW for the first time in February 2024, reaching 12 thousand 425 MW. The share of renewable energy in electricity production was over 51 percent in January and February (T.R. Energy and Natural Resources Ministry, 2024).

Although Turkey's use of solar energy has an important place in Europe, it is not yet at the top in overall European solar energy production. However, Turkey's solar energy capacity and usage has been increasing rapidly in recent years. As of 2022, the share of solar energy in Turkey's total electricity production is 4.7%. This rate lags behind many European countries, which have lower solar potential but a higher share of solar energy in energy production. For example, the Netherlands obtained 14% of its electricity production from solar energy in 2022, and Poland obtained 6.6% from solar energy in the first half of 2023 (Ember, 2023).

Despite its high solar potential, Turkey's solar energy use lags behind countries such as Spain, Greece and Italy, which had a solar energy share of 10% or more in their energy production (Ember, 2023).

2.4. Environmental Impacts of Recycling Solar Panels

Recycling solar panels is advantageous in terms of generating revenue from recycled materials and providing a more economical and environmentally friendly approach by using the materials in other areas. PV module disposal in landfills might result in a large spatial demand and a reduction in the quantity of land that can be used for other purposes. Additionally, improper storage can pollute soil and allow dangerous elements like selenium, cadmium, and lead to seep out of PV components. By recovering valuable materials and lowering the need for raw material extraction, recycling can have a favorable effect on land use. There are also cases where recycling solar panels has negative effects. For example, water can be utilized in huge quantities for material separation, washing, and rinsing during the recycling of PV modules. Also, PV module recycling and disposal may produce a number of contaminants, such as solid waste, gaseous emissions, wastewater, and noise (Abdelkareem et al., 2021).

Therefore, when it comes to circular economy, not only the advantages to be gained from recycling solar panels, but the entire process should be considered (Bošnjakovic et al., 2023).

2.5. Circular Economy

Global resource use increased from 23.7 to 70.1 billion tonnes between 1970 and 2010, driven by changes in consumption patterns, population growth, and the economy (UNEP, 2016). It is anticipated that the pattern of escalating waste production and exploitation of natural resources would continue (UNEP, 2015) (ISWA, 2015).

Unsustainable resource management contributes to environmental degradation, which has a negative influence on fundamental human rights such the rights to life, food, water, and self-determination. It also threatens economic stability (UNEP, 2015).

The circular economy has been suggested as a way to reduce waste production and raw material input. A circular economy is a comprehensive strategy for advancing the economy that is intended to benefit industry, society, and the environment. A circular economy is regenerative by design and seeks to gradually divorce growth from the consumption of scarce resources, in contrast to the 'take-make-waste' linear paradigm. It is founded on three design-driven tenets: eradicating waste and pollution, circulate products and resources at their best value, and regenerating the natural world (Khalifa et al., 2022).

The use of durable materials, reuse/refurbishment, remanufacturing/re-designing of module components, recommissioning of modules for a second life and extending the service life of modules, recycling of post-consumer fabrication scrap are examples of circularity practices for solar panels. It entails the extraction of materials through enhanced module lifespan and efficiency, which produce high value using less material resources. A comprehensive review is needed to fully understand the effects and technological trends of each circularity practice on waste creation and resource depletion, as R&D activities persist in tackling the technological, operational, and economic obstacles of diverse circularity paths (Khalifa et al., 2022).

2.6. The Role of Management of Solar e-Waste in the Green and Circular Transition

In order to make the best use of products and resources, to eliminate waste and pollution and to protect nature, it was evaluated to direct the revenue obtained from the recycling of solar panels or secondary materials to the right areas within the scope of the study.

Within the scope of this study, it was examined whether the revenue obtained from the recycling of solar panels was redirected to the solar sector and directed to the production of conventional monocrystalline solar panels or new technology organic solar panels in support of R&D studies. In addition, it was examined that the secondary materials obtained from the recycling of solar panels were directed to other sectors to reduce expenses and provide a more environmentally friendly approach.

Directing revenues for the circular economy

While revenue can be made by selling the materials obtained from the recycling process, costs can be avoided by using them as raw materials in other industries. How this revenue will be used depends on need and feasibility. Production costs increase when the entrepreneur decides to use green design, choose environmentally friendly materials, or aim for sustainable design, that is, adopt circular economy strategies. Government support and financing of such innovations may be encouraging (Patti, 2023).

Since the Circle Economy Foundation began tracking it in 2018, the worldwide cyclicality rate has gradually decreased, reaching 7.2% in 2023 from 9.1% in 2018. This indicates that we are consuming more raw materials than ever before out of all the resources utilized globally. It demonstrates that less secondary materials are being used (Circle Economy Foundation, 2024). However, the European Union is very successful in circular economy and hundreds of billions of euros can be saved. A circular economy can spur innovation, spending reduction, employment and economic recovery. For this purpose, it is recommended to make adjustments in the legislation, to transform the production processes of companies and to increase cooperation (Patti, 2023).

Primary vs Secondary Resources

Primary resources are unprocessed goods that will serve as raw materials for future final products. Secondary resources are materials resulting from the recycling process that become inputs in a new production. In order to create a greener and less risky economy within the scope of the transition to a circular economy, it is important to use secondary resources in lieu of primary resources in the supply chain. This helps minimize the criticality of the materials to be used and also offers a more economical approach. In addition, obtaining secondary resources from the EoL states of products is an environmentally friendly approach in terms of preventing waste generation (Hackenhaar et al., 2024).

Although primary resource use is currently the most preferred resource use in the world, secondary resource use is also encouraged. In this context, in some cases, there may be competition between primary and secondary resource uses. Different obstacles are encountered in the value chain of secondary resource markets, such as legislation, technology, quality, cost and competition arising from energy use (Mhatre et al., 2023). But all secondary resource markets could potentially benefit from the removal of certain regulatory, economic or technical barriers (European Environment Agency, 2022). Three factors play a key role in the demand for secondary material use including the effect of price, the effect of increase in the use of secondary resources compared to the use of primary resources, the effect of competition between primary & secondary resources, as detailed in the upcoming sections separately.

Additionally, comparing the environmental impacts of primary and secondary material use is an important issue in terms of sustainability. Extraction of primary materials can lead to depletion of natural resources. Resources such as mines, forests and oil are limited. Operations such as mining, logging and oil extraction can cause habitat destruction, soil erosion and water pollution. Processing primary materials often requires high energy, resulting in large amounts of greenhouse gas emissions (Zhang et al., 2022). Secondary materials ensure the conservation of natural resources and reduce natural resource depletion by reusing raw materials. Processing recycled materials generally requires less energy. For example, processing recycled aluminum requires much less energy than primary aluminum. Recycling and reuse reduces the amount of waste and eases the burden on landfills. Less energy requirements mean fewer greenhouse gas emissions, contributing to the fight against climate change (Llamas-Orozco et al., 2023). Although primary resource use is currently the most preferred resource use in the world, secondary resource use is also encouraged circularity.

The effect of price

Extracting primary materials is getting increasingly more difficult. The cost is rising in direct proportion to the energy needs and emissions related to extraction. By 2050, mineral extraction is predicted to supply 40% of the world's energy. Primary materials are becoming more expensive due to rising global demand brought on by population and economic growth worldwide. Therefore, it is predicted that as primary material costs increase, secondary material prices will become more competitive (Renewi, 2023). Typically, secondary materials are less expensive to acquire than primary raw materials. Industries may reduce manufacturing costs and lessen their reliance on finite primary resources by emphasizing the use of secondary materials (Circle Economy Foundation, 2024). In terms of the ecology and finances, it is more favorable. For instance, compared to extracting aluminum from bauxite ore, processing aluminum from recycled cans requires up to 95% less energy (Raabe et al., 2022).

Manufacturers purchase secondary materials produced by reprocessors by quoting prices based on the quality of the materials. Prices may vary significantly depending on the market situation (European Commission, 2022).

In this context, dynamic pricing is applied in the secondary material market. This leads to more stable margins. Depending on the situation, long-term and fixed price sales contracts can be applied (Renewi, 2023).

Changes in interest rates may affect the facilities' interest guarantee agreement and income statement. In order to monitor and manage risk, borrowings and the expected interest cost for the year should be regularly estimated and made sensitive to potential changes. Assuming that supply is elastic and basic costs per unit of output are constant over the relevant output range, the market will not be assumed to be trying to maximize profits in any way during the price-fixing process. When determining the price, average main costs and the prices of other companies producing similar products should be taken into account. One must ensure that the price is not too high compared to other market as this will greatly reduce sales (Kalecki, 2013). For this, the price should be fixed at a reasonable level and the aim should be to provide an advantage in this way.

OECD's report examines the effects of government supports on primary and secondary metal production. The report highlights that the environmental costs of primary production are high and recycling significantly reduces these costs. It is also stated that the use of secondary materials should be encouraged (OECD, 2018).

The effect of increase in the use of secondary resources compared to the use of primary resources

In this section, in order to clarify the effect of the use of secondary resources being preferred over primary resources, information were first be given about the relationship between primary resources markets and secondary resource markets, and then the obstacles to secondary resource markets were mentioned. Primary resource markets are markets where good quality raw materials are supplied. However, primary resource markets cannot be a reference for secondary resource markets. Because secondary resource markets have their own unique characteristics. First of all, they interact with the primary materials market, providing expense prevention as they are obtained by recycling materials considered waste. Like major primary materials markets, the secondary materials market produces a price that is recognized by market operators as a reference for transactions and contracts.

An economic barrier for secondary materials markets is comparing the market structures of the recycling industry and the primary raw materials sector. Businesses that generate the majority of original raw materials typically have an entirely different average size than recycling businesses. The majority of companies in the recycling sector are still family-owned companies, and they frequently lack the financial means or access to capital required to create innovative technological alternatives (European Environment Agency, 2022).

An important factor in the pricing competition between primary and secondary materials is the established perceptions of the stakeholders. For a variety of reasons, stakeholders frequently believe that employing secondary resources in production processes carries greater risk than using primary materials. These include the lack of standardization and supply instability as well as the recession brought on by supply agreements with major producers of raw materials. A reduced willingness to pay for secondary materials in comparison to primary options results from this perceived risk.

Supply and demand proximity

There are major economic barriers to secondary resource markets. Recycled materials are generally not in high demand. Production cost affects the price of raw materials. In contrast, production costs have little impact on the demand for recycled materials. The price of virgin resources is the main determinant of demand for recycled materials. In other words, if the price of virgin material is more expensive than secondary materials, a reason is created to prefer secondary materials. These demand problems in secondary material markets raise serious doubts about the financial sustainability of investments in recycling infrastructure (European Environment Agency, 2022).

The current state of secondary material markets is often deficient, and waste and environmental restrictions could help to improve this. 'Well-functioning' status still requires several conditions to be met. The reason for this is that they cannot maintain the supply-demand balance and their market share is low compared to similar markets based on main materials (European Environment Agency, 2022).

In order to improve secondary material markets, there needs to be more support for knowledge on the different kinds of recycled materials that are available, their qualities and environmental benefits, and producer/consumer options. In the secondary materials market, networking and information-sharing initiatives are going to reinforce the relationship between supply and demand (European Environment Agency, 2022).

Recent studies support the idea that increased competition between sectors may cause prices to rise. For instance, an OECD paper on innovation and competition makes the argument that greater rivalry, particularly in industries with substantial market power, may result in price increases because of the greater expenses related to preserving innovation and competitive advantage (OECD, 2023). Furthermore, while competition reforms are generally good for the long-term health of the economy, the International Monetary Fund (IMF) has found that they can cause short-term price rises as markets adjust to new competitive dynamics (IMF, 2019).

In this case, when there is competition between sectors for secondary resource use within the scope of the study, prices will increase. A key idea in microeconomics is the law of demand, which asserts that quantity requested and price have an inverse relationship. When all else is equal, a good's quantity requested will drop when its price increases and the reverse will occur when its price drops (Jaiswal, 2024). In this case, when prices increase, demand will also decrease. Therefore, the desired circular approach will not be achieved. Interventions by governments and regulators, such as price controls or subsidies, protect consumers by regulating competition between sectors. These interventions affect how prices are set and competition is shaped. As a precursor to these price fluctuations, the use of secondary resources is again encouraged if governments force them to fix prices or use a certain amount of secondary resources. It has been determined that strengthening control and feedback mechanisms, applying state subsidies and strongly supporting businesses that include technological innovations will create a positive effect and discourage businesses from pursuing rent (Li & Rao, 2023). In addition, local governments need to understand the degree and timing of state intervention and establish a reasonable and orderly competition model. The government-led local government should combine the new concept of common development within the scope of the new normal and ensure the formation of a reasonable and orderly local government competition model. Local governments should take into account the situation of local businesses and offer certain supports, such as loan guarantees and other issues, to businesses that make the transition to green energy (Kou & Xu, 2022).

2.7. Green Transition

The "green transition" refers to the process of shifting from an economy and society that rely heavily on fossil fuels and other environmentally damaging practices to one that is sustainable, low-carbon, and environmentally friendly. This transition encompasses various sectors and activities, including energy production, transportation, industry, agriculture, and urban planning.

The following policies can be put into place for green transition (Kemp & Never, 2017):

- In sector policy: using regulations or economic incentives, removing barriers to the development of system innovations, and formulating long-term goals and visions to guide research and innovation;
- In science policy: use of sustainability assessments of system innovations, retrospective evaluation, and transition path mapping;
- In innovation policy: forming innovation alliances, stepping up R&D programs for sustainable technologies, conducting transition experiments, and coordinating innovation policies with environmental policies.

In a study, it was determined that investors' willingness to pay increased by increasing the promotion of solar photovoltaic tiles to be used in the transition to green energy, the government providing financial support for project construction, and encouraging the use of commercial income (Tan et al., 2023).

2.8. Life Cycle Assessment

Every phase of a product's life cycle can be assessed and measured using the Life Cycle Analysis (LCA) technique. The ISO standards 14040 and 14044 outline the steps of a life cycle assessment (Bjorn et al., 2020).

A Life Cycle Assessment Consists Of 4 Steps:

- Definition of Goal and Scope
- Inventory Analysis
- Impact Assessment
- Interpretation

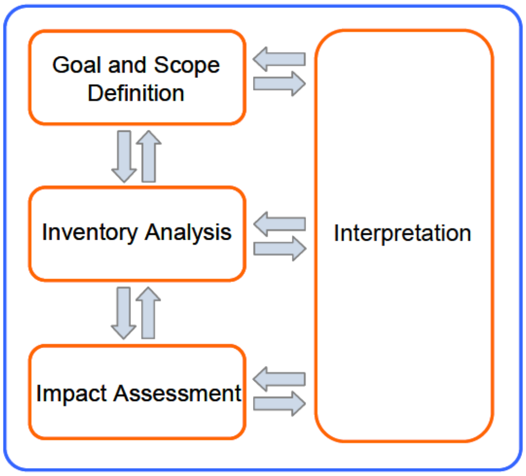

Figure 8. The methodological framework for LCA (ISO 14040, 2006)

1. Goal and scope definition

While establishing the scope entails defining the system limits and level of detail, defining the aim entails determining the purpose of the LCA research, the target audience, and the intended application.

2. Inventory analysis

The life cycle inventory analysis (LCI) phase, which is the second stage of LCA, involves inventorying the input and output data of the system being studied in order to gather the information required to accomplish the study's goals. A few examples of potential data sources are measurements made on the production site, databases that are currently in use, and bibliographic searches.

3. Impact assessment

Life cycle impact assessment, or LCIA, is the third step of life cycle assessment (LCA) that aims to convert the results of LCI into pertinent environmental consequences, including effects on the environment, human health, and natural resource usage.

The two required procedures in the effect assessment phase are characterization and classification. Putting LCI results into impact categories is the first step in classifying them. A set of scientific parameters is used in the characterization process to determine the possible impact of each emission or resource use. Normalization and weighting, the final two LCIA procedures, are optional. By normalizing estimated effects by the total affects in a region or nation during a specific time period, for example, one can put them in the proper context. By giving each consequence a value, weighting enables decision makers to express which effects are most significant to them. As a result, effects are combined into a single environmental impact number, which can help in decision-making, especially when contrasting various options according to various standards (Hauschild & Huijbregts, Life Cycle Impact Assessment, 2015).

There are several LCIA approaches that can be used. Their selection of indicators, effect categories they address, and geographic emphasis may vary. It depends on the circumstances of each instance which LCIA methodology is best.

4. Interpretation

The life cycle interpretation step of the LCA process involves summarizing and debating the findings of an LCI and LCIA in order to provide a foundation for conclusions, suggestions, and decision-making based on the definition of purpose and scope (Hauschild et al., Life cycle assessment, 2018).

In Life Cycle Analysis (LCA), impact categories are used to classify and quantify the various environmental impacts associated with the different stages of a product's life cycle. These categories help in assessing the overall environmental performance of products, processes, or services. Here are some common impact categories and their descriptions:

- ***Global Warming Potential (GWP) / Climate Change:*** Measures the potential impact on global warming by quantifying greenhouse gas emissions. Expressed in terms of equivalent kilograms of CO_2 (CO_2e).
- ***Ozone Depletion Potential (ODP):*** Assesses the potential impact on the stratospheric ozone layer, which protects life on Earth from harmful ultraviolet radiation. Expressed in terms of equivalent kilograms of CFC-11.
- ***Acidification Potential (AP):*** Measures the potential for acidifying substances to affect terrestrial and aquatic ecosystems. Expressed in terms of equivalent kilograms of sulfur dioxide (SO_2).

- ***Eutrophication Potential (EP):*** Evaluates the potential for nutrient enrichment in aquatic environments, leading to excessive plant growth and oxygen depletion. Expressed in terms of equivalent kilograms of phosphate (PO_4^{3-}).
- ***Photochemical Ozone Creation Potential (POCP) / Smog Formation:*** Measures the potential for ground-level ozone formation, which can harm human health and vegetation. Expressed in terms of equivalent kilograms of ethylene (C_2H_4).
- ***Human Toxicity Potential (HTP):*** Assesses the potential impact of toxic substances on human health. Can be divided into carcinogenic and non-carcinogenic effects. Expressed in terms of equivalent kilograms of 1,4-dichlorobenzene (1,4-DCB).
- ***Ecotoxicity Potential:*** Evaluates the potential impact of toxic substances on ecosystems. Often divided into freshwater, marine, and terrestrial ecotoxicity. Expressed in terms of equivalent kilograms of 1,4-dichlorobenzene (1,4-DCB).
- ***Resource Depletion***
- ***Abiotic Depletion Potential (ADP):*** Measures the depletion of non-living (abiotic) resources, such as minerals and fossil fuels. Often expressed in terms of equivalent kilograms of antimony (Sb) for minerals and MJ for fossil fuels.
- ***Biotic Resource Depletion:*** Evaluates the depletion of living (biotic) resources, such as forests and fish stocks.
- ***Land Use:*** Assesses the impact on land use, including changes in land cover, land occupation, and transformation. Can affect biodiversity and ecosystem services.
- ***Water Use:*** Evaluates the consumption of freshwater resources. Considers both the quantity and quality of water used and potential impacts on water scarcity (Hauschild et al., Life cycle assessment, 2018).

The main impact categories affected in the life cycle analysis of solar panels are: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Human Toxicity Potential (HTP), Ecotoxicity Potential, Resource Depletion (Abiotic and Biotic), Land Use, and Water Use.

Within the scope of the study, the environmental impact of recycling solar panels, c-Si solar panels and organic solar panels was evaluated. In this way, the study included environmental evaluation as well as economic evaluation and had the foundations of the circular approach.

In a research conducted; It has been determined that monocrystalline solar panels require more energy consumption during their production. It was determined that organic solar panels can be produced with low energy consumption. The research revealed that more greenhouse gas emissions occur during the production of monocrystalline panels. It was determined that the reason for this is that high-purity silicon production processes require intense energy. It was determined that organic solar panels cause less greenhouse gas emissions during production processes. In particular, low-temperature processing and the use of lightweight materials have been shown to reduce environmental impacts (Muteri et al., 2020).

In a research conducted, a life cycle assessment case study comparing two types of organic photovoltaic technologies (PCBMdcb and FTOinkjet) and silicon solar panels is presented. The results showed that the energy payback time of the organic photovoltaic cell was 0.21 years (75 days), compared to 2.7 and 2.2 years of m-Si and a-Si, respectively. It was determined that the required minimum lifespan of organic cells should be between 1.2 and 8.9 years in order for their effects to be no worse than those of a-Si over 25 years. Effects were found to be higher for silicon-based solar cells in all effect categories compared to the OPV cells presented in this study. Default OPV effects were observed to be 93.0% lower on average compared to the worst performing silicon cell. The effects of OPV cells using inkjet printing for FTO deposition and DCB during PCBM fabrication have been observed to be on average 97% and 92% lower, respectively, than silicon-based cells (Tsang et al., 2015).

In a comprehensive life cycle assessment (LCA) conducted in Australia, three different end-of-life scenarios were considered for PV panels: landfill, recycling by laminated glass recycling facility (LGRF), and full recovery of EoL photovoltaics (FRELP). The study found that recycling technologies, particularly full recovery, reduce the overall environmental impact significantly. For instance, CO2 emissions were reduced from 0.059 kg CO2 per kWh (landfill) to 0.046 kg CO2 per kWh (FRELP) (Singh et al., 2021). A study on end-of-life (EoL) photovoltaic modules found that recycling materials can reduce carbon emissions by approximately 50% compared to using primary materials.

This is because the energy required to process recycled materials is generally lower than that needed for extracting and processing raw materials (Deng et al., 2023) (Chen et al., 2024).

2.9. Complex Systems Theory

In this section, complex systems theory, which is the subject of the creation and operation of the model subject to the study, is explained. A model was created using complex systems theory and the data obtained within the scope of the study was output. Numerous components that are capable of interacting with one another make up complex systems. Such a system is often best represented as a network, with junctions serving as components and connecting their interactions. Systems that have dependencies, rivalries, relationships, or other kinds of interactions between its components, or between a particular system and its surroundings, make them challenging to model in terms of behavior.

The simulation is either discrete or continuous, depending on how the system variables evolve over time. A simulation is deemed continuous if the values of the variables that establish the state of the system fluctuate continuously across time. Discrete simulations are defined as those in which the values of the variables that establish the state of the system vary at specific times.

2.9.1. Discrete Event Simulation

Discrete event simulation (DES) simulates how a system might function over time as a (discrete) series of occurrences. Every event happens at a certain point in time and denotes a shift in the system's state. Since it is expected that there are no system changes in between events, the simulation time can leap straight to the next event's occurrence time, also known as the next event's time advance (Robinson, 2014).

Chronological event steps are the definition of system operation in discrete event simulation. Every event happens all of a sudden and signals a shift in the system's status.

It is not necessary for discrete event simulations to replicate every time interval. With discrete event simulation, the simulation's state is altered in response to an event that happens at a specific time and is maintained there until the next event. Discrete event simulation is different from continuous simulation in this regard. In continuous simulation, the simulation time is divided into time periods, and the simulation continuously observes the dynamics of the system and updates the state of the system based on the activity sets that occur in each time period (Matloff, 2009).

2.9.2. Agent Based Modeling

A type of computer models known as agent-based models (ABMs) simulates the behaviors and interactions of autonomous agents, which are individual or collective entities like groups or organizations, in order to assess how their behaviors affect the system as a whole. It incorporates aspects of evolutionary programming, game theory, complex systems, emergence, sociology of computation, and multi-agent systems. Randomness is introduced by the use of Monte Carlo methods (Helbing, 2012).

A subset of microcelluit models known as agent-based models simulates the concurrent actions and interactions of several agents in an effort to replicate and forecast the occurrence of complex events. From lower (micro) levels to larger (macro) levels, the process takes place. Thus, the idea that complex behavior is produced by simple norms of conduct is crucial to take into account (Bonabeau, 2002).

2.9.3. System Dynamics

System Dynamics (SD) is an approach to large-scale complicated engineering problems that goes beyond the scope of typical systems approaches. By fusing ideas like stock, flow, feedback, and delays, SD captures the dynamic component of a system and deals with how different aspects interact over time, giving insight into the system's dynamic behavior. Systems design is a branch of systems engineering and systems analysis that makes sense as a body of knowledge. SD specifically takes into account the system's feedback and delays that cause dynamic behavior (Yi et al., 2023).

There are two primary system principles that form the foundation of System Dynamics. The first is that system behavior is determined by stocks, flows, and delays. Limitations on rationality are the second. System dynamics concentrates on the variables that are crucial to the problem and its context, or the "environment" as defined by the analyst, rather than attempting to handle every variable in the problem (Kim, 1999).

The father of system dynamics, Jay W. Forrester, oversaw Division 6 at Lincoln Laboratory, which created the computers for North America's SAGE (Semi-Automatic Ground Environment) air defense system. One well-known illustration of a large-scale intricate engineering system is SAGE. Forrester's "systems thinking" has been greatly influenced by his vast experience overseeing research projects on complicated engineering systems under his direction.

The foundation of system dynamics (SD) is feedback control theory. SD makes use of a variety of control mechanisms, including delay times and feedback loops, to monitor system behavior and trends (Victor & Vijay, 2001).

The fundamental building blocks of complex system dynamics are stocks and flows. A basic idea in differential equations, calculus, and other modeling paradigms is state variables and the rates at which they change. Any resource pool within a system is referred to as a stock. Changes in these levels are called flows. Variables, such as flow rate or maximum quantity of stock, are modifiable aspects of the system that impact stocks and flows. Critical systems thinking skills include being able to identify these stocks, flows, and other variables and comprehend how they function (Arnold & Wade, 2015).

It has been said that both the system dynamics approach and the agent-based simulation are appropriate for modeling nonlinear systems. However, the system dynamics approach breaks the system down into smaller subsystems and looks at the relationships between the system's variables, whereas the agent-based simulation models the relationships between the system's individual entities. By modeling individual variables in agent-based simulation, behavioral variations amongst agents can be investigated. In contrast to agent-based simulation, which focuses primarily on environmental adaption and experience-based learning, system dynamics aims to modify the system's state through feedback.

While causal relationships and feedback mechanisms are at the forefront in system dynamics, there is no feedback priority in discrete event simulation. While discrete event simulation offers an analytical perspective, system dynamics offers a holistic perspective. For all these reasons, it was decided to use the System Dynamics approach in this study. Many software can be used when modeling with the System Dynamics approach. Some of them are Vensim PLE, Stella Software, AnyLogic. Vensim PLE software was used in this study.

Vensim PLE

Ventana Systems is the developer of the simulation program Vensim. It is mostly capable of supporting agent-based modeling and discrete events, but it also enables continuous simulation (system dynamics).

In Vensim PLE, stocks are used. Ratio integration or accumulation is how stocks alter in value. This implies that even if rates fluctuate periodically, stock values vary continuously over time. Flows, or rates, are what affect stock values. Another name for stocks is accumulations, levels, or state variables (Garcia, 2023).

Figure 9. Stock icon representation for Vensim PLE software

Flows: Accumulations are complemented by flows. These are varying flows that fill or empty accumulations by providing material flow.

The direction in which material can flow is indicated by the single arrowhead on Flow (which can only increase Stock). This is merely a graphic; the equation determines the direction in which material can flow in a simulation model. Nonetheless, we can determine whether the flow will be unidirectional or bidirectional using the diagram (Vensim Help, 2024).

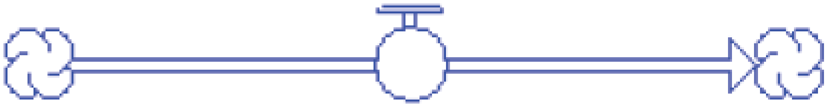

Figure 10. Flow diagram representation for Vensim PLE software

Causal Loop Diagramming (CLD): Because each link has a causal interpretation, causal loop diagrams get their name. Diagrams of causal loops are a great tool for explaining and understanding concepts. When two or more variables influence one another, either directly or indirectly, a feedback loop is created (Reumers et al., 2022).

3. PREVIOUS STUDIES

Previous studies in the literature on modeling the circularity of end-of-life (EoL) waste materials in solar photovoltaic (PV) modules are given in Table 3. Previous studies are examined in the table under the categories of Main Goal and Scope, Target System, Causal Connection, Simulation Software, Geographical Scale, Time Period, Conclusion and Missing Points.

Although studies such as recycling of solar panels and environmental and economic evaluation of panel types are available in the literature, studies are lacking both in terms of waste management and secondary resource use analysis. This study has carried out an economic and environmental analysis of the recycling of solar panels in the context of circularity and then directing revenue to R&D studies, the solar industries or other industries as secondary resource use. This study provides originality especially in the analysis of secondary resource use and regulation of secondary market fluctuations with price fixation policy. By incorporating policy adjustments and secondary material management, the thesis offers a novel contribution with a more comprehensive perspective on how to enhance the sustainability of photovoltaic technologies and reduce their environmental impact.

The studies in Table 3 are briefly described below.

The effects of design, operation, and features of end-of-life (EOL) waste paths on material circularity in silicon solar photovoltaic (PV) modules were examined by Khalifa et al. The study found that reusing old modules has minimal impact on the waste stream, but dedicated PV recycling and component remanufacturing are the most successful circularity solutions for waste minimization (Khalifa et al., 2021).

A study by Salim et al. presents the creation of a System Dynamics (SD) model based on the circular economy concept for the management of EoL rooftop PV panels. Based on the study's findings, the implementation of shared responsibility has yielded equitable outcomes throughout all the domains analyzed, encompassing the consequences on the payback period and the outcomes of collection and recovery (Salim H. K. et al., 2021).

Xin-gang et al. builds a system dynamics model to investigate the effects of R&D expenditures on China's solar energy manufacturing sector. This study generally focused on the photovoltaic industry, and the environmental impacts of the PV industry were not sufficiently taken into account. Additionally, the study does not cover the waste PV industry (Xin-gang et al., 2021).

The cumulative energy consumption, carbon footprint, water footprint, and life cycle cost of residential grid-connected (GC) and stand-alone (SA) solar PV systems were assessed by Ren et al. This study does not cover the waste PV industry (Ren et al., 2020).

Salim H. et al. conducted a study to better understand the challenges associated with management of residential solar photovoltaic (PV) and battery energy storage systems (BESS) near the end of their useful lives. In this study, residential solar photovoltaic (PV) and battery energy storage systems (BESS) were studied in PV waste management, and the environmental impacts of non-residential panels were not adequately evaluated (Salim H. et al., 2020).

Zhang et al. conducted a study to examine the impact of a subsidy policy on the comprehensive economic feasibility of waste module recycling and determine a reasonable subsidy scheme. This study generally focused on the economics of the photovoltaic waste panel industry in China, and the environmental impacts of the PV industry have not been sufficiently taken into account (Zhang et al., 2022).

A study by Marcuzzo et al. describes how the end-of-life (EoL) photovoltaic solar panels (PVSP) can present a financial opportunity for the recovery and disposal of their primary components. The 5 most significant nations were the focus of this investigation. Although this represents a major advancement in terms of total PV capacity, other industrialized and developing nations that may experience difficulties disposing of their PVSP in the near future ought to adopt it as well (Marcuzzo et al., 2022).

A study by Ovaitt et al. uses current reliability data, PV ICE, an open-source Python tool that follows module material flows throughout PV life cycles, provides dynamic baselines encapsulating PV module and material changes for this study. The junction box, remaining system components, processing materials and further PV technologies are not included in the foundations utilized in this work; only c-Si materials included (Ovaitt et al., 2022).

In a study conducted by Mathur et al., the model calculated the environmental impacts in terms of Global Warming Potential (GWP) using a System Dynamics (SD) model under various recovery scenarios. However, it is important to note that this study does not encompass the use of secondary materials (Mathur et al., 2023).

Table 3. Summary of previous studies on the circularity of waste solar panels

Study No	Reference	Main Goal And Scope	Target System	Causal Connection	Simulation Software	Geographical Scale	Time Period	Conclusion	Missing Points
1	(Khalifa et al., 2021)	This article studies the impacts of design, operational, and end-of-life (EOL) waste pathways' characteristics on material circularity in silicon solar photovoltaic (PV) modules.	Circular economy	Relationship between bifacial modules and various module design trends including thinner glass sheets and lighter frames - amount of PV waste.	-	United States of America	100 years (from 2000 to 2100)	It finds out that the characteristics that have the biggest effects on waste reduction and resource conservation are module efficiency and reliability. Reusing obsolete modules had minimal impact on the waste stream, but dedicated PV recycling and component remanufacturing were determined to be the most successful circularity solutions for waste minimization.	The study does not cover the secondary material utilization.
2	(Salim H. K. et al., 2021)	The creation of a System Dynamics (SD) model based on the circular economy concept for the management of EoL rooftop PV panels is presented in this study.	Circular economy	Four scenarios: (1) market-driven growth, (2) conservative development, (3) shared responsibility, and (4) disruptive change to business as usual. Scenario analysis results: (a) collection	Vensim DSS	South Australia	49 years (from 2001 to 2050)	According to the study's conclusion, shared responsibility has produced balanced results in all areas examined, including the effects on the payback period and the results of collection and	While this study solely assumed intrinsic material recovery growth limits in the four transition routes, future research should take into account the dynamics

Study No	Reference	Main Goal And Scope	Target System	Causal Connection	Simulation Software	Geographical Scale	Time Period	Conclusion	Missing Points
				rate, (b) collection rate, (c) total material recovered, (d) waste storage in landfill, (e) payback period, and (f) number of residences with PV.				recovery. Even though the disruptive change pathway has the best performance, by 2050 it is expected to reduce PV adoption by 7.3%.	surrounding material recovery growth and its economic aspects.
3	(Xin-gang et al., 2021)	In order to investigate the effects of R&D spending on China's solar power production sector, this paper builds a system dynamics model. It also examines the effects of other incentive programs, including the Feed-in Tariff (FIT), on the photovoltaic sector.	Economy	Three scenarios: The impact of FIT price on the photovoltaic power generation industry, the impact of R&D investment in the photovoltaic power generation industry, and the impact of comprehensive scenarios on the photovoltaic power generation industry.	Vensim PLE	China	-	The findings indicate that: firstly, FIT and R&D expenditure support China's photovoltaic power generation industry's technological improvement. Second, the photovoltaic power business can experience additional cost reductions with more research and development investment. At last, it is clearer how FIT encourages the industry for solar power generation to increase its installed capacity.	This study generally focused on the photovoltaic industry, and the environmental impacts of the PV industry were not sufficiently taken into account. Additionally, the study does not cover the waste PV industry.
4	(Ren et al., 2020)	The cumulative energy consumption, carbon footprint, water footprint, and life cycle cost of residential grid-	Circular economy	Residential grid-connected (GC) and stand-alone (SA) solar PV systems	Vensim DSS	A residential prototype house in Boston	-	The greatest economic and environmental benefits of GC system design occur when no battery is installed,	The study does not cover the waste PV industry.

Study No	Reference	Main Goal And Scope	Target System	Causal Connection	Simulation Software	Geographical Scale	Time Period	Conclusion	Missing Points
		connected (GC) and stand-alone (SA) solar PV systems were assessed in this work by combining system dynamics modeling with life cycle assessment and life cycle cost evaluation.		- evaluate cumulative energy demand, carbon footprint, water footprint and life cycle cost				and these benefits rise with the size of the panel. There will be trade-offs when it comes to installing batteries to store extra energy, too, such as when there are governmental restrictions like grid sales limitations or limits.	
5	(Salim H. et al., 2020)	The purpose of this study was to better understand the challenges associated with maintaining residential solar photovoltaic (PV) and battery energy storage systems (BESS) near the end of their useful lives (EoL) in order to facilitate decision-making that minimizes unfavorable effects on the product life cycle.	Circular economy	The developed causal loop diagram (CLD) was categorized into three subsystems: (1) waste flows; (2) regulatory aspects; and (3) industry strategies and government incentives. When looking at CLD, two main system archetypes were identified; fixes that fail and drifting goals.	-	Australia	-	The feedback loops that were found point to the necessity of implementing a thorough national product management strategy, enforcing complementing landfill regulations, and offering sufficient incentives to businesses in order to promote recovery efforts in the residential PV panel and BESS sectors.	In this study, residential solar photovoltaic (PV) and battery energy storage systems (BESS) were studied in PV waste management, and the environmental impacts of non-residential panels were not adequately evaluated.
6	(Zhang et al., 2022)	The purpose of this article is to investigate the impact of a subsidy policy on the comprehensive	Economy	Simulating the dynamic evolution of return on investment, recovery rate and subsidy cost of recycling under	-	China	In the next 10 ~30 years.	According to the findings, recycling has a low comprehensive cost economic feasibility in its early	This study generally focused on the economics of the photovoltaic

Study No	Reference	Main Goal And Scope	Target System	Causal Connection	Simulation Software	Geographical Scale	Time Period	Conclusion	Missing Points
		economic feasibility of waste module recycling and determine a reasonable subsidy scheme.		different scenarios to clarify the impact of different factors such as learning rate, transportation distance, buyback price, subsidy and subsidy reduction				phases (before 2026), necessitating the necessity for subsidy policies that promote and direct recycling.	waste panel industry in China, and the environmental impacts of the PV industry have not been sufficiently taken into account.
7	(Marcuzzo et al., 2022)	The article clarifies how the end-of-life (EoL) photovoltaic solar panels (PVSP) can present a financial opportunity for the recovery and disposal of their primary components.	Circular economy	Result comparison for recycling materials by 2030 and 2050 for 5 countries result comparison for PVSP (Photovoltaic Solar Panels) a EoL and PVSP in landfills by 2050	-	China, Germany, Japan, United States of America, and India	-	When photovoltaic equipment's typical service life extends to 40 years, the amounts that need to be recycled will decrease as PVSP (S1)'s service life grows. However, the introduction of stringent laws requiring recycling (such as S2 and S3) indicated that there was more material available for recycling.	The 5 most significant nations were the focus of this investigation. Other industrialized and developing nations that may experience difficulties disposing of their PVSP in the near future ought to adopt it as well.
8	(Ovaitt et al., 2022)	Retired module circular selections help cut waste and balance the use of virgin resources. Using current reliability data, PV ICE, an open-source	Circular economy	Relationship between evolving module technology and material composition fundamentals – economics	PV ICE: Photovoltaics in the Circular Economy Tool	United States of America	by 2050	The findings demonstrate that production savings, which account for more than 20% of the 9 million tonnes of trash predicted overall	The study does not cover the secondary material utilization and policy adjustments.

Study No	Reference	Main Goal And Scope	Target System	Causal Connection	Simulation Software	Geographical Scale	Time Period	Conclusion	Missing Points
		Python tool that follows module material flows throughout PV life cycles, provides dynamic baselines encapsulating PV module and material changes for this study.						by 2050, have a significant impact on material demand. The greatest ways to cut waste by 56% while keeping installed capacity are through circular pathways and reliability. Modules with a shorter lifespan generate 81% more waste and 6% less capacity in 2050.	
9	(Mathur et al., 2023)	The aim of this project is to develop an Integrated Model to evaluate the end-of-life recovery pathways of Solar Photovoltaic (PV) panels. This model combines the Material Recovery Hierarchy and System Dynamics (SD) approaches to understand the environmental impacts of recovery processes.	Circular economy	The SD model takes into account the c-Si PVs' increasing demand, lifespan, and ensuing EoU phase. The model's output, which is based on the idea of MRH, is the net GWP (kg CO2 eq) for the years 2016–2050 under various EoU treatment paths.	AnyLogic	-	2016–2050	The model calculated the environmental impacts in terms of GWP (Global Warming Potential) using the SD Model under varying recovery scenarios. As predicted, the largest GWP impacts are caused by landfilling, however over the next several years, the recovery of EoU PVs has the potential to substantially decrease GWP impacts.	The study does not cover the secondary material utilization.

4. METHODOLOGY

In this section, data sources, the structure of the thesis and the methodology followed step by step are explained.

The steps of this study are explained below:

Step 1 – Techno-economic assessment: Techno-economic assessment includes the evaluation of the current disposal of solar panel waste and the recommendations presented within the scope of this study.

Step 2 - Developing scenarios: It includes 2 separate scenarios in terms of evaluating the income obtained from recycling solar panel waste.

Step 3 - Data collection: It includes the collection and compilation of the necessary data for the scenarios to be modeled.

Step 4 - Scenario modeling: It includes the modeling and interpretation of the scenarios in Vensim PLE, a System Dynamics software.

Step 5 - Environmental Impact Assessment: It includes the use of SimaPro, an LCA software, for the environmental assessment of the EoL management of solar panels.

Step 6 - Evaluation of results: It includes evaluation and interpretation of model results obtained from Vensim PLE and SimaPro software.

The flowchart of the methodology is schematized in the flowchart given in Figure 11.

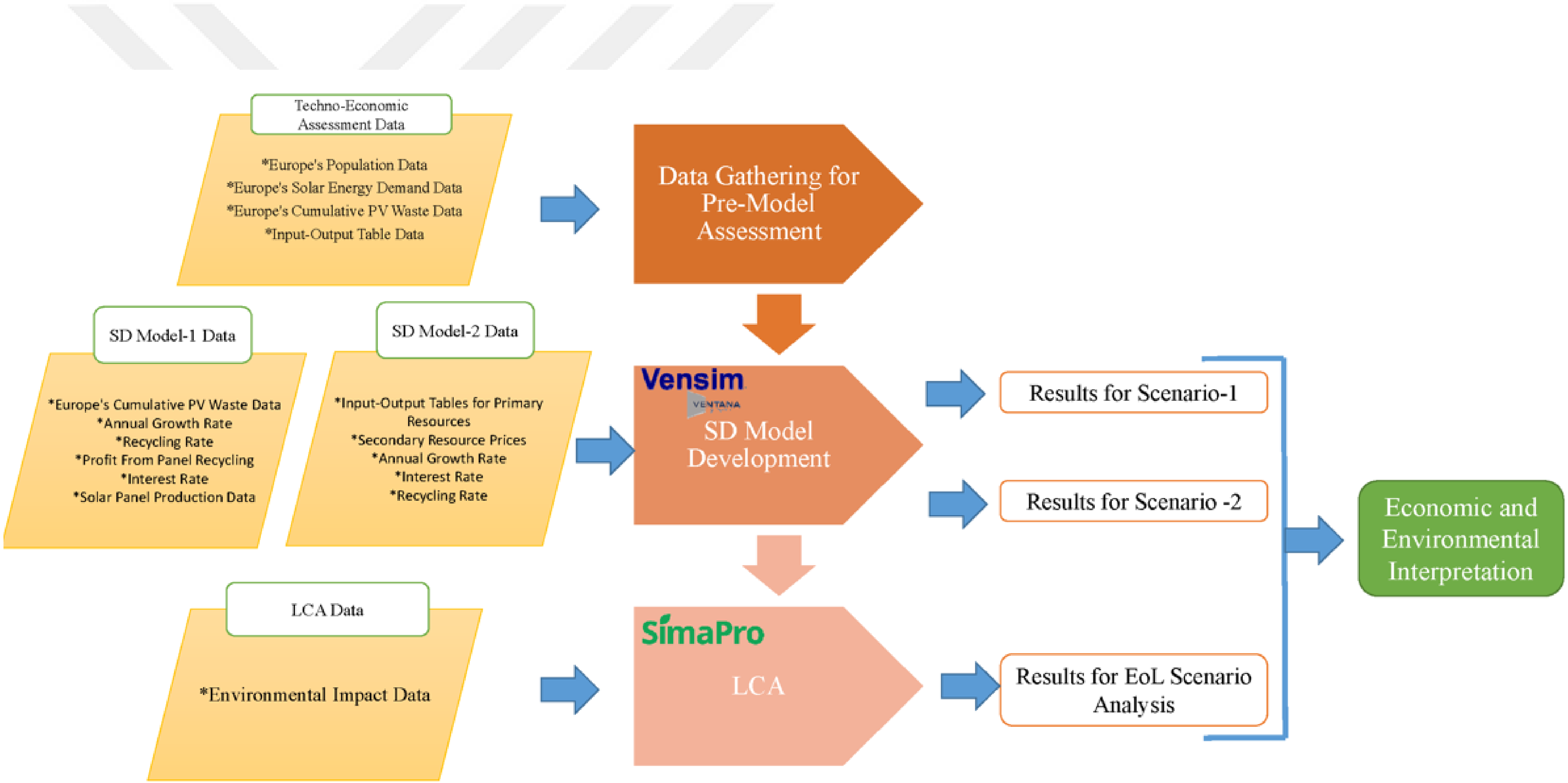

Figure 11. Methodology Flowchart of the Study

4.1. Techno-Economic Assessment

A preliminary assessment was conducted as part of the techno-economic evaluation, the first stage of this project, to ensure sure that the revenue generated from recycling solar panel waste could be contributed to beneficial use in industries.

Recycling is a unique method for receiving disposal of waste from solar panels that has benefits including recovering precious materials and minimizing environmental effects, but it also comes with significant prices and technological infrastructure requirements. While reuse extends the life of the panels and saves on new production costs, it also includes difficulties such as limited market and demand. Although landfill offers the advantage of low technological requirements and short-term low cost, it faces long-term environmental damage and regulatory compliance problems. Special disposal facilities, on the other hand, offer the potential to use advanced technology and minimize environmental impact, but require high initial and operating costs. This assessment reveals important technological and economic factors that will help determine the most appropriate method for the disposal of solar panel waste (IRENA, 2016).

According to United Nations (UN) population projections, Europe's population is expected to remain more or less stable or increase slightly by 2030. According to the World Population Expectations report published by the UN in 2022, the population of Europe is predicted to be approximately 736,574 million in 2030 (United Nations, 2022).

According to the REPowerEU Plan, in the medium scenario, Europe's solar energy fleet in 2030 will reach 920 GW (SolarPower Europe, 2022).

In this context, analysis were carried out in Europe between 2030 and 2050. Based on data from IRENA (International Renewable Energy Agency), Europe is expected to produce roughly 35.5 thousand tons of cumulative waste from c-Si modules and 1.9 thousand tons of waste from thin-film modules by 2030 (IRENA, 2023). Therefore, this value was considered as the main input for the quantity of recyclable solar panels. This value was selected as the baseline input since it is the most credible and realistic data. As a result, the baseline data for 2030 was determined to be 35.5 thousand tons of cumulative waste from c-Si modules and 1.9 thousand tons of waste from thin-film modules.

Input-Output tables were used to analyze the management of secondary resources derived from the recycling of solar panels and their reuse in other sectors.

4.1.1. Input-Output Tables

The amounts of primary resources flowing the sectors under normal conditions were obtained from OECD (Organization for Economic Co-operation and Development) Stat Input-Output Tables (IOTs) 2021 edition data (OECD, 2021).

The transactions between producers and consumers within an economy are depicted by input-output tables (IOTs). These tables illustrate the flows of intermediate and final goods and services, which can be represented either by product outputs (product-by-product tables) or by industry outputs (industry-by-industry tables).

These data were obtained separately for countries in Europe and then their cumulative totals were taken. Figure 12 shows an example of the Input-Output table for Germany.

Dataset: Input-Output Tables (IOTs) 2021 ed.								
Variable	TTL: Total							
Country	DEU: Germany							
Time	2018							
Unit	US Dollar, Millions							
To industry / sector	D01T02:	D03: Fishing and	D05T06: Mining and	D07T08: Mining and	D09: Mining support	D10T12: Food	D13T15: Textiles,	D16: Wood and
From industry / sector								
TTL_01T02: Agriculture, hunting, forestry	3.767,900	1,400	68,900	10,900	0,000	36.525,800	120,700	3.313,500
TTL_03: Fishing and aquaculture	1,900	44,700	0,000	0,000	0,000	491,600	0,100	0,100
TTL_05T06: Mining and quarrying, energy producing products	81,300	0,900	1.914,000	46,000	1,400	1.525,700	184,900	68,800
TTL_07T08: Mining and quarrying, non-energy producing products	43,900	1,000	4,900	110,500	1,300	129,000	4,200	7,700
TTL_09: Mining support service activities	1,600	0,000	115,600	9,100	1,700	4,000	0,200	0,200
TTL_10T12: Food products, beverages and tobacco	3.584,000	1,600	22,600	8,600	0,100	28.041,100	126,300	53,500
TTL_13T15: Textiles, textile products, leather and footwear	85,100	20,700	1,900	0,600	0,100	132,400	2.333,100	14,600
TTL_16: Wood and products of wood and cork	82,400	0,700	9,000	9,900	0,200	269,500	45,200	5.172,900
TTL_17T18: Paper products and printing	77,900	4,200	17,400	31,000	0,100	4.031,300	531,000	147,700
TTL_19: Coke and refined petroleum products	1.662,200	9,400	111,200	52,300	1,900	527,200	157,000	132,200
TTL_20: Chemical and chemical products	2.556,800	2,700	42,500	23,900	1,800	1.798,300	2.086,700	1.149,800
TTL_21: Pharmaceuticals, medicinal chemical and botanical products	198,200	0,400	7,300	2,500	0,100	443,700	81,500	40,900
TTL_22: Rubber and plastics products	296,900	1,700	12,300	3,700	0,400	2.648,100	508,100	187,300
TTL_23: Other non-metallic								

Figure 12. IOT for Germany (OECD, 2021)

4.2. Development of Model Scenarios

The study was divided into two main branches according to the use of the revenue obtained from the recycling of solar panels: ***revenue directed to solar industries*** & ***revenue directed to other industries***. Recycling solar panels generates revenue, and directing this revenue to the right areas is very important from an environmental and economic perspective. In this context, it was analyzed that the revenue were redirected to the solar sector to produce new solar panels and used in R&D studies to invest in the production of new technology panels. In addition, the effects of using secondary materials derived from the recycling of solar panels as raw materials in other sectors were examined. The effects of price, increase in revenue, competition between primary & secondary resources, increase in the use of secondary resources compared to the use of primary resources and also the environmental effects were analyzed within these main branches are explained below.

4.2.1. Scenario 1: Revenue Directed to Solar Industries

Two alternatives have been identified for the use of revenue directed to solar energy:

Alternative 1: Using the revenue to produce organic solar panels

The entire revenue obtained from the total recyclable solar panels were used in R&D studies, and as a result of these studies, the effects that will occur as a result of increasing the investment in more environmentally friendly and advanced organic solar panels and increasing the use of these panels were analyzed.

Alternative 2: Using the revenue to produce monocrystalline solar panels

The effects of using the entire revenue from total recyclable solar panels in the production of monocrystalline solar panels were analyzed.

The question of whether an innovative strategy or a Business-As-Usual (BAU) approach was more circular was investigated by examining these alternatives.

SD Model-1 of using recycling revenues in solar panel production is given in Figure 13. According to the diagram, as the total recyclable waste increases under the influence of the annual growth rate, the net profit rates to be obtained from panel recycling constitute the total revenue. A flow has been created to direct the revenue to R&D studies or to use it directly in the production of conventional monocrystalline solar panels.

Using the revenue to produce organic solar panels involves directing the entire revenue to R&D studies and then producing organic solar panels. Another option examined in the study is the use of the revenue to produce monocrystalline solar panels, and the transfer of the revenue directly to production was examined.

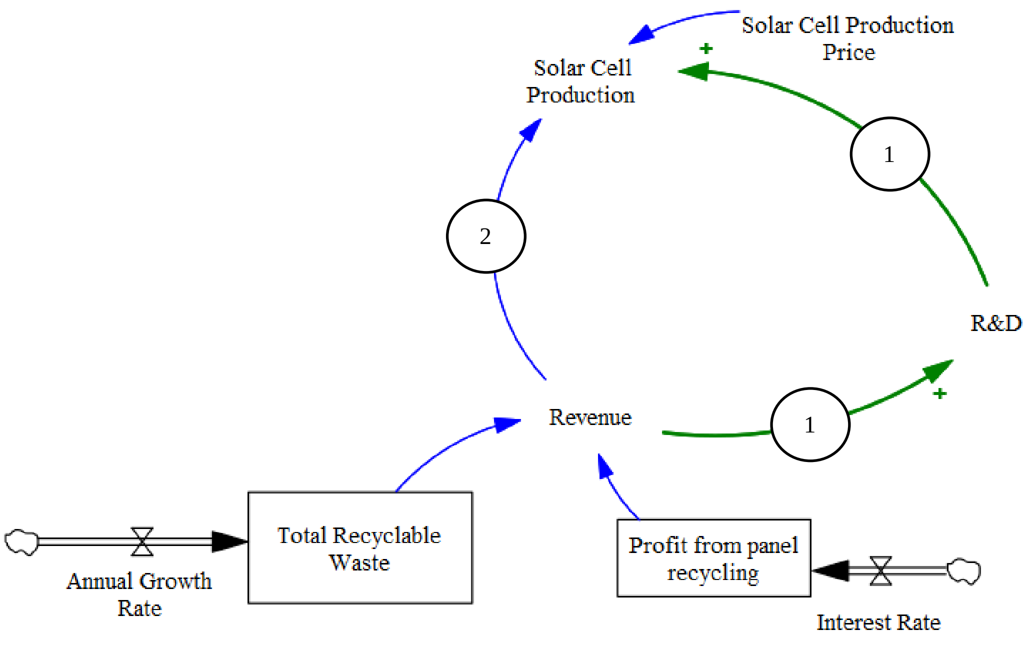

Figure 13. SD Model-1 created in Vensim PLE software for the evaluation of Scenario 1 (Directing the revenue to R&D studies and then producing organic solar panels (1), Directing the revenue to produce monocrystalline solar panels (2))

The input data used in the Scenario 1 model is explained below.

Input Data for Scenario 1: Revenue Directed to Solar Industries

- ✓ **Total Recyclable Waste:** In 2030; 35.5 thousand tons of cumulative waste from c-Si modules + 1.9 thousand tons of waste from thin-film modules = **37.4 thousand tons of total cumulative PV waste** (IRENA, 2023).

  When total cumulative PV waste is multiplied by the recycling rate, total recyclable waste is obtained.

  Total Recyclable Waste = Total Cumulative PV waste * Recycling Rate

- ✓ **Recycling Rate:** Recycling rate was used as a variable in this study. The various recycling rates used in the model are: 0.7 and 0.35.

  According to one estimate, the average global recycling rate of PV modules was 14% in 2019 and could rise to 70% by 2050 (Bošnjakovic et al., 2023) . Because of this, the recycling rate values of 0.35, which is likewise assessed from a pessimistic point of view, and 0.7, which is optimistic but may be possible with sufficient effort, were taken into consideration in this study.

- ✓ **Profit from Panel Recycling:** The profit from recycling a typical solar panel requires accounting for a few expenses. The expenses are categorized into process cost, investment cost, environmental externality cost, equipment cost, recovered metals cost, transportation cost, policy benefit cost, and landfill tipping cost (Preet & Smith, 2024).

  Total cost of PV recycling = ∑ private cost + ∑ external cost - ∑ benefits

  (Equation 1)

  The private cost = Investment cost + Process cost + Transport cost

  (Equation 2)

  In calculating private costs, expenses related to various aspects of the recycling process are taken into account, including investments in tools, materials and electricity required for the operation. Additionally, transportation costs for transporting PV panels to recycling facilities are taken into account.

External costs include environmental damage from the release of pollutants during recycling and vehicles transporting damaged PV panels. The benefit cost to be obtained from recycling solar panels is subtracted from the private costs and external costs. To facilitate a general assessment across Europe in calculating transportation costs, the analysis assumed an average distance of 400 km between waste solar panel collection centers and recycling facilities (Preet & Smith, 2024).

When the cost spent on recycling crystalline silicon PV panels and transportation cost are deducted, a net profit of **1.19 dollars** is obtained per 1 m^2 of crystal recycling (Preet & Smith, 2024). Assuming that a typical 1 square meter solar panel weighs approximately 0.015 tons, it has been determined that the net gain from recycling 1 ton of solar panels will be 79.33 dollars. This net income will increase with ***interest rate*** added each year.

- ✓ **Annual Growth Rate:** Annual growth rate was used as a variable in this study. The various annual growth rates used in the model are: 0.2 and 0.4.

  To indicate the annual growth rate of solar panel waste, the values of 0.2 and 0.4 are utilized as annual growth rates in order to compare the more optimistic scenario with the more reasonable and realistic one.

- ✓ **Interest Rate:** In this study, interest rate was used as a variable. The various interest rates used in the model are: 0.2 and 0.6.

  In order to indicate the interest rate added to the profit to be obtained from the recycling of solar panel waste, the interest rate values of 0.2 and 0.6 are used, similar to the annual growth rate, to evaluate the comparison between the reasonable and realistic scenario and the more optimistic scenario.

- ✓ **Solar Cell Production Price:** Solar panel production price was used as a variable in this study. The various solar panel production prices used in the model are:

Organic Solar Cell Production Price:

Lower Price 2.22E-05 ton organic solar cell production / $

Higher Price 1.33E-05 ton organic solar cell production / $

Monocrystalline Solar Cell Production Price:

Lower Price 3.33E-05 ton monocrystalline solar cell production / $

Higher Price 1.66E-05 ton monocrystalline solar cell production / $

These costs are being used in order to assess that the more optimistic scenario and the reasonable and realistic scenario compare.

Additionally, Sensitivity Analysis was performed for this model study. Within the scope of sensitivity analysis, the annual growth rate value was taken as 1 at the maximum value and 0 at the minimum value, and the change in the results was observed. Since the annual growth rate parameter is one of the most effective parameters on the total recyclable waste solar panel and revenue, the effect of changing this parameter was examined.

4.2.2. Scenario 2: Revenue Directed to Other Industries

The products that will emerge from the recycling of panels are as follows: Aluminum and Steel, Electronic Components, Glass, Plastic, Pure Silicone. When examining the use of revenue in different sectors, it is necessary to determine the key sectors in which recycled materials can be used first. Within the scope of this study, key sectors were determined as Construction Industry, Packaging Industry, Health and Medical Industry and Automotive Industry.

The key sectors selected were the Construction, Packaging, Health and Medical, and Automotive sectors since these industries have the highest demand for the secondary resources produced by recycling solar panels.

Based on the analysis of the data in the Input-Output Tables as aforementioned in ***Section 4.1.1***, Construction, Packaging, Health and Medical, and Automotive sectors seemed to be the industries that utilized materials such as aluminum, glass, and silicon derived from the recycling of solar panels the most, allowing these sectors to be identified as key sectors. It was expected that key sectors with high primary source input flows of these materials would also have significant secondary source input flows of these materials. Although this is a limitation, it was hypothetically accepted as such within the scope of this study.

The final table that was created by gathering information from the Input-Output Tables (IOT) regarding the materials that will be utilized for each industry (Aluminum, Silicone, Glass, etc.) is shown in Table 4.

The data used in the table consists of the sum of European state data. Within the scope of the study, the data in this table was multiplied by the coefficient of 0.03 and the amounts spent for solar panels were calculated with this assumption (Wood Mackenzie, 2021).

Table 4. Sectoral data table for EU (OECD, 2021)

Unit: US Dollar, Millions	**Construction Industry**	**Packaging Industry**	**Health and Medical Industry**	**Automotive Industry**
Aluminum and Steel	2,838.819	299.232	0	1,798.524
Electronic Components	0	0	57.078	614.97
Glass	512.052	195.45	916.545	376.629
Plastic	1,623.543	611.394	135.819	1,316.79
Pure Silicone	3,881.727	0	67.158	238.131

Causal loop diagrams were created in Vensim PLE software to analyze resource flows for each sector. To determine primary resource use by the sectors, were analyzed. In addition, the reuse of secondary resources derived from the recycling of solar panels in sectors were analyzed. Alternative of acquisition of secondary in place of primary materials were considered. Outputs were obtained by running the causal loop diagram in Figure 14 separately for each affected sector (Construction Industry, Packaging Industry, Health and Medical Industry, Automotive Industry).

The input data used in the Scenario 2 model is explained below.

Input Data for Scenario 2: Revenue Directed to Other Industries

- ✓ **Total Recyclable Waste:** In 2030; 35.5 thousand tons of cumulative waste from c-Si modules + 1.9 thousand tons of waste from thin-film modules = **37.4 thousand tons of total cumulative PV waste** (IRENA, 2023).

  When total cumulative PV waste is multiplied by the recycling rate, total recyclable waste is obtained.

  Total Recyclable Waste = Total Cumulative PV waste * Recycling Rate

- ✓ **Secondary Resource Quantity:**

  First, the percentage of materials to be derived from the recycling of solar panels was used to determine the amount of each secondary material that would be obtained in order to compute the quantity of secondary resources.

  The percentage of materials derived from recycled solar panels is as follows: 67% glass, 18% aluminum, 11% plastic, 3% pure silicon and 1% electronic components (Máčalová et al., 2021). These values are the rates that will be derived from the recycling of monocrystalline solar panels that dominate the market. The amount of material in tons for each materials were determined using these rates from the quantity of waste solar panels that recycled.

  Furthermore, the amount of secondary resources that will be allocated to each sector following the recycling of 37,000 tons of solar panel waste was determined. In order to compute the quantity of secondary resources flowing the sectors, a distribution was made in accordance with the percentage rates of the primary resource flows from the Input - Output table of the sectors. In this context, the quantity of secondary resources directed to sectors are given in Table 5.

Table 5. Quantity of secondary resources directed to key sectors for baseline year of 2030

Total of PV waste (tons)	Quantity Directed to Construction Industry (tons)	Quantity Directed to Packaging Industry (tons)	Quantity Directed to Health and Medical Industry (tons)	Quantity Directed to Automotive Industry (tons)
37,400.00	21,391.28	2,671.64	2,841.98	10,495.10

These values were determined for the baseline year of 2030, and as a result of entering the data into the model and including parameters such as annual growth rate and interest rate, the trend was calculated from 2030 to 2050.

- ✓ **Primary Resource Quantity:** The amounts of primary resources flowing the sectors under normal conditions were obtained from OECD (Organization for Economic Co-operation and Development) Stat Input-Output Tables (IOTs) 2021 edition data (OECD, 2021). These data were obtained separately for countries in Europe and then their cumulative totals were taken. The data obtained from the Input-Output tables of the input of each primary resources into the sectors for the countries in Europe are given in **APPENDIX-1**. Additionally, Turkey's share in all of Europe is also given in the appendix tables.

- ✓ **Recycling Rate:** Recycling rate was used as a variable in this study. The recycling rate used in this model is 0.7. The recycling rate value of 0.7 was taken into account in the study's evaluation, which is optimistic but may be possible with sufficient effort.

- ✓ **Secondary Resource Price:** Secondary resource price is taken as $800/ton for Al&Steel, $70.14/ton for Glass, $489.89/ton for plastic, $145/ton for Electronic Components, $350/ton for Silicon. These values are the average values prevailing in the market and have fluctuated in line with the interest rate within the model.

- ✓ **Primary Resource Price:** Primary resource price is taken as 0.002705 million dollars / ton for Al & Steel, 0.000035 million dollars / ton for Glass, 0.001 million dollars / ton for plastic, 0.0005 million dollars / ton for Electronic Components, 0.0011 million dollars / ton for Silicon. These values are the average values prevailing in the market and have fluctuated in line with the interest rate within the model.

- ✓ **Annual Growth Rate:** Annual growth rate was used as a variable in this study. The annual growth rate used in this model is 0.2. The value of 0.2 was used to indicate the annual growth rate, thus aiming to provide a more reasonable and realistic result.

- ✓ **Interest Rate:** In this study, interest rate was used as a variable. The interest rate affecting only primary sources was taken as 5.85 by taking the average of the latest interest rates of European countries (Trading Economics, 2024). The interest rate value of each country used to obtain this average value is given in **APPENDIX-2**. Also, the interest rate affect secondary resource prices was used as 0.2. The reason for using this value is to provide a more reasonable and realistic result.

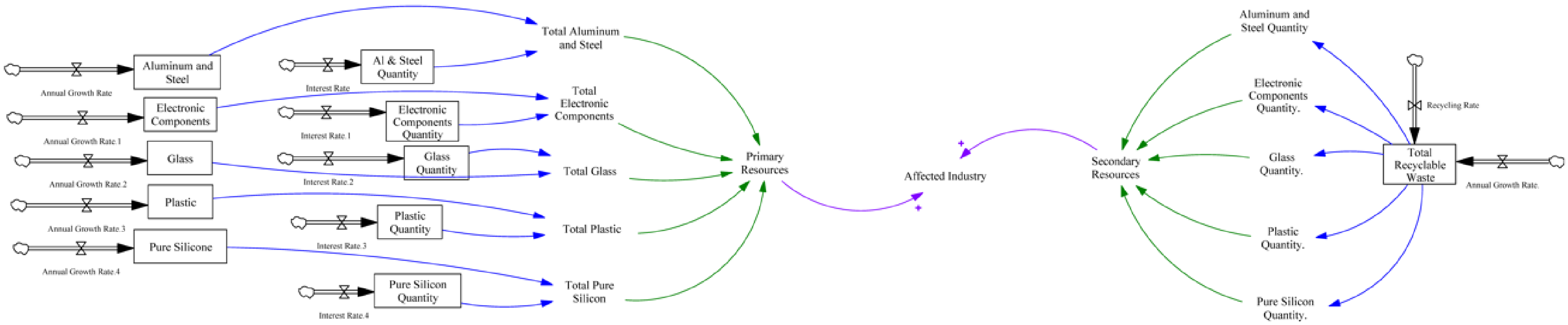

Figure 14. SD Model-2 created in Vensim PLE software for the evaluation of Scenario 2

Four aspects of the system that may affect the outcome was determined. Specific effects were analyzed when considering directing revenue to these sectors:

- The effect of increase in revenue from the solar panel recycling process
- The effect of increase in the use of secondary sources compared to the use of primary resources
- The effect of price
- The effect of competition between primary & secondary resources

The effect of increase in revenue from the solar panel recycling process were affect the new panel production amount in the solar panel industry. It was determined that the higher the revenue provided the higher the production of new panels. The difference between investing the revenue in new technologies such as organic solar panels for use in R&D studies and conventional monocrystalline solar panels was examined.

The effects of increasing the use of secondary resources compared to primary resources include reducing economic costs, protecting natural resources, and saving energy. First of all, the increased use of secondary materials has created many positive effects, such as reducing economic costs, protecting natural resources, saving energy and reducing environmental pollution. At the same time, it is posited that it is an approach that supports long-term environmental and economic sustainability by contributing to sustainable production and consumption models. Therefore, promoting recycling and expanding the use of secondary materials is important for both industrial and environmental policies. Hence, it was determined that these positive effects could be benefited by sanctions to encourage sectors to use secondary resources.

The effect of price on secondary resource markets depends on a variety of factors including the balance of supply and demand, processing costs, raw material market fluctuations, material quality and government policies. Each of these factors play a role in the market prices of recycled materials and contributes to the development of sustainable economic models. Competitive prices of secondary materials provide both economic and environmental benefits and make it easier to achieve circular economy goals.

As a result of the increased use of secondary resources, there has been an increase in secondary resource prices due to the increase in competition between sectors. As a result of this increase, there has been a decrease in the use of secondary resources. Within the scope of this study, the solution offered to prevent price fluctuations in secondary resource markets is that the state increases the demand for secondary resources by fixing the prices of secondary resources. In this context, the effect of the implementation of the solution on fluctuations in secondary resource use was analyzed.

Two methods were used within the scope of the study: System Dynamics (SD) and Life Cycle Assessment (LCA).

4.3. System Dynamics Modeling

System Dynamics offers thorough examination of how components relate to one another and change over time since it is especially good at simulating complicated systems with feedback loops and temporal delays (Yi et al., 2023). Any change in the causal loop variable will eventually have a positive influence on it, according to positive feedback, and the opposite is true according to negative feedback (Forrester, 1961).

The reason why system dynamics was preferred in the thesis is that system dynamics has the ability to better model complex and dynamic processes. The recycling process of solar panel waste involves many factors that change over time, such as the growth rate in the amount of waste, the profit from recycling and the potential for use of these materials in different sectors. System dynamics allows analyzing the behavior and interactions of such dynamic systems over time, thus allowing to more accurately predict future scenarios and the effects of policies. In this study, using Vensim PLE software, the changes of different components over time and the effects of these changes on the system were modeled in detail.

To perform these analyses, two main causal loop diagrams were created in Vensim PLE software. These diagrams cover two main scenarios: directing the revenue from recycling solar panels directly to solar industries and directing it to other industries.

Scenario 1: Revenue directed to solar industries.

In this scenario, it was analyzed that the revenue were used again in the production of monocrystalline solar panels and then used in innovative and environmentally friendly organic solar panels to contribute to R&D studies.

Scenario 2: Revenue directed to other industries

In this scenario, the supply of recycled solar panel waste to various sectors and their use by these sectors were examined.

4.4. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a systematic method used to evaluate the environmental impacts of a product or service. LCA considers each stage of the product's life cycle: raw material extraction, production, distribution, use and final disposal or recycling. SimaPro, an LCA software, was used to evaluate the environmental impacts of the scenarios to be studied within the scope of this study.

Within the scope of the study, the environmental impact of recycling solar panels, c-Si solar panels and organic solar panels was evaluated. In this way, the study included environmental evaluation as well as economic evaluation and had the foundations of the circular approach. In the SimaPro software, 1 kg c-Si solar cell and 1 kg organic solar cell were determined as functional units and their emissions were determined.

Input Data

Landfill

- ✓ Functional unit: 1 kg c-Si solar cell
  - Waste, from silicon wafer production, inorganic {CH}| treatment of, residual material landfill | APOS, S
  - Waste glass {CH}| treatment of, inert material landfill | APOS, S
  - Waste aluminium {CH}| treatment of, sanitary landfill | APOS, S
  - Waste plastic plaster, for final disposal {CH}| treatment of waste plastic plaster, inert material landfill | Conseq, S

c-Si solar panels and organic solar panels

- ✓ Functional unit: 1 kg c-Si solar cell
  - o Photovoltaic laminate, single-Si wafer {GLO}| market for | APOS, S
  - o Glass cullet, sorted {GLO}| market for | APOS, S
  - o Inverter, 0.5kW {GLO}| market for | APOS, S
- ✓ Functional unit: 1 kg organic solar cell

5. RESULTS AND DISCUSSION

In this section, the scenario-based evaluation of the model results and the subsequent LCA analysis are presented. Economic and environmental evaluations were made within the scope of the results obtained.

The results are presented through analyzes made in two scenarios: directing the revenue obtained from recycling solar panels to solar industries and other industries. Evaluations have been made within the scope of certain effects within the framework of these main branches. These effects are as follows; the effect of increase in revenue from the solar panel recycling process, the effect of increase in the use of secondary resources compared to the use of primary resources, the effect of price, the effect of competition between primary & secondary resources.

5.1. Statistical Analysis of Techno-Economic Data

As a result of the analysis of the preliminary evaluations made within the scope of the techno-economic assessment, a projection of population growth and energy demand over the years in Europe was created.

The graph of increasing population and increasing energy demand with population, obtained by adding IRENA and SolarPower Europe data to the model, is given in Figure 15. Accordingly, by 2050, while the population in Europe will reach 739.156 million people, solar energy demand will reach 2,441.03 GW.

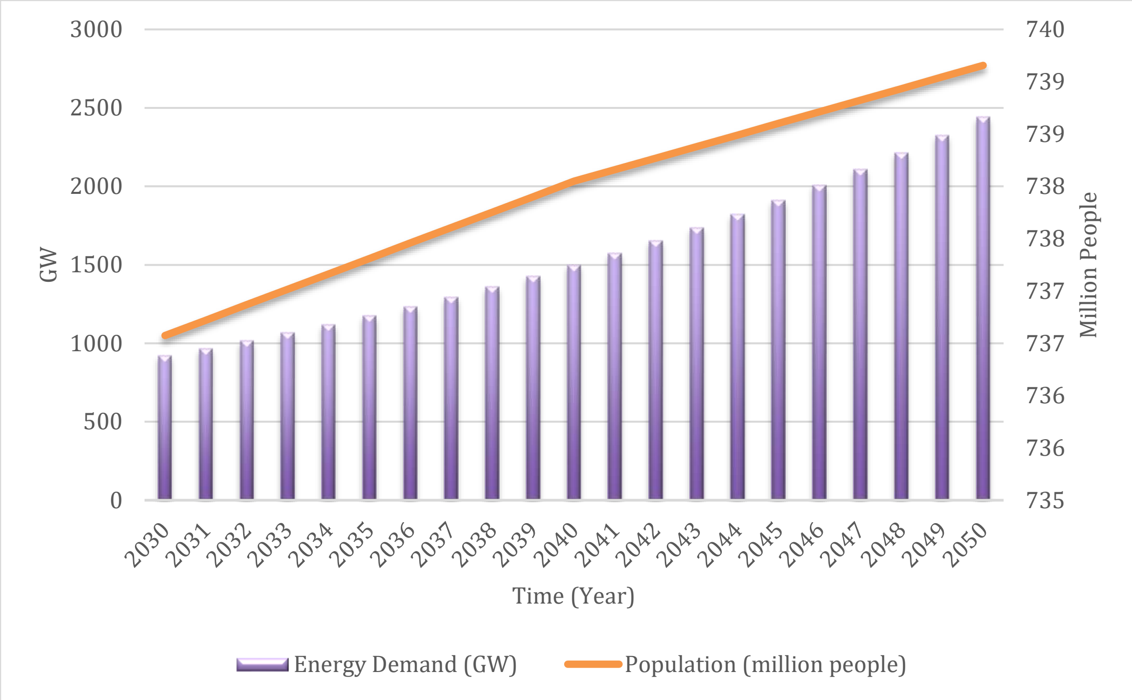

Figure 15. Population and energy demand projection for Europe in 2030-2050

5.1.1. Input-Output Tables Data

The primary resource amounts used in the Construction Industry, Packaging Industry, Health and Medical Industry and Automotive Industry, which were determined as the key sectors where recycled materials can be used, were determined. The amounts of primary resources flowing the sectors in business as usual scenario were obtained from OECD (Organization for Economic Co-operation and Development) Statistical Input-Output Tables (IOTs) 2021 edition data (Table 4).

When the data obtained was entered into the model prepared in Vensim PLE, the change in primary resource use over the years was obtained. In the Business as usual scenario, the use of primary resources in 2030 was obtained to be 2.08E+07 tons in the Construction Industry, 6.31E+06 tons in the Packaging Industry, 2.65E+07 tons in the Health and Medical Industry, and 1.42E+07 tons in the Automotive Industry.

In 2050, it was obtained that the use of primary resources in construction sector was 4.13E+25 tons, in the Packaging Industry was 1.25E+25 tons, in the Health and Medical Industry was 5.26E+25 tons, in the Automotive Industry was 2.81E+25 tons. A total of

6.78E+07 tons of resource use in all sectors in 2030 and 1.35E+26 tons in 2050 has been obtained. Primary resource uses of key sectors are given in **APPENDIX-3** together with the quantity of materials flowing each sector. In addition, the data graph of primary resource use obtained as a result of the model is given in Figure 16.

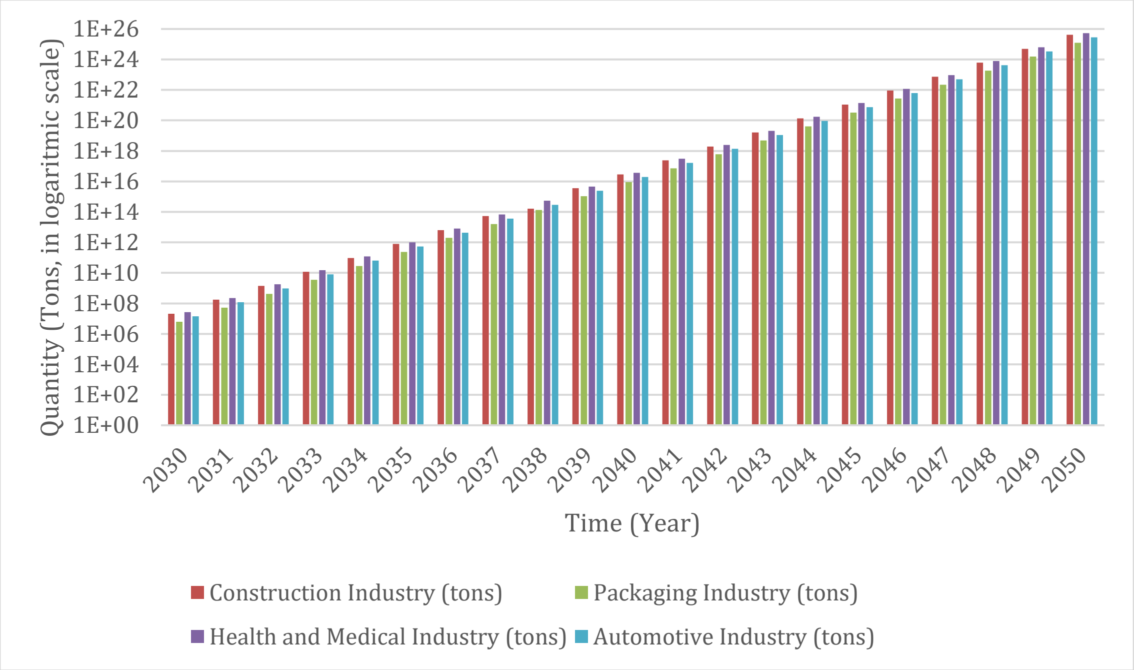

Figure 16. The use of primary resources in the Business as usual scenario for Europe in 2030-2050

5.2. Results of Model Scenarios

The models are developed based on the methodology presented in ***Section 4.2***. Within the scope of the study, two separate main scenarios and impact-based evaluations were made.

5.2.1. Scenario 1: Revenue Directed to Solar Industries

Green Transition and its Effect on Solar Market Diversification Scenario: No Secondary Resources Use

Without considering the effect of secondary materials, running a model for the impact of the green transition is shown in Figure 17 as the increase in waste production and the increase in revenue generated by recycling this waste.

The basis of this scenario is hypothetically based on the examination of the scenario that would emerge as a result of governments introducing new sanctions for the green transition and setting a target to recycle 70% of the waste solar panels that could be produced. Total recyclable waste and the revenue to be obtained are given in **APPENDIX-4**.

The results obtained by running the *SD Model 1* (See Figure 13) based on the input data in Table 6 are given in the graph below.

Table 6. SD Model 1 Input Data

SD Model 1 Input Data	
-Annual growth rate: 0.2 -Total Recyclable Waste: 37,400 tons -Recycling Rate: 0.7	-Interest Rate: 0.2 -Profit from Panel Recycling: 79.33 dollars -Organic Solar Cell Production Price: 1.8E-05 ton organic solar cell production / dollars

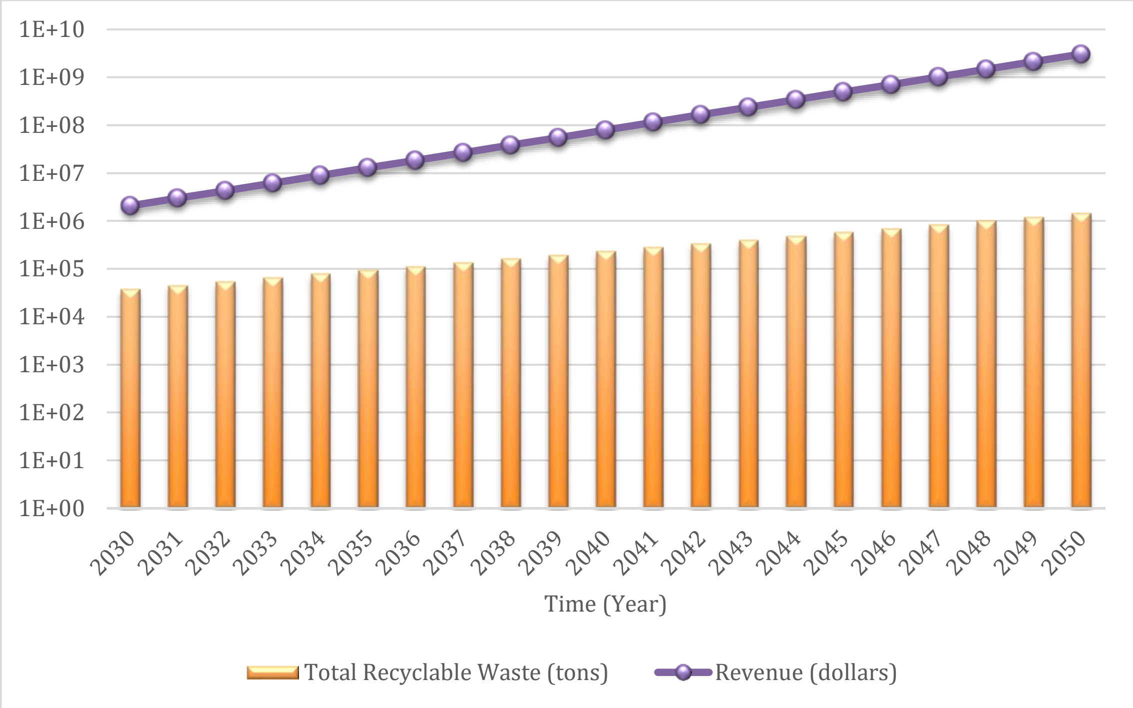

Figure 17. The increase in waste production and in revenue for Europe in 2030-2050

As seen in Figure 17, the total cumulative amount of recyclable waste solar panels from 2030 to 2050 may reach up to 1.43E+06 tons. With the new sanctions of governments towards green transformation, a total cumulative revenue of 3.05E+09$ (Approximately three billion fifty million dollars) may be obtained between 2030 and 2050 by recycling 70% of waste solar panels.

Additionally, the Sensitivity Analysis Results performed for this model study is given in **APPENDIX-4**. Within the scope of sensitivity analysis, the annual growth rate value was taken as 1 at the maximum value and 0 at the minimum value, and the change in the results was observed. As a result of the sensitivity analysis, it was determined that when the annual growth rate value was given a minimum of 0, there would be a revenue approximately 38 times below the model data in 2050. It has been determined that when the annual growth rate value is given a maximum of 1, there will be a revenue of approximately 2.74E+04 times higher than the model data in 2050.

Subsequently, the use of the revenue obtained from solar panel recycling in the production of organic solar panels by investing them in R&D studies was examined. Organic solar panels are a new technology design and are still quite new in the solar energy market.

As shown in Figure 18, a trend has been produced on how many organic solar panels can be brought to the solar energy market with the revenues generated. Accordingly, as a result of directing the revenue to R&D studies, the potential to produce organic solar panels by 2050 is 54,945.20 tons. The potential production quantity of organic solar panels obtained from the model is given in **APPENDIX-5.**

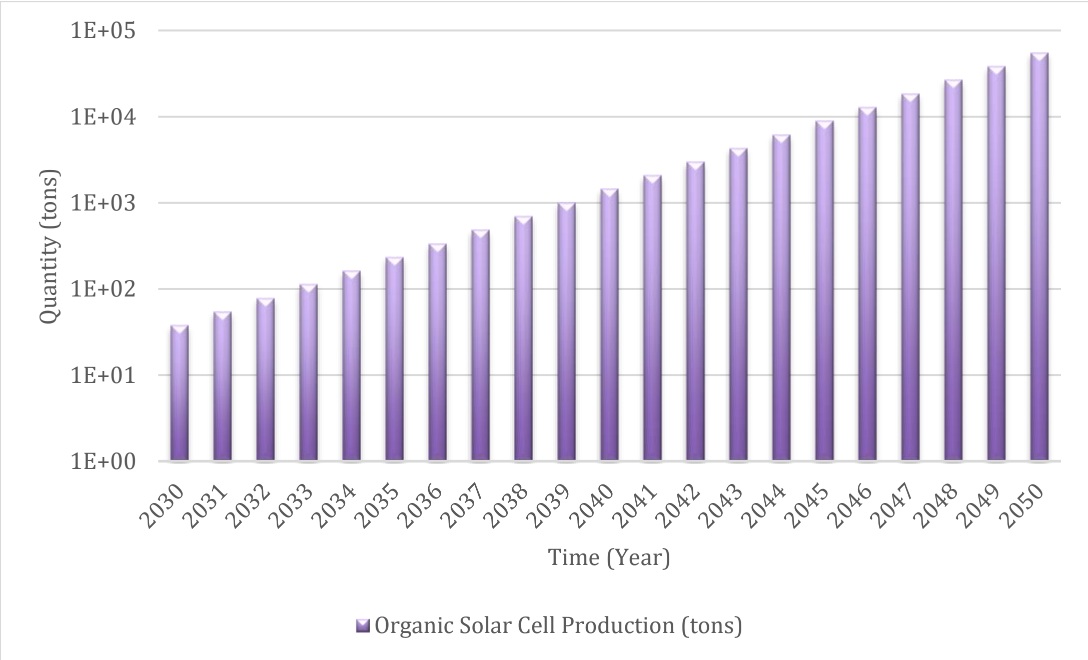

Figure 18. Organic solar panel production potential with revenue for Europe in 2030-2050

Although this scenario is an optimistic approach, it can become a realistic approach with the sanctions that the state will impose. If more efforts are implemented, a scenario where 70% of solar panel waste can be recycled will allow the revenue from this recycling to be directed to the manufacturing of organic solar panels, possibly achieving the potential illustrated in Figure 18 for organic solar panel production.

- **The effect of increase in revenue from the solar panel recycling process**

While analyzing whether the revenue obtained from the recycling of solar panels should be directly invested in the solar sector again, two evaluations were made, maximum and minimum. In addition, it was analyzed that the revenue transferred to the solar sector was used in conventional monocrystalline solar panels and contributed to R&D studies by using it in innovative organic solar panels. Analyzes where the revenue was used directly in the solar sector were made by running the SD Model 1 created in Vensim PLE software (See Figure 13).

The results obtained by running the "*SD Model 1: The effect of increase in revenue from the solar panel recycling process"* based on the input data in Table 7 are given in Table 8.

Table 7. SD Model 1 (The effect of increase in revenue from the solar panel recycling process) Input Data

SD Model 1: The effect of increase in revenue from the solar panel recycling process		
-Total Recyclable Waste: 37,400 tons -Profit from Panel Recycling: 79.33 dollars -Organic Solar Cell Production Price: 1.8E-05 ton organic solar cell production / dollars -Monocrystalline Solar Cell Production Price: 2.5E-05 ton monocrystalline solar cell production / dollars		
	Minimum Scenario	**Maximum Scenario**
Annual Growth Rate of Solar Waste	0.2	0.4
Recycling Rate	0.35	0.7
Interest rate for revenue from panel recycling	0.2	0.6

According to one estimate, the average global recycling rate of PV modules was 14% in 2019 and could rise to 70% by 2050 (Bošnjakovic et al., 2023) . Within the scope of this study, the recycling rate was taken as 0.35 in the minimum scenario and 0.7 in the maximum scenario.

In order to address the economic performance of recycled solar panels, the model created in the Vensim PLE software was run to determine the revenue to be obtained from recycling solar panels and how much organic solar panels and monocrystalline solar panels could be invested with this revenue. In this context, it was determined that solar panel recycling would yield 1.04E+06 dollars in 2030 and 1.53E+09 dollars in 2050 in the minimum scenario, and 2.08E+06 dollars in 2030 and 2.10E+13 dollars in 2050 in the maximum scenario. It is assumed that all of the revenue obtained from the recycling of solar panel waste will be allocated to the use of the solar sector. Solar panel recycling revenue from minimum and maximum scenarios are given in **APPENDIX-6.**

The data obtained as a result of the analysis are given in Table 8. Accordingly, since the production cost of organic solar panels is high, fewer organic solar panels are generally produced than monocrystalline solar panels. The production quantity of monocrystalline solar panels and organic solar panels in minimum and maximum scenarios is given in **APPENDIX-6**.

Table 8. The quantity of solar panels produced as considering directing the revenue to the solar industry

	Minimum Scenario	**Maximum Scenario**
Monocrystalline solar cell production quantity (tons)	Year 2030: 25.96	Year 2030: 51.92
	Year 2050: 3.82E+04	Year 2050: 5.25E+08
Organic solar cell production quantity (tons)	Year 2030: 18.80	Year 2030: 37.59
	Year 2050: 2.76E+04	Year 2050: 3.80E+08

- **The effect of price**

In order to analyze the effect of price on the use of revenue directed to solar energy industries to produce monocrystalline solar panels and organic solar panels, the model was run by changing the price of organic and monocrystalline solar panels. While making this analysis, the maximum scenario in Table 7 was taken as basis. The effect of low and high price in the maximum scenario effect was analyzed.

The results obtained by running the "*SD Model 1: The effect of price*" based on the input data in Table 9 are given in Table 10.

Table 9. SD Model 1 (The effect of price) Input Data

SD Model 1: The effect of price
-Annual growth rate: 0.4 -Total Recyclable Waste: 37,400 tons -Recycling Rate: 0.7 -Interest Rate: 0.6 -Profit from Panel Recycling: 79.33 dollars -Organic Solar Cell Production Price: Lower Price 2.22E-05 ton organic solar cell production / dollars Higher Price 1.33E-05 ton organic solar cell production / dollars -Monocrystalline Solar Cell Production Price: Lower Price 3.33E-05 ton monocrystalline solar cell production / dollars Higher Price 1.66E-05 ton monocrystalline solar cell production / dollars

According to this analysis, the effect of price changes on the quantity of solar panels produced is given in Table 10. Accordingly, in low and high price models operated within the scope of the maximum scenario, the model in which monocrystalline panels can be produced in the low price band was determined to be the best model. The production potential of monocrystalline and organic solar panels in low and high price bands over the years is given in **APPENDIX -7.**

Table 10. Quantity of solar panels produced as a result of price effect

	Lower Price Scenario	**High Price Scenario**
Monocrystalline solar cell production quantity (tons)	Year 2030: 69.16	Year 2030: 34.48
	Year 2050: 7.00E+08	Year 2050: 3.49E+08
Organic solar cell production quantity (tons)	Year 2030: 46.11	Year 2030: 27.62
	Year 2050: 4.66E+08	Year 2050: 2.79E+08

5.2.2. Scenario 2: Revenue Directed to Other Industries

Circularity Driven Innovation: Secondary Resources Use

Scenario 2 is concerned with the positive effect of revenue from secondary material use catalyzing innovation and further enhancing the dominance of solar market in the energy generation. In this case, secondary materials are expected to faster diffusion over the years in key sectors, as shown in Figure 19, highlighting the dominance in the solar market. Secondary resource uses and the amounts of cost to be avoided by these uses are given in **APPENDIX-8**.

Figure 19. Diffusion of the use of secondary resources in key sectors for Europe in 2030-2050

Costs in primary material acquisition will drop market costs increasing demand in these sectors. The reduction of costs for the construction sector will increase driving demand and total output. Costs avoided may also translate to innovation, again diversifying the products of these sectors that may result in a reduction or increase in primary material consumption.

Intersectoral dependencies through resource flows based on IOT structure of the EU economy shows that the most affected sector is the construction sector followed by automotive sector. It has been observed that the packaging sector and the health and medical sector are the least affected sectors. This is because the impact is directly proportional to the demand. Therefore, the sector with high demand is the most affected sector.

- **The effect of increase in the use of secondary resources compared to the use of primary resources**

In this section, the revenue resulting from the use of secondary resources as a result of transferring the revenue directly to other industries was evaluated. While examining the use of revenue in different sectors, the primary resource amounts used in the Construction Industry, Packaging Industry, Health and Medical Industry and Automotive Industry, which were determined as the key sectors where recycled materials can be used, were determined. The amounts of primary resources flowing the sectors in business as usual scenario were obtained from OECD (Organization for Economic Co-operation and Development) Statistical Input-Output Tables (IOTs) 2021 edition data (Table 4).

The results obtained by running the "*SD Model 2: The effect of increase in the use of secondary resources compared to the use of primary resources"* based on the input data in Table 11 are given in Figure 20.

Table 11. SD Model 2 (The effect of increase in the use of secondary resources compared to the use of primary resources) Input Data

SD Model 2: The effect of increase in the use of secondary resources compared to the use of primary resources
-Input-Output Tables Data: Sectoral data table for EU (OECD, 2021) given in Table 4. -Annual growth rate: 0.2 -Interest Rate: 5.85 (the average of the latest interest rates of European countries) -Primary Resource Price: 0.002705 million dollars / ton for Al & Steel, 0.000035 million dollars / ton for Glass, 0.001 million dollars / ton for plastic, 0.0005 million dollars / ton for Electronic Components, 0.0011 million dollars / ton for Silicon. -Total Recyclable Waste: 37,400 tons -Recycling Rate: 0.7

First of all, for the primary resource usage analysis, the data taken from the Input-Output Tables and other variables were entered into the model and analyzed. Primary resource uses of key sectors are given in **APPENDIX-3** together with the quantity of materials flowing each sector. In addition, the data graph of primary resource use is given in ***Section 5.1.1*** Figure 16.

In the next step of the study, the use of secondary resources derived from the recycling of solar panels in other sectors was analyzed. Outputs were obtained according to this created scenario model.

Secondary resource use in the construction sector increased the most because the demand of this sector is the highest, 21,391.30 tons in 2030 and 293,991.00 tons in 2050. Secondary resource use in the packaging sector was 2,671.64 tons in 2030 and 36,717.70 tons in 2050. Secondary resource use in the health and medical sector was 2,841.98 tons in 2030 and 39,058.70 tons in 2050. Secondary resource use in the automotive sector was 10,495.10 tons in 2030 and 144,239.00 tons in 2050. The results were expected to increase the use of secondary resources, because there will also be an increase in the use of secondary resources in line with the demands of the sectors. The results obtained have shown that there will be an increase in the use of secondary resources over the years and that this increase will be experienced the most in the sector with the highest demand. Secondary resource uses of key sectors are given in **APPENDIX-9** together with the quantity of materials flowing each sector. In addition, the data graph of secondary resource use obtained as a result of the model is given in Figure 20.

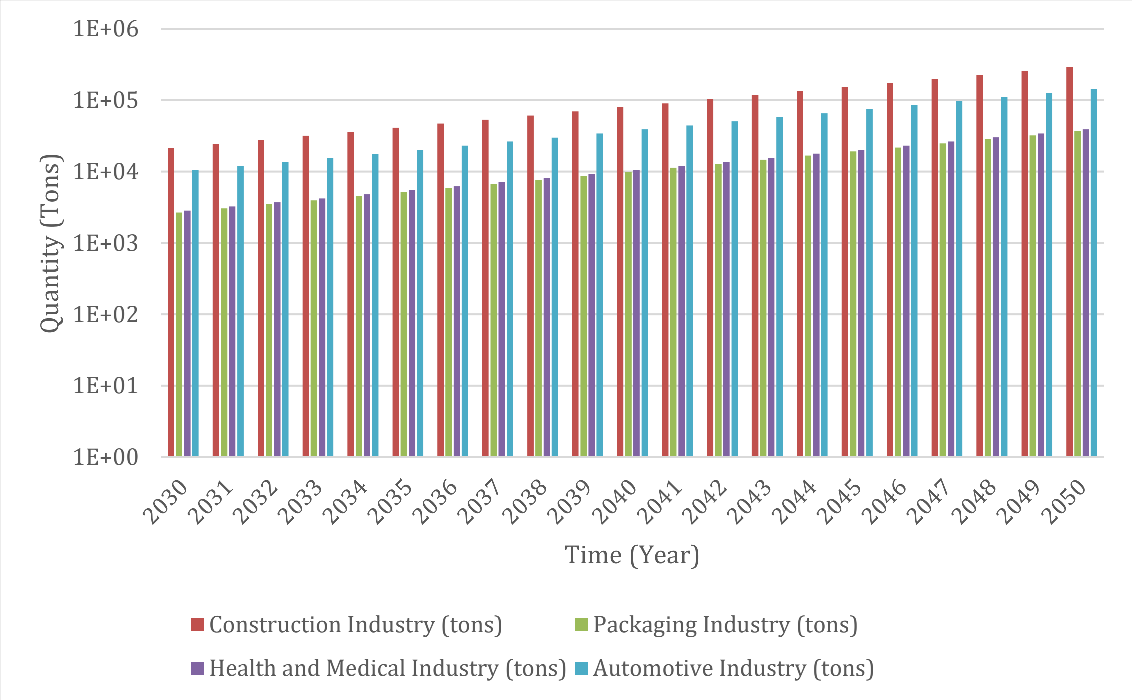

Figure 20. The use of secondary resources in key sectors for Europe in 2030-2050

Utilizing secondary materials is advised in order to minimize resource consumption within the parameters of the study, as the circular economy seeks to minimize resource consumption while extending the useful life of materials and products. When a material is extracted and processed appropriately, there are limits to resource consumption as it can be used as raw material in the production cycles of other industries after reaching the end of its useful life. The results show that the use of secondary materials has increased to very high levels and thus there has been a reduction in the use of primary resources. Since each sector has its own circularity value, the use of secondary resources has made the sectors more circular within the parameters of this study.

- **The effect of price**

The use of primary resources will be restricted as a result of the use of secondary resources in sectors. Procuring products from secondary resources will offer a more economical approach. Products that are more expensive when resourced from primary resources will be cheaper when sourced from secondary resources. In the economic analysis carried out in this context, how much price would be paid if we bought the product quantities to be derived from secondary resources from primary resources and how much price would be paid if we bought from secondary resources were calculated.

The results obtained by running the "*SD Model 2: The effect of price"* based on the input data in Table 12 are given in Figure 21-22.

Table 12. SD Model 2 (The effect of price) Input Data

SD Model 2: The effect of price
-Total Recyclable Waste: 37,400 tons -Recycling Rate: 0.7 -Annual Growth Rate: 0.2 -Interest Rate: 0.2 -Primary Resource Price: Average Price: 0.002705 million dollars / ton for Al & Steel, 0.000035 million dollars / ton for Glass, 0.001 million dollars / ton for plastic, 0.0005 million dollars / ton for Electronic Components, 0.0011 million dollars / ton for Silicon. Higher Price: 0.005 million dollars / ton for Al & Steel, 0.0001 million dollars / ton for Glass, 0.01 million dollars / ton for plastic, 0.003 million dollars / ton for Electronic Components, 0.02 million dollars / ton for Silicon. -Secondary Resource Price: $800/ton for Al & Steel, $70.14/ton for Glass, $489.89/ton for plastic, $145/ton for Electronic Components, $350/ton for Silicon.

While performing this analysis, calculations were first made for the average price band. According to the calculated data in average price scenario, it has been determined that the use of secondary resources in lieu of primary resources will bring a total avoided cost of 11.05 million dollars in 2030 and 5.82E+03 million dollars in 2050 for all sectors. The graph in Figure 21 shows the distribution of calculated avoided cost according to sectors. The cost to be avoided by using secondary resources in lieu of primary resources for all sectors is given in **APPENDIX-10**.

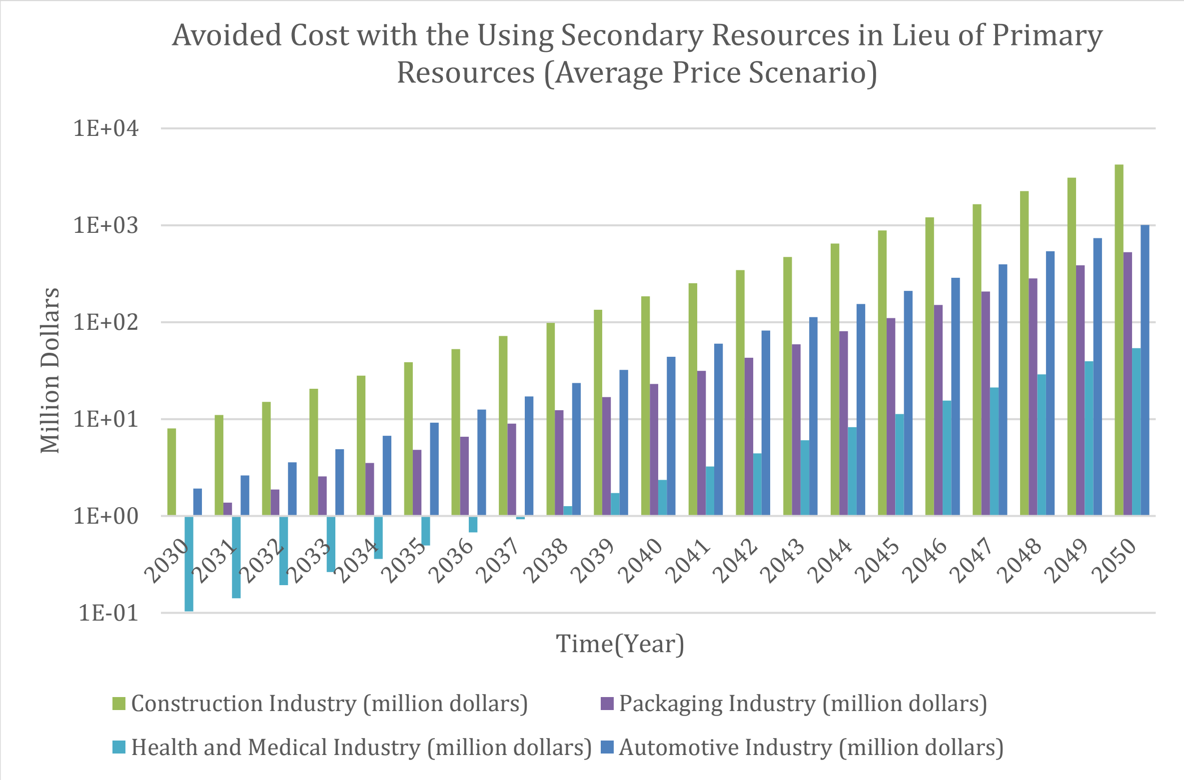

Figure 21. Avoided cost with the using secondary resources in lieu of primary resources (Average price scenario)

In the analysis that examined the effect of keeping the price at the highest level by seeing the extreme values, a consideration was made especially for the high price band. According to the calculated data in high price scenario, it has been determined that the use of secondary resources in lieu of primary resources will bring a total avoided cost of 66.46 million dollars in 2030 and 3.50E+04 million dollars in 2050 for all sectors. The graph in Figure 22 shows the distribution of calculated avoided cost according to sectors. The cost to be avoided by using secondary resources in lieu of primary resources for all sectors is given in **APPENDIX-10**.

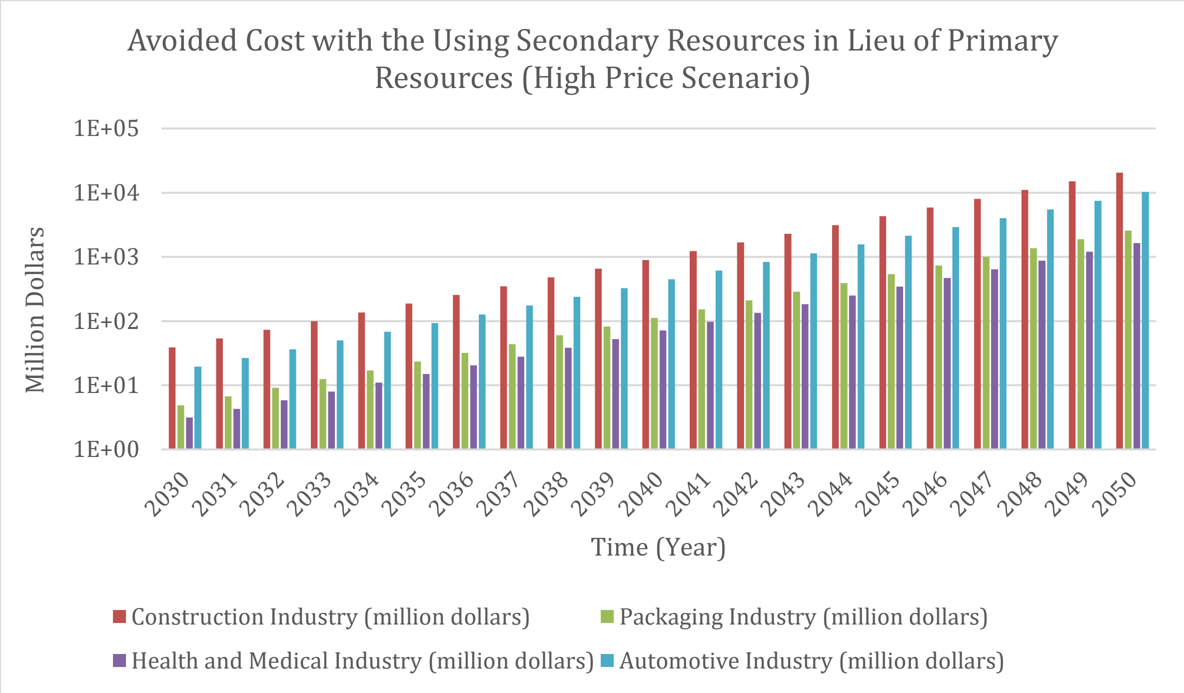

Figure 22. Avoided cost with the using secondary resources in lieu of primary resources (High price scenario)

As a result, the use of secondary materials derived from recycling solar panels in solar panels or in different sectors makes great contributions to the protection of natural resources, waste management and economic sustainability. According to a study, secondary materials that can be technically recovered from PV panels could generate a cumulative value of up to $450 million globally by 2030 (IRENA, 2016). Within the scope of this study, it was determined that a cost of 11.05 million dollars would be avoided from secondary resources in 2030 in the average price scenario, and 66.46 million dollars in 2030 in the high price scenario. Since the data obtained is European data, it could not be compared with the global $450 million earnings value found in the study in question.

- **The effect of competition between primary & secondary resources**

Circularity Driven by Policy: The Effect of Fixed-Price Policy

Within the scope of this study, the solution analyzed to prevent price fluctuations in secondary resource markets are price fixing policy of states in secondary resources.

Increasing competition between sectors has increased prices. In this case, when prices increased, demand also decreased. For this reason, the desired circular approach limit could not be reached. Within the scope of this study, the solution analyzed to prevent price fluctuations in secondary resource markets are price fixing policy of states in secondary resources.

The results obtained by running the "*SD Model 2: The effect of competition between primary & secondary resources"* based on the input data in Table 13 are given in Figure 23.

Table 13. SD Model 2 (The effect of competition between primary & secondary resources) Input Data

SD Model 2: The effect of competition between primary & secondary resources
-Total Recyclable Waste: 37,400 tons -Secondary Resource Price: $800/ton for Al&Steel, $70.14/ton for Glass, $489.89/ton for plastic, $145/ton for Electronic Components, $350/ton for Silicon.

In this case, the data obtained for the change in secondary resource use with the intervention of governments are presented below.

It has been determined that there will be a 30% decrease in purchasing quantity with the increase in prices in the secondary material market. Accordingly, it has been determined that the purchase of secondary materials will be 14973.90 tons in the construction sector, 1870.15 tons in the packaging sector, 1989.39 tons in the health and medical sector and 7346.57 tons in the automotive sector in 2030. It has been determined that the amount of purchases in secondary resources will also increase when the prices are reduced and fixed after the state intervenes and provides support. Accordingly, it has been determined that as a result of price fixation, the purchase of secondary materials in 2030 will be 17219.98 tons in the construction sector, 2150.67 tons in the packaging sector, 2287.79 tons in the health and medical sector and 8448.55 tons in the automotive sector. A total of approximately 13% increase in secondary resource use was observed in all sectors. However, if demand increases while supply remains constant, a supply-demand imbalance may occur, resulting in shortages of secondary materials or supply difficulties. For this reason, the amount of secondary resources should be increased by increasing the recycling rate of solar panel waste. The effects of fixed price policy for secondary resource use as a result of Business as usual, Increased price and Price Fixation is given in the graph in Figure 23 and in **APPENDIX 11**.

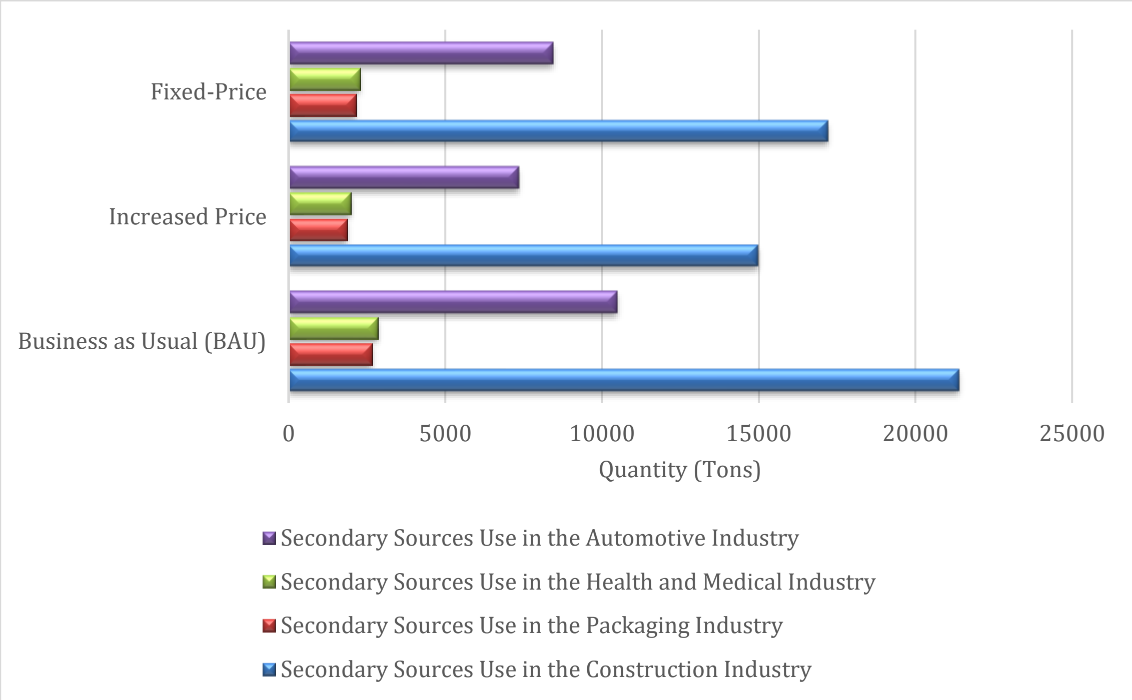

Figure 23. The effects of fixed price policy for secondary resource use

As can be seen from the Figure 23, price fixation has led to an increase in the use of secondary resources. It has been determined that the sector most affected by price changes is the construction sector. This is because the impact is directly proportional to the demand. Therefore, the sector with high demand is the most affected sector.

In a study, it was determined that, compared to the free competition mechanism, a higher investment capacity in renewable technology will be achieved through a fixed price premium policy (Liu et al., 2016). This shows that the data obtained in this study are consistent when compared.

In this analysis, the effect of price fixation on secondary resource use was examined, but the secondary market is a highly variable market, and since it is under the influence of many factors at the same time, its impact cannot be determined only by changes in price. The factors affecting the secondary resource market are multifaceted and complex. The supply of recycled materials depends on recycling capacity, the efficiency of waste collection systems and the capacity of processing industries. The demand for secondary materials is shaped by industrial needs, consumer preferences and demand for sustainable products. Increasing environmental awareness may increase the demand for recycled materials. Advances in recycling technologies make recycling processes more efficient and reduce costs. Tax breaks, subsidies and other incentives provided by governments can increase recycling activities and support the market for secondary materials. The quality of recycled materials is also an important factor affecting demand. Since all these factors affect secondary material markets, all factors must be analyzed in order to make the most accurate assessment in terms of approach to circularity (European Environment Agency, 2022).

Recommended solutions to increase the use of secondary materials;

- Setting targets for recycling companies,
- Waste export restrictions,
- Improving collection plans,
- Standardization of secondary material markets,
- End of waste criteria,
- Recycled content requirements,
- Tax increase on the use of primary raw materials,
- Implementation of value added tax reduction in secondary material markets

Economical recycling solutions should be created, in addition to actions like setting up regional recycling industries and utilizing cutting-edge techniques in PV system design to facilitate recycling, in order to reduce the barriers to more efficient recycling. Global harmonization and development of rules and regulations pertaining to PV waste management are also necessary. Approaches from the circular economy to PV EoL are suggested because they could provide social progress and environmental justice. EoL is a crucial component of a PV system's environmental sustainability that shouldn't be disregarded. At this point, the environmental impact can be reduced and economic advantage can be increased by putting into practice suitable waste management and recycling plans and practices (Bošnjakovic et al., 2023) .

5.3. Assessment of Environmental Impacts

Although solar panels are clean energy sources and do not produce emissions during their operation, emissions may occur during activities such as production, transportation, installation and recycling. In a study, the amount of emissions released from the production of solar panels to their recycling were found with the help of LCA (Singh et al., 2023). Accordingly, a net benefit was found when the emission amounts that would occur during recycling were compared with the emissions prevented by recycling, and it was determined that recycling was effective in reducing the emission amounts. Study findings are presented in Table 14. In the study, the functional unit was determined as 1 kg of c-Si solar panel and the outputs were obtained according to this data.

Table 14. EIA of recycling option for all impact categories (Singh et al., 2023)

Impact category	Unit	Takeback and recycling, c-Si PV module	Avoided burden from recycling, c-Si PV module	Net environmental benefit
Global warming	kg CO2 eq	4.14E-01	-6.18E-01	-1.03E+00
Stratospheric ozone depletion	kg CFC11 eq	1.99E-07	7.30E-08	-1.26E-07
Ionizing radiation	kBq Co-60 eq	-2.64E-03	1.19E-02	1.45E-02
Ozone formation, Human health	kg NOx eq	2.71E-04	-4.37E-03	-4.64E-03
Fine particulate matter formation	kg PM2.5 eq	-1.24E-05	-5.29E-03	-5.28E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	2.82E-04	-4.39E-03	-4.67E-03
Terrestrial acidification	kg SO2 eq	-2.94E-04	-1.04E-02	-1.01E-02
Freshwater eutrophication	kg P eq	-1.48E-04	-4.22E-03	-4.07E-03
Marine eutrophication	kg N eq	9.50E-06	6.45E-05	5.50E-05
Terrestrial ecotoxicity	kg 1,4-DCB	1.28E+00	-7.62E+01	-7.75E+01
Freshwater ecotoxicity	kg 1,4-DCB	1.75E-02	-6.89E-01	-7.07E-01
Marine ecotoxicity	kg 1,4-DCB	2.35E-02	-9.85E-01	-1.01E+00
Human carcinogenic toxicity	kg 1,4-DCB	7.60E-05	-3.58E-01	-3.58E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	2.60E-01	-2.49E+01	-2.52E+01

Impact category	Unit	Takeback and recycling, c-Si PV module	Avoided burden from recycling, c-Si PV module	Net environmental benefit
Land use	m^2a crop eq	- 5.52E-02	-5.64E-02	-1.20E-03
Mineral resource scarcity	kg Cu eq	4.03E-04	1.26E-02	1.22E-02
Fossil resource scarcity	kg oil eq	3.37E-02	-1.43E-01	-1.77E-01
Water consumption	m^3	- 4.69E-03	- 1.25E-02	-7.81E-03

Then, LCA outputs were obtained with the help of SimaPro for landfill, which is one of the options if recycling is not done. The functional unit was determined as 1 kg of c-Si solar panel and the outputs were obtained according to this data. Emission data obtained from SimaPro for the Landfill option is given in Table 15.

Table 15. EIA of landfill option for all impact categories

Impact category	Unit	Landfill, c-Si PV module
Global warming	kg CO2 eq	5.35E-05
Stratospheric ozone depletion	kg CFC11 eq	1.08E-06
Ionizing radiation	kBq Co-60 eq	5.79E-05
Ozone formation, Human health	kg NOx eq	3.51E-05
Fine particulate matter formation	kg PM2.5 eq	8.43E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.13E-05
Terrestrial acidification	kg SO2 eq	1.41E-05
Freshwater eutrophication	kg P eq	0.000151
Marine eutrophication	kg N eq	8.09E-07
Terrestrial ecotoxicity	kg 1,4-DCB	0.00029
Freshwater ecotoxicity	kg 1,4-DCB	0.009252
Marine ecotoxicity	kg 1,4-DCB	0.011656
Human carcinogenic toxicity	kg 1,4-DCB	0.865126
Human non-carcinogenic toxicity	kg 1,4-DCB	0.009192
Land use	m^2a crop eq	2.41E-06
Mineral resource scarcity	kg Cu eq	6.9E-09
Fossil resource scarcity	kg oil eq	4.33E-05
Water consumption	m^3	8.42E-06

The LCA analysis showed that the recycling option is more environmentally friendly than landfilling, resulting in lower emissions across various impact categories. The primary reasons for this include the recovery and reuse of valuable materials like silicon and aluminum during the recycling process, which reduces the need for energy-intensive and environmentally harmful raw material extraction. Additionally, recycling prevents the release of hazardous substances that could leach into soil and water during landfilling, thereby minimizing long-term negative impacts on ecosystems and human health. By reducing the volume of waste, recycling also extends the lifespan of existing landfill sites and decreases the need for new ones, contributing to a more sustainable waste management approach.

While performing LCA analysis, although the sizes of landfill areas vary across Europe, a general evaluation was made without taking these differences into account in the analysis. This approach enabled comparison of environmental impacts per unit and obtaining overall results, using a standardized methodology in the analysis. Although this method is not valid for all of Europe, it is considered a sufficient assumption to prove that the landfill option is less environmentally friendly than recycling.

The graph in Figure 24 shows the comparison of emission values of recycling and landfill options. EIA of recycling and landfill options for c-Si PV for all impact categories is given in **APPENDIX-12.**

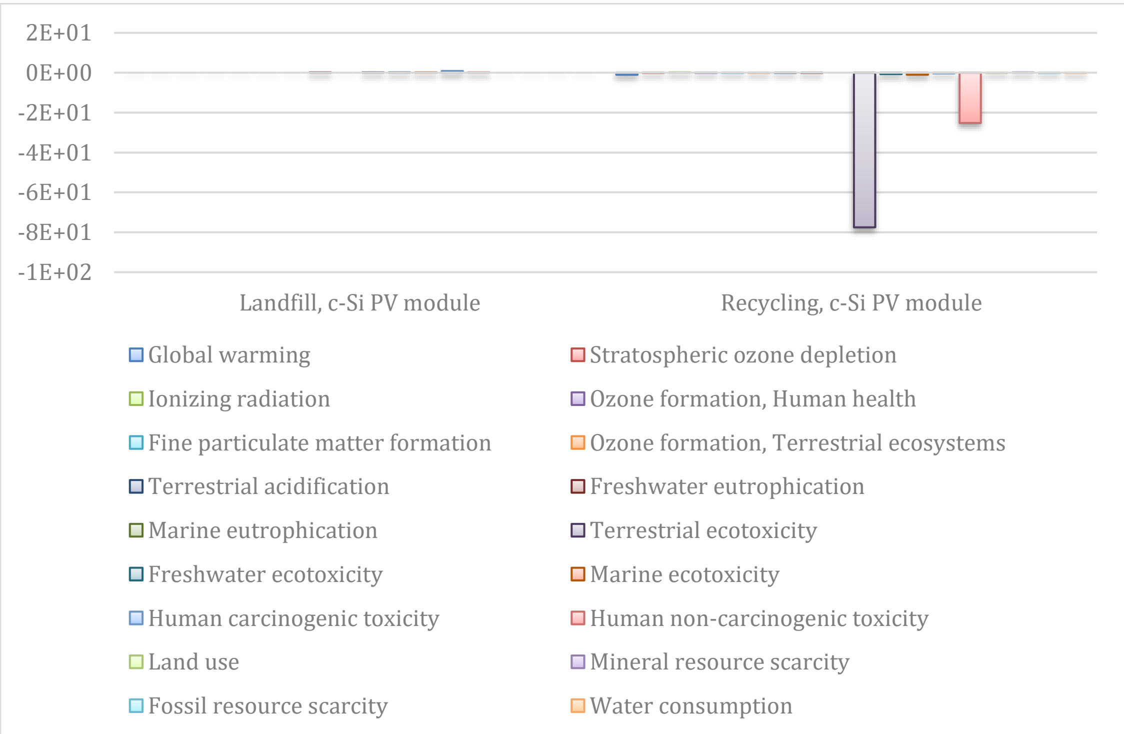

Figure 24. EIA of recycling and landfill options for c-Si PV for all impact categories

Contributing to R&D studies by using the revenue obtained from recycling solar panels in organic solar panels is one of the scenarios examined within the scope of the study. In this context, the environmental impact of organic solar panels was evaluated and compared with conventional c-Si panels. In the SimaPro software, 1 kg c-Si solar cell and 1 kg organic solar cell were determined as functional units and their emissions were determined. Accordingly, it has been determined that organic solar panels emit much less emissions than c-Si solar panels, and results have been obtained that prove the study from Tsang et al. given in *Section 2.8.* The results obtained are given in Figure 25. Emission values of organic solar panels and c-Si solar panels obtained from SimaPro are given in **APPENDIX-13**.

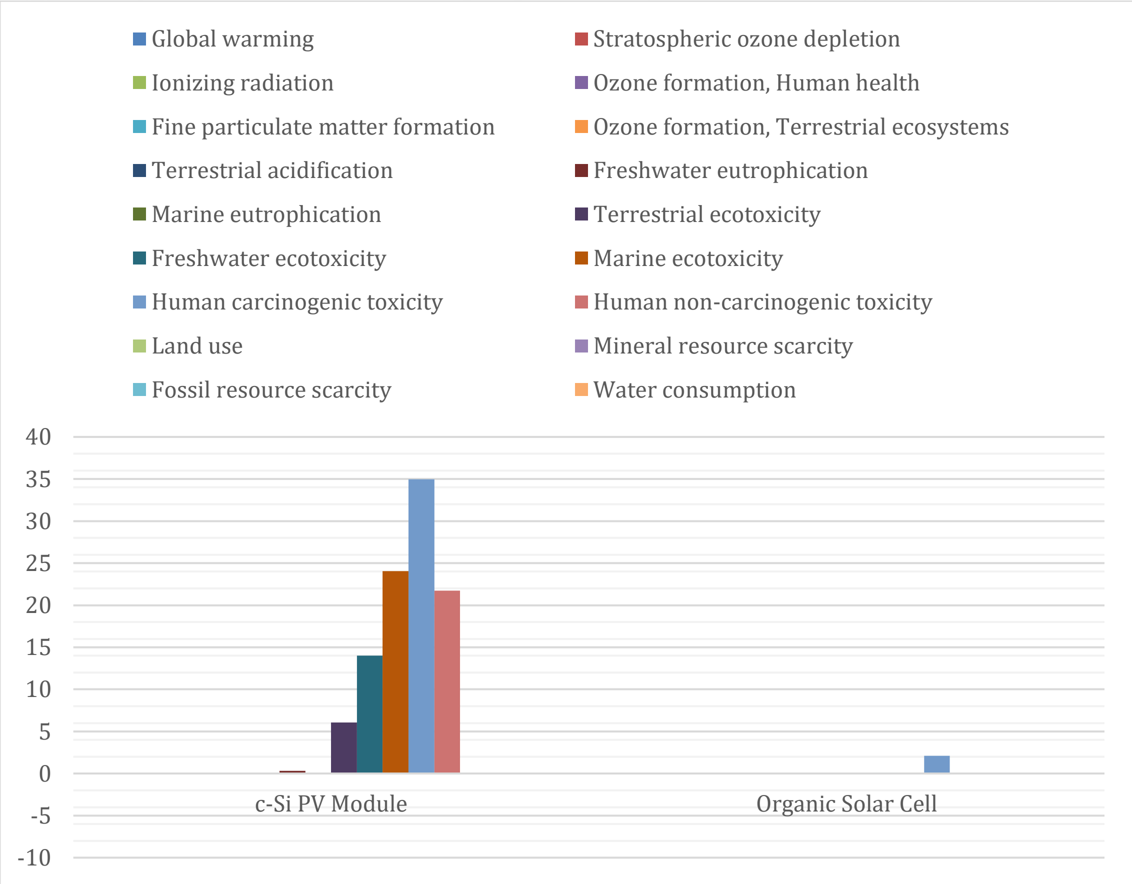

Figure 25. EIA of organic and monocrystalline solar panels for all impact categories

Based on the LCA analysis, c-Si PV modules were found to have higher values in impact categories such as terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, and human non-carcinogenic toxicity compared to organic solar cells. The primary reasons for this include the energy-intensive production processes of c-Si modules, the environmental toxicity associated with the raw materials used, the presence of chemicals in the manufacturing process that can be harmful to human health and the environment, and challenges in waste management due to the difficulties in recycling these modules. Additionally, the global supply chains involved in their production and transportation further exacerbate the ecological and toxicological impacts (Tsang et al., 2015).

5.4. Evaluation of Results

Comparison of general results within the scope of the study is given in Table 16-17. The results stated in the tables show that, while the production of monocrystalline solar panels offers a more economical solution in using the revenue obtained from recycled solar panels to produce solar panels again, organic solar panels offer a more environmentally friendly solution. In addition, cost was avoided in a considerable degree by using recycled materials as secondary resources in other sectors. Additionally, recycling solar panels has been found to be a more environmentally friendly solution than landfilling.

Table 16. Summary of economic assessment results

Economic Assessment			
Revenue from recycling solar panels		Avoided Cost with the Using Secondary Resources in lieu of Primary Resources	
Minimum Scenario	Maximum Scenario	Average Price Scenario	High Price Scenario
Year 2030: 1.04E+06 dollars Year 2050: 1.53E+09 dollars	Year 2030: 2.08E+06 dollars Year 2050: 2.10E+13 dollars	Year 2030: 11.05 million dollars Year 2050: 5.82E+03 million dollars	Year 2030: 66.46 million dollars Year 2050: 3.50E+04 million dollars

Table 17. Summary of environmental assessment results

Environmental Assessment			
Landfill Process Solar Panel	Recycling Process of Solar Panel	Organic Solar Panels	Monocrystalline Solar Panels
Less favorable to the environment	More favorable to the environment	More favorable to the environment	Less favorable to the environment

6. CONCLUSION AND RECOMMENDATIONS

This study aims to outline a method for assessing the recycling potential of solar panel waste and to guide the development of a waste management strategy aligned with circular economy principles.

The approach in this study took into account the potential revenue from recycling solar panels and reinvesting it in R&D to improve solar panel technology. Additionally, it anticipated the amounts of secondary resources that could be acquired through recycling and projected their total availability in Europe between 2030 and 2050, assessing their potential for use as raw materials in other industries.

The data shows that the recycling revenue of solar panels is quite high and should be evaluated in line with circular economy applications for use in the solar sector or other sectors. Thus, while economic gains are achieved, a more beneficial application will also be provided to the environment. However, it was determined that there may be fluctuations in prices in the secondary material market due to reasons such as competition. Based on this result it is recommended that states adopt sanctions such as price fixation policy to prevent this.

The project's contributions to society and the environment include reducing environmental impacts, reducing greenhouse gas emissions and improving public health and environmental quality by using natural resources more efficiently. In addition, transferring the economic income obtained from recycling to R&D studies and transferring it to other sectors will provide economic growth. By showing the potential financial gains from recycling initiatives, the model will encourage businesses to adopt more sustainable practices. The study provides a model that future researchers can study to investigate various scenarios and their economic and environmental impacts. By changing and improving this model, various data can be obtained and new evaluations can be made. LCA and economic analyzes can be references for researchers who want to examine recycling scenarios in different contexts. Policy makers can take reference from the recommendations presented in the study to develop regulations and incentives that encourage the recycling of solar panels.

Additionally, the integration of economic and environmental analyzes in the thesis can promote interdisciplinary research. It can support the need for collaboration among economists, environmental scientists, engineers, and policymakers to comprehensively address the study issue. Future research could examine the social dimensions of recycling and circular economy models, such as their impact on communities and consumer behavior.

When considering the thesis's larger impact, it may become obvious how crucial it is to recycle solar panels and migrate to a circular economy, educating the public and companies about the ways to make the paths to a green transition. Despite the study's narrow emphasis on a particular area or time period, its conclusions apply global. The created models and ideas can be modified and implemented in other regions of the world, thereby supporting global efforts towards sustainability.

Some recommendations for the future studies are as follows:

- Since the secondary materials market is a very dynamic structure affected by many parameters that are not within the scope of this study, it can be subjected to more detailed economic analysis and market evaluation.
- Targets such as determining end-of-waste criteria for recycling companies can be set and their impact evaluated.
- The impact of sanctions such as restrictions on waste exports, imposing taxes on the use of primary raw materials and applying value added tax reductions in secondary material markets can be examined.
- Future research could examine the social dimensions of recycling and circular economy models, such as their impact on communities and consumer behavior.
- Finally, studies can be conducted on the effect of providing training on ways to a green transition on the adoption of these practices by the public.

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APPENDICES

APPENDIX 1 – DATA FROM INPUT-OUTPUT TABLES

Table 18. Primary Resource Quantity from Input-Output Tables (OECD, 2021).

Aluminum and Steel (Unit: US Dollar, Millions)	Construction Industry	Packaging Industry	Health and Medical Industry	Automotive Industry
Countries				
Austria	1902.9	628.9		682.2
Belgium	2249.1	342.7		421.4
Czechia	655.7	87.1		2222.6
Denmark	1854.3	197.9		42.4
Estonia	270.6	28.8		14.5
Finland	2189.5	98.4		100.4
France	15026.2	1574.9		5058.2
Germany	16216.6	1062.5		17786.2
Greece	783.2	320.1		6.4
Hungary	845.5	218.7		1436.6
Iceland	262.5	10.7		0.5
Ireland	618.4	77.7		16.5
Italy	6704.3	576.1		8429.5
Latvia	208.5	22.2		39.7
Lithuania	76.1	10.4		40.2
Luxembourg	81.8	1.3		5.7
Netherlands	5624.4	877.3		629.7
Norway	1149.3	120.4		26.4
Poland	5122.9	480.8		4262.2
Portugal	1059	267.1		287.3
Slovakia	528.3	35.3		2643.8
Slovenia	257.9	36.5		198.1
Spain	3318.4	884.2		7870.2
Sweden	1688.1	165.4		1660.6
Turkey	5158.8	283.7		708.2
United Kingdom	8448.8	509.4		3340.1
Bulgaria	238.3	24.5		21.7
Croatia	179.1	88.7		7
Cyprus	134.1	11.3		0.9
Malta	66.4	7.4		0.1
Romania	1462.6	48.8		567.5
Russia	10245.7	875.2		1424

Electronic Components (Unit: US Dollar, Millions)	Construction Industry	Packaging Industry	Health and Medical Industry	Automotive Industry
Countries				
Austria			61.3	365
Belgium			13.5	286.8
Czechia			27.3	2990.7
Denmark			31.5	13.3
Estonia			1.9	19.7
Finland			71.6	15.4
France			71.9	1264.9
Germany			385.4	5618.9
Greece			4.5	1.1
Hungary			10.5	1500
Iceland			0.3	0.1
Ireland			37.3	14.7
Italy			299.8	2097.7
Latvia			1.3	0.7
Lithuania			2.5	10.8
Luxembourg			1	3.1
Netherlands			114	165.2
Norway			67.6	15.8
Poland			167.2	700.6
Portugal			8.2	307
Slovakia			5.7	407.5
Slovenia			7.4	115.3
Spain			76.7	1743.1
Sweden			30.8	410.1
Turkey			64.2	648.3
United Kingdom			205.7	523.2
Bulgaria			3.4	118.2
Croatia			4.4	1.6
Cyprus			1.4	0.2
Malta			0.7	0
Romania			12.6	551.1
Russia			111	588.9
Glass (Unit: US Dollar, Millions)	Construction Industry	Packaging Industry	Health and Medical Industry	Automotive Industry
Countries				
Austria	297.4	108.8	492.4	145.3
Belgium	407.3	246.2	690.6	114
Czechia	163.3	122.8	285.8	435.9

Denmark	282.9	62.7	537.9	5.2
Estonia	50.1	13	72.3	2.7
Finland	371.7	160.5	272.3	9.3
France	2998.9	350	3034.6	2326.8
Germany	782.4	852.5	8492.9	4544.6
Greece	74.9	55.6	332.4	1
Hungary	109.7	40	205.8	164.4
Iceland	26.6	15.6	17.4	0.1
Ireland	651.4	216.7	151.8	14.6
Italy	2256.5	410.4	5103.5	1025.5
Latvia	17.2	18.6	21.5	1.2
Lithuania	51	20.7	71.2	2.2
Luxembourg	8.6	0.4	45.6	0.6
Netherlands	1387.6	620.7	538.3	127.1
Norway	532.1	193.1	246.1	18.6
Poland	1022	303.6	1000.6	302.5
Portugal	123.9	239.3	235.9	55.1
Slovakia	73.3	46.5	161.8	105.3
Slovenia	59.7	17.1	76	39.8
Spain	1111.5	492.3	2070.3	1557.1
Sweden	440.8	95.3	355	246.1
Turkey	910	276.3	1644	137.7
United Kingdom	1213.1	897.7	2825.9	524
Bulgaria	111.8	45.6	16.6	12.9
Croatia	64.4	26.5	235.5	1
Cyprus	8.3	4.9	16.3	0.1
Malta	35.3	10.3	35.2	0.1
Romania	314.9	23.1	44.3	470.4
Russia	1109.8	528.2	1221.7	163.1
Plastic (Unit: US Dollar, Millions)	Construction Industry	Packaging Industry	Health and Medical Industry	Automotive Industry
Countries				
Austria	1045.5	427.2	299.7	287
Belgium	1777.1	872.7	98.9	455.7
Czechia	424.7	179.4	22.8	4905.7
Denmark	605.8	281.9	132.3	14.6
Estonia	150	49.7	4.8	8.8
Finland	1093	239.1	37.8	29.2
France	4857.8	2379.2	393.2	3404.6
Germany	13795.6	2648.1	946	14845.3
Greece	75.8	105.7	7.2	1.7
Hungary	516.5	265.9	61.6	1147.2
Iceland	67.6	28.6	2.8	0.1
Ireland	281.5	147.3	40.4	6.8

Italy	3353	1819.5	714.5	2975.7
Latvia	52.8	92	1.3	2.6
Lithuania	117.3	102.5	4.3	6.6
Luxembourg	91.4	7.9	1	8.4
Netherlands	1911.1	697.3	302.1	476.4
Norway	884.9	325.5	87.6	9
Poland	6320.9	772.3	87	1900
Portugal	542.6	433.9	38	198.6
Slovakia	156	197.7	10.4	1972.1
Slovenia	61.6	42.8	5.8	134.2
Spain	1514.3	1837.2	152.5	3368.8
Sweden	635.2	220.5	200.4	843.7
Turkey	3580.4	992.2	70.2	937.6
United Kingdom	2828	2620.2	621	3010.5
Bulgaria	161.2	181.8	18.5	4.2
Croatia	128	157.9	13.6	6.1
Cyprus	8	13.5	1.8	0.6
Malta	31.2	12.5	0.6	0.3
Romania	616.5	93.8	15.8	1399.1
Russia	6432.8	2134	133.4	1531.8
Pure Silicone (Unit: US Dollar, Millions)	Construction Industry	Packaging Industry	Health and Medical Industry	Automotive Industry
Countries				
Austria	2932.4		52.1	60.7
Belgium	4198.1		23.1	94.4
Czechia	1587.2		9.2	180.4
Denmark	2151.7		21.5	7.4
Estonia	358.2		1.6	1
Finland	2185.5		33	13.3
France	15012.5		684.7	731.3
Germany	21681.5		204.2	2069.7
Greece	1000.4		16.6	0.8
Hungary	1326.9		14.1	277.3
Iceland	267.9		1.1	0.1
Ireland	1298		2.3	0.3
Italy	7251.5		168.7	1091.3
Latvia	422.9		3.4	0.7
Lithuania	196.9		1.1	3.2
Luxembourg	366.7		2.6	1.8
Netherlands	4741		78.7	41.9
Norway	2501.2		42.3	11.4
Poland	5553.3		99.2	200.9
Portugal	1741		13.7	81.8

Slovakia	696.1		3.7	46.6
Slovenia	443.1		2.4	35.5
Spain	7342.6		294	1075.4
Sweden	2604.6		38.7	262.9
Turkey	11423.9		221.2	211.2
United Kingdom	10946.2		107.8	916.9
Bulgaria	544.7		4.5	1.5
Croatia	599.9		10.1	1.2
Cyprus	198.2		5.2	0.2
Malta	110.3		0.9	0
Romania	3197.6		8.3	101.4
Russia	14508.9		68.6	415.2

Total of Europe

Table 19. Primary resources total quantity of Europe

Unit: US Dollar, Millions	Construction Industry	Packaging Industry	Health and Medical Industry	Automotive Industry
Aluminum and Steel	94627.3	9974.4	0	59950.8
Electronic Components	0	0	1902.6	20499
Glass	17068.4	6515	30551.5	12554.3
Plastic	54118.1	20379.8	4527.3	43893
Pure Silicone	129390.9	0	2238.6	7937.7

The final table obtained by obtaining data on the materials to be used for each sector (Aluminum, Silicone, Glass, etc.) from Input-Output Tables (IOTs) is given above. The data used in the table consists of the sum of European state data. Within the scope of the study, the data in this table was multiplied by the coefficient of 0.03 and the amounts spent for solar panels were calculated with this assumption (Wood Mackenzie, 2021). The final table is given below.

Table 20. Total primary resource usage to be used in the model

Unit: US Dollar, Millions	Construction Industry	Packaging Industry	Health and Medical Industry	Automotive Industry
Aluminum and Steel	2,838.819	299.232	0	1,798.524
Electronic Components	0	0	57.078	614.97
Glass	512.052	195.45	916.545	376.629
Plastic	1,623.543	611.394	135.819	1,316.79
Pure Silicone	3,881.727	0	67.158	238.131
Total	8,856.141	1,106.076	1,176.6	4,345.044

Turkey's share among European states in the tables above is given below.

Table 21. Turkey's share among European states in primary resource use

	Construction Industry	Packaging Industry	Health and Medical Industry	Automotive Industry
Europe Total (Unit: US Dollar, Millions)	8856.141	1106.076	1176.6	4345.044
Turkey Total (Unit: US Dollar, Millions)	632.193	46.566	59.988	79.29
Percentage of Turkey in Europe (%)	7.14	4.21	5.10	1.82

APPENDIX 2 – INTEREST RATE

In this study, interest rate was used as a variable. The interest rate affecting only primary sources was taken as 5.85 by taking the average of the latest interest rates of European countries (Trading Economics, 2024).

Table 22. Interest rate values

Country	Interest Rate
Austria	3.72
Belgium	4.25
Estonia	4.25
Finland	3.05
France	3.15
Germany	2.48
Greece	3.55
Ireland	2.93
Italy	3.94
Latvia	3.43
Lithuania	2.88
Luxembourg	2.94
Netherlands	2.82
Portugal	3.19
Slovakia	3.69
Slovenia	3.32
Spain	3.35
Croatia	3.41
Cyprus	3.34
Malta	3.55
Denmark	3.35
Bulgaria	3.63
Sweden	3.75
Norway	4.50
Czechia	4.75
United Kingdom	5.25
Poland	5.75
Romania	6.75
Hungary	7.00
Iceland	9.25
Russia	16.00
Turkey	50.00
Interest Rate Average	**5.85**

APPENDIX 3 - PRIMARY RESOURCE USES OF KEY SECTORS IN BAU

Table 23. Model result: Primary resource use of key sectors for the business as usual scenario

Construction Industry						
Time (Year)	Total Aluminum and Steel (tons)	Total Electronic Components (tons)	Total Glass (tons)	Total Plastic (tons)	Total Pure Silicon (tons)	Total (tons)
2030	1.05E+06	0	1.46E+07	1.62E+06	3.53E+06	2.08E+07
2031	8.63E+06	0	1.20E+08	1.33E+07	2.90E+07	1.71E+08
2032	7.09E+07	0	9.89E+08	1.10E+08	2.38E+08	1.41E+09
2033	5.83E+08	0	8.13E+09	9.02E+08	1.96E+09	1.16E+10
2034	4.79E+09	0	6.68E+10	7.41E+09	1.61E+10	9.51E+10
2035	3.94E+10	0	5.49E+11	6.09E+10	1.32E+11	7.82E+11
2036	3.24E+11	0	4.51E+12	5.01E+11	1.09E+12	6.43E+12
2037	2.66E+12	0	3.71E+13	4.12E+12	8.95E+12	5.28E+13
2038	2.19E+13	0	3.05E+13	3.38E+13	7.36E+13	1.60E+14
2039	1.80E+14	0	2.51E+15	2.78E+14	6.05E+14	3.57E+15
2040	1.48E+15	0	2.06E+16	2.29E+15	4.97E+15	2.93E+16
2041	1.21E+16	0	1.69E+17	1.88E+16	4.09E+16	2.41E+17
2042	9.99E+16	0	1.39E+18	1.54E+17	3.36E+17	1.98E+18
2043	8.21E+17	0	1.14E+19	1.27E+18	2.76E+18	1.63E+19
2044	6.75E+18	0	9.41E+19	1.04E+19	2.27E+19	1.34E+20
2045	5.55E+19	0	7.73E+20	8.58E+19	1.87E+20	1.10E+21
2046	4.56E+20	0	6.36E+21	7.05E+20	1.53E+21	9.05E+21
2047	3.75E+21	0	5.22E+22	5.80E+21	1.26E+22	7.44E+22
2048	3.08E+22	0	4.29E+23	4.77E+22	1.04E+23	6.12E+23
2049	2.53E+23	0	3.53E+24	3.92E+23	8.52E+23	5.03E+24
2050	2.08E+24	0	2.90E+25	3.22E+24	7.00E+24	4.13E+25
Packaging Industry						
Time (Year)	Total Aluminum and Steel (tons)	Total Electronic Components (tons)	Total Glass (tons)	Total Plastic (tons)	Total Pure Silicon (tons)	Total (tons)
2030	110622	0	5.58E+06	611394	0	6.31E+06
2031	909311	0	4.59E+07	5.03E+06	0	5.18E+07
2032	7.47E+06	0	3.77E+08	4.13E+07	0	4.26E+08
2033	6.14E+07	0	3.10E+09	3.40E+08	0	3.5E+09
2034	5.05E+08	0	2.55E+10	2.79E+09	0	2.88E+10
2035	4.15E+09	0	2.10E+11	2.29E+10	0	2.37E+11
2036	3.41E+10	0	1.72E+12	1.89E+11	0	1.95E+12
2037	2.81E+11	0	1.42E+13	1.55E+12	0	1.6E+13
2038	2.31E+12	0	1.16E+14	1.27E+13	0	1.31E+14

2039	1.90E+13	0	9.57E+14	1.05E+14	0	1.08E+15
2040	1.56E+14	0	7.86E+15	8.61E+14	0	8.88E+15
2041	1.28E+15	0	6.46E+16	7.08E+15	0	7.3E+16
2042	1.05E+16	0	5.31E+17	5.82E+16	0	6E+17
2043	8.65E+16	0	4.37E+18	4.78E+17	0	4.93E+18
2044	7.11E+17	0	3.59E+19	3.93E+18	0	4.05E+19
2045	5.85E+18	0	2.95E+20	3.23E+19	0	3.33E+20
2046	4.81E+19	0	2.43E+21	2.66E+20	0	2.74E+21
2047	3.95E+20	0	1.99E+22	2.18E+21	0	2.25E+22
2048	3.25E+21	0	1.64E+23	1.79E+22	0	1.85E+23
2049	2.67E+22	0	1.35E+24	1.48E+23	0	1.52E+24
2050	2.19E+23	0	1.11E+25	1.21E+24	0	1.25E+25
Health and Medical Industry						
Time (Year)	Total Aluminum and Steel (tons)	Total Electronic Components (tons)	Total Glass (tons)	Total Plastic (tons)	Total Pure Silicon (tons)	Total (tons)
2030	0	114156	2.62E+07	135819	61052.7	2.65E+07
2031	0	938362	2.15E+08	1.12E+06	501853	2.18E+08
2032	0	7.71E+06	1.77E+09	9.18E+06	4.13E+06	1.79E+09
2033	0	6.34E+07	1.45E+10	7.54E+07	3.39E+07	1.47E+10
2034	0	5.21E+08	1.20E+11	6.20E+08	2.79E+08	1.21E+11
2035	0	4.28E+09	9.83E+11	5.10E+09	2.29E+09	9.94E+11
2036	0	3.52E+10	8.08E+12	4.19E+10	1.88E+10	8.17E+12
2037	0	2.89E+11	6.64E+13	3.44E+11	1.55E+11	6.72E+13
2038	0	2.38E+12	5.46E+14	2.83E+12	1.27E+12	5.52E+14
2039	0	1.96E+13	4.49E+15	2.33E+13	1.05E+13	4.54E+15
2040	0	1.61E+14	3.69E+16	1.91E+14	8.60E+13	3.73E+16
2041	0	1.32E+15	3.03E+17	1.57E+15	7.07E+14	3.07E+17
2042	0	1.09E+16	2.49E+18	1.29E+16	5.81E+15	2.52E+18
2043	0	8.93E+16	2.05E+19	1.06E+17	4.78E+16	2.07E+19
2044	0	7.34E+17	1.68E+20	8.73E+17	3.93E+17	1.7E+20
2045	0	6.03E+18	1.38E+21	7.18E+18	3.23E+18	1.4E+21
2046	0	4.96E+19	1.14E+22	5.90E+19	2.65E+19	1.15E+22
2047	0	4.08E+20	9.35E+22	4.85E+20	2.18E+20	9.46E+22
2048	0	3.35E+21	7.69E+23	3.99E+21	1.79E+21	7.78E+23
2049	0	2.75E+22	6.32E+24	3.28E+22	1.47E+22	6.39E+24
2050	0	2.26E+23	5.19E+25	2.69E+23	1.21E+23	5.26E+25
Automotive Industry						
Time (Year)	Total Aluminum and Steel (tons)	Total Electronic Components (tons)	Total Glass (tons)	Total Plastic (tons)	Total Pure Silicon (tons)	Total (tons)
2030	664889	1.23E+06	1.08E+07	1.32E+06	216483	1.42E+07
2031	5.47E+06	1.01E+07	8.85E+07	1.08E+07	1.78E+06	1.17E+08

2032	4.49E+07	8.31E+07	7.27E+08	8.90E+07	1.46E+07	9.59E+08
2033	3.69E+08	6.83E+08	5.98E+09	7.31E+08	1.20E+08	7.88E+09
2034	3.04E+09	5.62E+09	4.91E+10	6.01E+09	9.88E+08	6.48E+10
2035	2.50E+10	4.62E+10	4.04E+11	4.94E+10	8.12E+09	5.32E+11
2036	2.05E+11	3.79E+11	3.32E+12	4.06E+11	6.68E+10	4.38E+12
2037	1.69E+12	3.12E+12	2.73E+13	3.34E+12	5.49E+11	3.6E+13
2038	1.39E+13	2.56E+13	2.24E+14	2.74E+13	4.51E+12	2.96E+14
2039	1.14E+14	2.11E+14	1.84E+15	2.26E+14	3.71E+13	2.43E+15
2040	9.36E+14	1.73E+15	1.52E+16	1.85E+15	3.05E+14	2E+16
2041	7.70E+15	1.42E+16	1.25E+17	1.52E+16	2.51E+15	1.64E+17
2042	6.33E+16	1.17E+17	1.02E+18	1.25E+17	2.06E+16	1.35E+18
2043	5.20E+17	9.62E+17	8.42E+18	1.03E+18	1.69E+17	1.11E+19
2044	4.28E+18	7.91E+18	6.92E+19	8.47E+18	1.39E+18	9.12E+19
2045	3.51E+19	6.50E+19	5.69E+20	6.96E+19	1.14E+19	7.5E+20
2046	2.89E+20	5.34E+20	4.68E+21	5.72E+20	9.41E+19	6.16E+21
2047	2.37E+21	4.39E+21	3.84E+22	4.70E+21	7.73E+20	5.07E+22
2048	1.95E+22	3.61E+22	3.16E+23	3.87E+22	6.36E+21	4.17E+23
2049	1.60E+23	2.97E+23	2.60E+24	3.18E+23	5.22E+22	3.42E+24
2050	1.32E+24	2.44E+24	2.13E+25	2.61E+24	4.29E+23	2.81E+25

Table 24. Model result: Total of primary resource use of key sectors for the business as usual scenario

Time (Year)	Total of Construction Industry (tons)	Total of Packaging Industry (tons)	Total of Health and Medical Industry (tons)	Total of Automotive Industry (tons)	Total of Key Sectors (tons)
2030	2.08E+07	6.31E+06	2.65E+07	1.42E+07	6.78E+07
2031	1.71E+08	5.18E+07	2.18E+08	1.17E+08	5.58E+08
2032	1.41E+09	4.26E+08	1.79E+09	9.59E+08	4.58E+09
2033	1.16E+10	3.50E+09	1.47E+10	7.88E+09	3.77E+10
2034	9.51E+10	2.88E+10	1.21E+11	6.48E+10	3.10E+11
2035	7.82E+11	2.37E+11	9.94E+11	5.32E+11	2.55E+12
2036	6.43E+12	1.95E+12	8.17E+12	4.38E+12	2.09E+13
2037	5.28E+13	1.60E+13	6.72E+13	3.60E+13	1.72E+14
2038	1.60E+14	1.31E+14	5.52E+14	2.96E+14	1.14E+15
2039	3.57E+15	1.08E+15	4.54E+15	2.43E+15	1.16E+16
2040	2.93E+16	8.88E+15	3.73E+16	2.00E+16	9.55E+16
2041	2.41E+17	7.30E+16	3.07E+17	1.64E+17	7.85E+17
2042	1.98E+18	6.00E+17	2.52E+18	1.35E+18	6.45E+18
2043	1.63E+19	4.93E+18	2.07E+19	1.11E+19	5.31E+19
2044	1.34E+20	4.05E+19	1.70E+20	9.12E+19	4.36E+20
2045	1.10E+21	3.33E+20	1.40E+21	7.50E+20	3.58E+21

2046	9.05E+21	2.74E+21	1.15E+22	6.16E+21	2.95E+22
2047	7.44E+22	2.25E+22	9.46E+22	5.07E+22	2.42E+23
2048	6.12E+23	1.85E+23	7.78E+23	4.17E+23	1.99E+24
2049	5.03E+24	1.52E+24	6.39E+24	3.42E+24	1.64E+25
2050	4.13E+25	1.25E+25	5.26E+25	2.81E+25	1.35E+26

APPENDIX 4 - TOTAL RECYCLABLE WASTE AND THE REVENUE GENERATED

Table 25. Model result: Total recyclable waste and the revenue generated for EU in 2030-2050

Time (Year)	Revenue (dollars)	Total Recyclable Waste (tons)
2030	2.08E+06	37400
2031	2.99E+06	44880
2032	4.31E+06	53856
2033	6.20E+06	64627.2
2034	8.93E+06	77552.6
2035	1.29E+07	93063.2
2036	1.85E+07	111676
2037	2.67E+07	134011
2038	3.84E+07	160813
2039	5.53E+07	192976
2040	7.96E+07	231571
2041	1.15E+08	277885
2042	1.65E+08	333462
2043	2.38E+08	400155
2044	3.42E+08	480186
2045	4.93E+08	576223
2046	7.10E+08	691467
2047	1.02E+09	829761
2048	1.47E+09	995713
2049	2.12E+09	1.19E+06
2050	3.05E+09	1.43E+06

Sensitivity Analysis

The sensitivity analysis for this model is given below. Within the scope of sensitivity analysis, the annual growth rate value was taken as 1 at the maximum value and 0 at the minimum value, and the change in the results was observed.

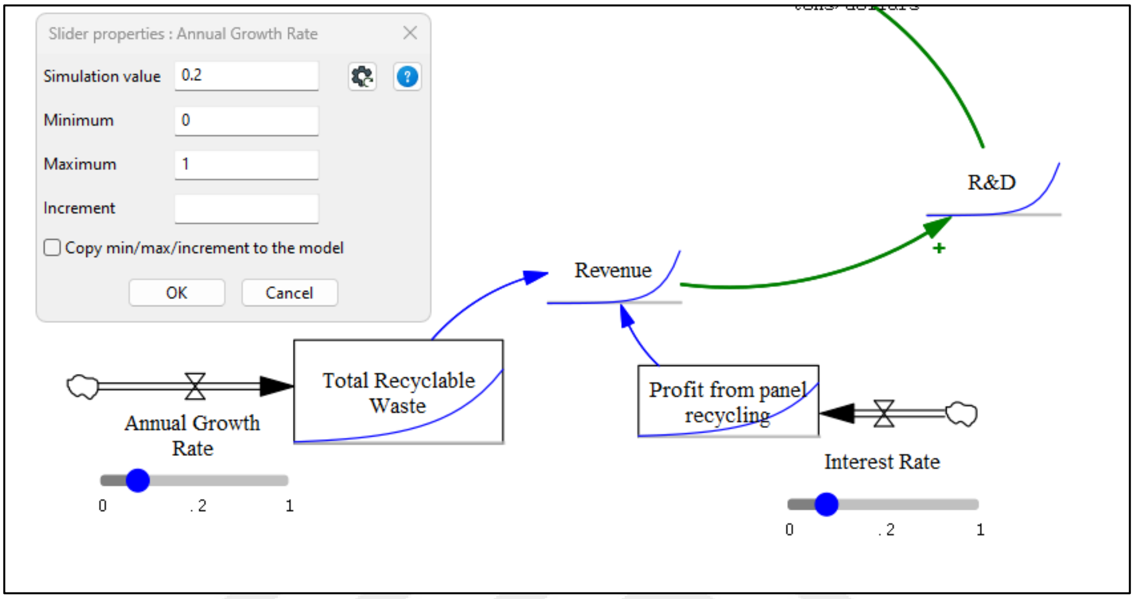

Figure 26. Annual growth rate model value in Vensim PLE

When the annual growth rate value is taken as 0 and 1 within the scope of sensitivity analysis, the Vensim PLE image is given in Figure 27.

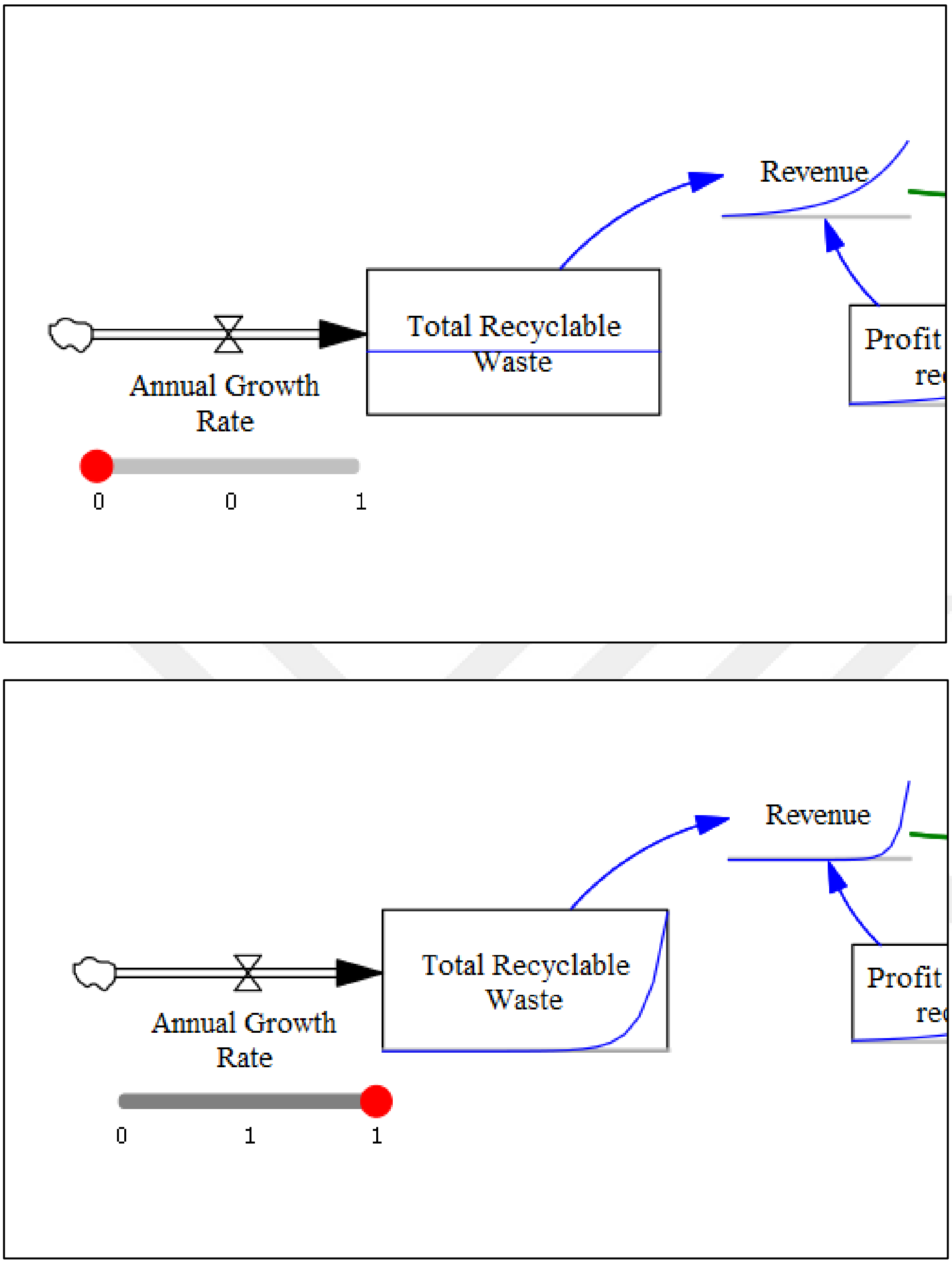

Figure 27. Annual growth rate sensitivity analysis values in Vensim PLE

The amount of revenue to be obtained when the annual growth rate value is taken as 0 and 1 within the scope of sensitivity analysis is given in Table 26.

Table 26. Change in the amount of revenue as a result of changing the annual growth rate value within the scope of sensitivity analysis

	Annual Growth Rate (0.2)	**Annual Growth Rate (Min Value 0)**	**Annual Growth Rate (Max Value 1)**
Time (Year)	**Revenue (dollars)**	**Revenue (dollars)**	**Revenue (dollars)**
2030	2.08E+06	2.08E+06	2.08E+06
2031	2.99E+06	2.49E+06	4.98E+06
2032	4.31E+06	2.99E+06	1.20E+07
2033	6.20E+06	3.59E+06	2.87E+07
2034	8.93E+06	4.31E+06	6.89E+07
2035	1.29E+07	5.17E+06	1.65E+08
2036	1.85E+07	6.20E+06	3.97E+08
2037	2.67E+07	7.44E+06	9.53E+08
2038	3.84E+07	8.93E+06	2.29E+09
2039	5.53E+07	1.07E+07	5.49E+09
2040	7.96E+07	1.29E+07	1.32E+10
2041	1.15E+08	1.54E+07	3.16E+10
2042	1.65E+08	1.85E+07	7.58E+10
2043	2.38E+08	2.22E+07	1.82E+11
2044	3.42E+08	2.67E+07	4.37E+11
2045	4.93E+08	3.20E+07	1.05E+12
2046	7.10E+08	3.84E+07	2.52E+12
2047	1.02E+09	4.61E+07	6.04E+12
2048	1.47E+09	5.53E+07	1.45E+13
2049	2.12E+09	6.64E+07	3.48E+13
2050	3.05E+09	7.96E+07	8.35E+13

As a result of the sensitivity analysis, it was determined that when the annual growth rate value was given a minimum of 0, there would be a revenue approximately 38 times below the model data in 2050. It has been determined that when the annual growth rate value is given a maximum of 1, there will be a revenue of approximately 2.74E+04 times higher than the model data in 2050.

APPENDIX 5 – THE QUANTITY OF ORGANIC SOLAR PANELS PRODUCTION

Table 27. Model result: The quantity of organic solar panels production for EU in 2030-2050

Time (Year)	Organic Solar Cell Production (tons)
2030	37.38
2031	53.83
2032	77.52
2033	111.63
2034	160.74
2035	231.47
2036	333.32
2037	479.97
2038	691.16
2039	995.27
2040	1433.19
2041	2063.80
2042	2971.87
2043	4279.49
2044	6162.47
2045	8873.95
2046	12778.50
2047	18401.00
2048	26497.50
2049	38156.40
2050	54945.20

APPENDIX 6 - THE QUANTITY OF MONOCRYSTALLINE AND ORGANIC SOLAR PANELS PRODUCTION AND REVENUE FOR MINIMUM AND MAXIMUM SCENARIOS

Table 28. Model result: Revenue for minimum and maximum scenarios

	REVENUE (DOLLARS)	
Time (Year)	**MINIMUM SCENARIO**	**MAXIMUM SCENARIO**
2030	1.04E+06	2.08E+06
2031	1.50E+06	4.65E+06
2032	2.15E+06	1.04E+07
2033	3.10E+06	2.33E+07
2034	4.47E+06	5.23E+07
2035	6.43E+06	1.17E+08
2036	9.26E+06	2.62E+08
2037	1.33E+07	5.88E+08
2038	1.92E+07	1.32E+09
2039	2.76E+07	2.95E+09
2040	3.98E+07	6.61E+09
2041	5.73E+07	1.48E+10
2042	8.26E+07	3.31E+10
2043	1.19E+08	7.42E+10
2044	1.71E+08	1.66E+11
2045	2.46E+08	3.73E+11
2046	3.55E+08	8.34E+11
2047	5.11E+08	1.87E+12
2048	7.36E+08	4.19E+12
2049	1.06E+09	9.38E+12
2050	1.53E+09	2.10E+13

APPENDIX 7 - THE QUANTITY OF MONOCRYSTALLINE AND ORGANIC SOLAR PANELS PRODUCTION

Table 29. Model result: The quantity of monocrystalline and organic solar panels production for high and low price band scenarios for EU in 2030-2050

	LOWER PRICE SCENARIO		**HIGHER PRICE SCENARIO**	
Time (Year)	**Monocrystalline Solar Cell Production (tons)**	**Organic Solar Cell Production (tons)**	**Monocrystalline Solar Cell Production (tons)**	**Organic Solar Cell Production (tons)**
2030	69.16	46.11	34.48	27.62
2031	154.92	103.28	77.23	61.87
2032	347.01	231.34	172.99	138.60
2033	777.31	518.21	387.49	310.46
2034	1741.18	1160.79	867.98	695.43
2035	3900.24	2600.16	1944.26	1557.75
2036	8736.54	5824.36	4355.15	3489.37
2037	19569.80	13046.60	9755.54	7816.19
2038	43836.50	29224.30	21852.40	17508.30
2039	98193.70	65462.50	48949.40	39218.50
2040	219954.00	146636.00	109647.00	87849.40
2041	492697.00	328464.00	245609.00	196783.00
2042	1.10E+06	735760.00	550163.00	440793.00
2043	2.47E+06	1.65E+06	1.23E+06	987377.00
2044	5.54E+06	3.69E+06	2.76E+06	2.21E+06
2045	1.24E+07	8.27E+06	6.18E+06	4.95E+06
2046	2.78E+07	1.85E+07	1.39E+07	1.11E+07
2047	6.22E+07	4.15E+07	3.10E+07	2.49E+07
2048	1.39E+08	9.29E+07	6.95E+07	5.57E+07
2049	3.12E+08	2.08E+08	1.56E+08	1.25E+08
2050	7.00E+08	4.66E+08	3.49E+08	2.79E+08

Table 30. Model result: The quantity of monocrystalline and organic solar panels production for minimum and maximum scenarios

	MINIMUM SCENARIO		**MAXIMUM SCENARIO**	
Time (Year)	**Monocrystalline Solar Cell Production (tons)**	**Organic Solar Cell Production (tons)**	**Monocrystalline Solar Cell Production (tons)**	**Organic Solar Cell Production (tons)**
2030	25.96	18.80	51.92	37.59
2031	37.38	27.07	116.30	84.20
2032	53.83	38.97	260.52	188.62
2033	77.52	56.12	583.57	422.50
2034	111.63	80.82	1307.19	946.41

2035	160.74	116.38	2928.11	2119.95
2036	231.47	167.58	6558.96	4748.69
2037	333.32	241.32	14692.10	10637.10
2038	479.97	347.50	32910.30	23827.00
2039	691.16	500.40	73719.00	53372.50
2040	995.27	720.58	165131.00	119554.00
2041	1433.19	1037.63	369892.00	267802.00
2042	2063.80	1494.19	828559.00	599877.00
2043	2971.87	2151.63	1.86E+06	1.34E+06
2044	4279.49	3098.35	4.16E+06	3.01E+06
2045	6162.47	4461.62	9.31E+06	6.74E+06
2046	8873.95	6424.74	2.09E+07	1.51E+07
2047	1.28E+04	9.25E+03	4.67E+07	3.38E+07
2048	1.84E+04	1.33E+04	1.05E+08	7.58E+07
2049	2.65E+04	1.92E+04	2.34E+08	1.70E+08
2050	3.82E+04	2.76E+04	5.25E+08	3.80E+08

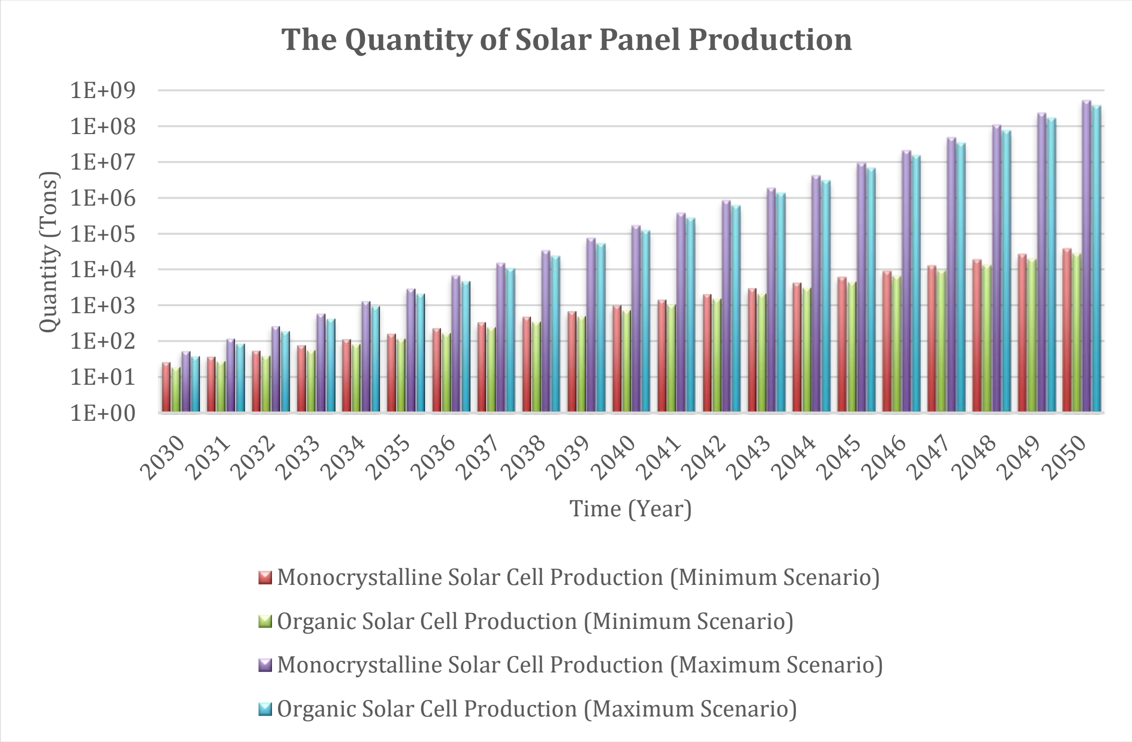

Figure 28. The quantity of monocrystalline and organic solar panels production for minimum and maximum scenarios

APPENDIX 8 - SECONDARY RESOURCES USE AND AVOIDED COST

Table 31. Model result: Secondary resources use and avoided cost

Time (Year)	**Secondary Resources Use in the Construction Industry (tons)**	**Secondary Resources Use in the Packaging Industry (tons)**	**Secondary Resources Use in the Health and Medical Industry (tons)**	**Secondary Resources Use in the Automotive Industry (tons)**	**Construction Ind. (million dollars)**	**Packaging Ind. (million dollars)**	**Health and Medical Ind. (million dollars)**	**Automotive Ind. (million dollars)**
2030	21391.30	2671.64	2841.98	10495.10	8.03	1.00	0.10	1.91
2031	24386.10	3045.67	3239.86	11964.40	10.99	1.37	0.14	2.62
2032	27800.10	3472.06	3693.44	13639.40	15.03	1.88	0.19	3.58
2033	31692.10	3958.15	4210.52	15549.00	20.56	2.57	0.26	4.90
2034	36129.00	4512.29	4799.99	17725.80	28.13	3.51	0.36	6.71
2035	41187.10	5144.01	5471.99	20207.40	38.48	4.81	0.49	9.17
2036	46953.30	5864.18	6238.07	23036.50	52.65	6.58	0.67	12.55
2037	53526.70	6685.16	7111.40	26261.60	72.02	9.00	0.92	17.16
2038	61020.50	7621.08	8106.99	29938.20	98.52	12.31	1.26	23.48
2039	69563.30	8688.04	9241.97	34129.50	134.77	16.84	1.73	32.12
2040	79302.20	9904.36	10535.80	38907.70	184.37	23.03	2.36	43.95
2041	90404.50	11291.00	12010.90	44354.70	252.21	31.50	3.23	60.11
2042	103061.00	12871.70	13692.40	50564.40	345.03	43.10	4.42	82.24
2043	117490.00	14673.70	15609.30	57643.40	471.99	58.96	6.04	112.50
2044	133938.00	16728.10	17794.60	65713.50	645.69	80.65	8.26	153.90
2045	152690.00	19070.00	20285.90	74913.40	883.30	110.33	11.30	210.53
2046	174066.00	21739.80	23125.90	85401.20	1208.35	150.93	15.46	288.00
2047	198435.00	24783.40	26363.50	97357.40	1653.02	206.47	21.14	394.00
2048	226216.00	28253.00	30054.40	110987.00	2261.36	282.44	28.92	538.98
2049	257887.00	32208.50	34262.00	126526.00	3093.51	386.38	39.56	737.33
2050	293991.00	36717.70	39058.70	144239.00	4231.90	528.56	54.11	1008.67

APPENDIX 9 - QUANTITY OF SECONDARY RESOURCE USE IN KEY SECTORS FOR EU IN 2030-2050

Table 32. Model result: Quantity of secondary resource use in key sectors for EU in 2030-2050

Construction Industry						
Time (Year)	Secondary Aluminum and Steel (tons)	Secondary Electronic Components (tons)	Secondary Glass (tons)	Secondary Plastic (tons)	Secondary Pure Silicon (tons)	Total (tons)
2030	3850.43	0.00	14332.20	2353.04	641.74	21391.30
2031	4389.49	0.00	16338.70	2682.47	731.58	24386.10
2032	5004.02	0.00	18626.10	3058.01	834.00	27800.10
2033	5704.58	0.00	21233.70	3486.13	950.76	31692.10
2034	6503.22	0.00	24206.40	3974.19	1083.87	36129.00
2035	7413.67	0.00	27595.30	4530.58	1235.61	41187.10
2036	8451.59	0.00	31458.70	5164.86	1408.60	46953.30
2037	9634.81	0.00	35862.90	5887.94	1605.80	53526.70
2038	10983.70	0.00	40883.70	6712.25	1830.61	61020.50
2039	12521.40	0.00	46607.40	7651.97	2086.90	69563.30
2040	14274.40	0.00	53132.50	8723.24	2379.07	79302.20
2041	16272.80	0.00	60571.00	9944.50	2712.14	90404.50
2042	18551.00	0.00	69051.00	11336.70	3091.83	103061.00
2043	21148.10	0.00	78718.10	12923.90	3524.69	117490.00
2044	24108.90	0.00	89738.60	14733.20	4018.15	133938.00
2045	27484.10	0.00	102302.00	16795.90	4580.69	152690.00
2046	31331.90	0.00	116624.00	19147.30	5221.98	174066.00
2047	35718.40	0.00	132952.00	21827.90	5953.06	198435.00
2048	40719.00	0.00	151565.00	24883.80	6786.49	226216.00
2049	46419.60	0.00	172784.00	28367.50	7736.60	257887.00
2050	52918.40	0.00	196974.00	32339.00	8819.72	293991.00
Packaging Industry						
Time (Year)	Secondary Aluminum and Steel (tons)	Secondary Electronic Components (tons)	Secondary Glass (tons)	Secondary Plastic (tons)	Secondary Pure Silicon (tons)	Total (tons)
2030	480.90	0.00	1790.00	293.88	0.00	2671.64
2031	548.22	0.00	2040.60	335.02	0.00	3045.67
2032	624.97	0.00	2326.28	381.93	0.00	3472.06
2033	712.47	0.00	2651.96	435.40	0.00	3958.15
2034	812.21	0.00	3023.24	496.35	0.00	4512.29
2035	925.92	0.00	3446.49	565.84	0.00	5144.01
2036	1055.55	0.00	3929.00	645.06	0.00	5864.18
2037	1203.33	0.00	4479.06	735.37	0.00	6685.16

2038	1371.80	0.00	5106.13	838.32	0.00	7621.08
2039	1563.85	0.00	5820.98	955.68	0.00	8688.04
2040	1782.78	0.00	6635.92	1089.48	0.00	9904.36
2041	2032.37	0.00	7564.95	1242.01	0.00	11291.00
2042	2316.91	0.00	8624.04	1415.89	0.00	12871.70
2043	2641.27	0.00	9831.41	1614.11	0.00	14673.70
2044	3011.05	0.00	11207.80	1840.09	0.00	16728.10
2045	3432.60	0.00	12776.90	2097.70	0.00	19070.00
2046	3913.16	0.00	14565.70	2391.38	0.00	21739.80
2047	4461.01	0.00	16604.90	2726.17	0.00	24783.40
2048	5085.55	0.00	18929.50	3107.83	0.00	28253.00
2049	5797.52	0.00	21579.70	3542.93	0.00	32208.50
2050	6609.18	0.00	24600.80	4038.94	0.00	36717.70
Health and Medical Industry						
Time (Year)	Secondary Aluminum and Steel (tons)	Secondary Electronic Components (tons)	Secondary Glass (tons)	Secondary Plastic (tons)	Secondary Pure Silicon (tons)	Total (tons)
2030	0.00	28.42	1904.13	312.62	85.26	2841.98
2031	0.00	32.40	2170.70	356.38	97.20	3239.86
2032	0.00	36.93	2474.60	406.28	110.80	3693.44
2033	0.00	42.11	2821.05	463.16	126.32	4210.52
2034	0.00	48.00	3215.99	528.00	144.00	4799.99
2035	0.00	54.72	3666.23	601.92	164.16	5471.99
2036	0.00	62.38	4179.51	686.19	187.14	6238.07
2037	0.00	71.11	4764.64	782.25	213.34	7111.40
2038	0.00	81.07	5431.69	891.77	243.21	8106.99
2039	0.00	92.42	6192.12	1016.62	277.26	9241.97
2040	0.00	105.36	7059.02	1158.94	316.08	10535.80
2041	0.00	120.11	8047.28	1321.20	360.33	12010.90
2042	0.00	136.92	9173.90	1506.16	410.77	13692.40
2043	0.00	156.09	10458.20	1717.03	468.28	15609.30
2044	0.00	177.95	11922.40	1957.41	533.84	17794.60
2045	0.00	202.86	13591.50	2231.45	608.58	20285.90
2046	0.00	231.26	15494.40	2543.85	693.78	23125.90
2047	0.00	263.64	17663.60	2899.99	790.91	26363.50
2048	0.00	300.54	20136.50	3305.99	901.63	30054.40
2049	0.00	342.62	22955.60	3768.82	1027.86	34262.00
2050	0.00	390.59	26169.30	4296.46	1171.76	39058.70
Automotive Industry						
Time (Year)	Secondary Aluminum and Steel (tons)	Secondary Electronic Components (tons)	Secondary Glass (tons)	Secondary Plastic (tons)	Secondary Pure Silicon (tons)	Total (tons)
2030	1889.12	104.95	7031.72	1154.46	314.85	10495.10

2031	2153.59	119.64	8016.16	1316.09	358.93	11964.40
2032	2455.10	136.39	9138.42	1500.34	409.18	13639.40
2033	2798.81	155.49	10417.80	1710.38	466.47	15549.00
2034	3190.65	177.26	11876.30	1949.84	531.77	17725.80
2035	3637.34	202.07	13539.00	2222.82	606.22	20207.40
2036	4146.56	230.37	15434.40	2534.01	691.09	23036.50
2037	4727.08	262.62	17595.20	2888.77	787.85	26261.60
2038	5388.87	299.38	20058.60	3293.20	898.15	29938.20
2039	6143.31	341.30	22866.80	3754.25	1023.89	34129.50
2040	7003.38	389.08	26068.10	4279.84	1167.23	38907.70
2041	7983.85	443.55	29717.70	4879.02	1330.64	44354.70
2042	9101.59	505.64	33878.10	5562.08	1516.93	50564.40
2043	10375.80	576.43	38621.10	6340.77	1729.30	57643.40
2044	11828.40	657.14	44028.00	7228.48	1971.40	65713.50
2045	13484.40	749.13	50192.00	8240.47	2247.40	74913.40
2046	15372.20	854.01	57218.80	9394.14	2562.04	85401.20
2047	17524.30	973.57	65229.50	10709.30	2920.72	97357.40
2048	19977.70	1109.87	74361.60	12208.60	3329.62	110987.00
2049	22774.60	1265.26	84772.20	13917.80	3795.77	126526.00
2050	25963.10	1442.39	96640.30	15866.30	4327.18	144239.00

Table 33. Model result: Total quantity of secondary resource use in key sectors for EU in 2030-2050

Time (Year)	**Total of Construction Industry (tons)**	**Total of Packaging Industry (tons)**	**Total of Health and Medical Industry (tons)**	**Total of Automotive Industry (tons)**	**Total of Key Sectors (tons)**
2030	21391.30	2671.64	2841.98	10495.10	37400.02
2031	24386.10	3045.67	3239.86	11964.40	42636.03
2032	27800.10	3472.06	3693.44	13639.40	48605.00
2033	31692.10	3958.15	4210.52	15549.00	55409.77
2034	36129.00	4512.29	4799.99	17725.80	63167.08
2035	41187.10	5144.01	5471.99	20207.40	72010.50
2036	46953.30	5864.18	6238.07	23036.50	82092.05
2037	53526.70	6685.16	7111.40	26261.60	93584.86
2038	61020.50	7621.08	8106.99	29938.20	106686.77
2039	69563.30	8688.04	9241.97	34129.50	121622.81
2040	79302.20	9904.36	10535.80	38907.70	138650.06
2041	90404.50	11291.00	12010.90	44354.70	158061.10
2042	103061.00	12871.70	13692.40	50564.40	180189.50
2043	117490.00	14673.70	15609.30	57643.40	205416.40
2044	133938.00	16728.10	17794.60	65713.50	234174.20

Time (Year)	Total of Construction Industry (tons)	Total of Packaging Industry (tons)	Total of Health and Medical Industry (tons)	Total of Automotive Industry (tons)	Total of Key Sectors (tons)
2045	152690.00	19070.00	20285.90	74913.40	266959.30
2046	174066.00	21739.80	23125.90	85401.20	304332.90
2047	198435.00	24783.40	26363.50	97357.40	346939.30
2048	226216.00	28253.00	30054.40	110987.00	395510.40
2049	257887.00	32208.50	34262.00	126526.00	450883.50
2050	293991.00	36717.70	39058.70	144239.00	514006.40

APPENDIX 10 - THE COST TO BE AVOIDED BY USING SECONDARY RESOURCES IN LIEU OF PRIMARY RESOURCES

Avoided Cost with the Using Secondary Resources in Lieu of Primary Resources (Average Price Scenario)

Table 34. Model results: The cost to be avoided by using secondary resources in lieu of primary resources (Average Price Scenario)

Construction Industry			
Time (Year)	**Secondary Resource Expenditure (million dollars)**	**Primary Resource Expenditure (million dollars)**	**Avoided Cost (million dollars)**
2030	646.98	655.01	8.03
2031	738.75	749.74	10.99
2032	843.81	858.84	15.03
2033	964.18	984.74	20.56
2034	1102.22	1130.35	28.13
2035	1260.71	1299.19	38.48
2036	1442.93	1495.58	52.65
2037	1652.77	1724.79	72.02
2038	1894.87	1993.39	98.52
2039	2174.80	2309.57	134.77
2040	2499.31	2683.68	184.37
2041	2876.63	3128.84	252.21
2042	3316.86	3661.89	345.03
2043	3832.53	4304.52	471.99
2044	4439.27	5084.96	645.69
2045	5156.78	6040.08	883.30
2046	6010.08	7218.43	1208.35
2047	7031.17	8684.19	1653.02
2048	8261.34	10522.70	2261.36
2049	9754.19	12847.70	3093.51
2050	11579.80	15811.70	4231.90
Packaging Industry			
Time (Year)	**Secondary Resource Expenditure (million dollars)**	**Primary Resource Expenditure (million dollars)**	**Avoided Cost (million dollars)**
2030	0.65	1.66	1.00
2031	0.90	2.27	1.37
2032	1.22	3.10	1.88
2033	1.68	4.24	2.57
2034	2.29	5.81	3.51
2035	3.14	7.94	4.81
2036	4.29	10.87	6.58

2037	5.87	14.86	9.00
2038	8.03	20.33	12.31
2039	10.98	27.81	16.84
2040	15.02	38.05	23.03
2041	20.55	52.05	31.50
2042	28.11	71.20	43.10
2043	38.45	97.41	58.96
2044	52.60	133.25	80.65
2045	71.95	182.28	110.33
2046	98.43	249.36	150.93
2047	134.66	341.12	206.47
2048	184.21	466.65	282.44
2049	251.99	638.37	386.38
2050	344.73	873.29	528.56
Health and Medical Industry			
Time (Year)	**Secondary Resource Expenditure (million dollars)**	**Primary Resource Expenditure (million dollars)**	**Avoided Cost (million dollars)**
2030	85.55	85.65	0.10
2031	97.59	97.74	0.14
2032	111.35	111.54	0.19
2033	127.06	127.33	0.26
2034	145.02	145.38	0.36
2035	165.55	166.05	0.49
2036	189.05	189.72	0.67
2037	215.95	216.87	0.92
2038	246.78	248.04	1.26
2039	282.14	283.87	1.73
2040	322.75	325.11	2.36
2041	369.46	372.69	3.23
2042	423.27	427.68	4.42
2043	485.37	491.41	6.04
2044	557.22	565.48	8.26
2045	640.57	651.87	11.30
2046	737.54	752.99	15.46
2047	850.77	871.91	21.14
2048	983.52	1012.44	28.92
2049	1139.88	1179.44	39.56
2050	1325.01	1379.12	54.11
Automotive Industry			
Time (Year)	**Secondary Resource Expenditure (million dollars)**	**Primary Resource Expenditure (million dollars)**	**Avoided Cost (million dollars)**
2030	317.44	319.35	1.91
2031	362.47	365.09	2.62

2032	414.02	417.60	3.58
2033	473.09	477.99	4.90
2034	540.83	547.53	6.71
2035	618.61	627.78	9.17
2036	708.04	720.59	12.55
2037	811.03	828.19	17.16
2038	929.86	953.34	23.48
2039	1067.27	1099.39	32.12
2040	1226.57	1270.52	43.95
2041	1411.83	1471.94	60.11
2042	1627.99	1710.23	82.24
2043	1881.23	1993.73	112.50
2044	2179.24	2333.14	153.90
2045	2531.72	2742.25	210.53
2046	2950.99	3238.99	288.00
2047	3452.80	3846.80	394.00
2048	4057.51	4596.49	538.98
2049	4791.51	5528.84	737.33
2050	5689.35	6698.02	1008.67

Total of All Sectors (Average Price Scenario)

Table 35. Model results: The total cost to be avoided by using secondary resources in lieu of primary resources (Average Price Scenario)

Time (Year)	Avoided Cost (million dollars)
2030	11.05
2031	15.12
2032	20.69
2033	28.30
2034	38.71
2035	52.95
2036	72.45
2037	99.10
2038	135.57
2039	185.45
2040	253.71
2041	347.05
2042	474.78
2043	649.49
2044	888.50
2045	1.22E+03
2046	1.66E+03
2047	2.27E+03
2048	3.11E+03
2049	4.26E+03
2050	5.82E+03

Avoided Cost with the Using Secondary Resources in Lieu of Primary Resources (High Price Scenario)

Table 36. Model results: The cost to be avoided by using secondary resources in lieu of primary resources (High Price Scenario)

Construction Industry			
Time (Year)	**Secondary Resource Expenditure (million dollars)**	**Primary Resource Expenditure (million dollars)**	**Avoided Cost (million dollars)**
2030	646.98	685.98	38.997
2031	738.75	792.09	53.345
2032	843.81	916.78	72.971
2033	964.18	1064.00	99.824
2034	1102.22	1238.77	136.55
2035	1260.71	1447.50	186.79
2036	1442.93	1698.46	255.53
2037	1652.77	2002.32	349.55
2038	1894.87	2373.04	478.17
2039	2174.80	2828.92	654.12
2040	2499.31	3394.13	894.82
2041	2876.63	4100.72	1224.09
2042	3316.86	4991.39	1674.53
2043	3832.53	6123.25	2290.72
2044	4439.27	7572.95	3133.68
2045	5156.78	9443.61	4286.83
2046	6010.08	11874.40	5864.32
2047	7031.17	15053.50	8022.33
2048	8261.34	19235.80	10974.46
2049	9754.19	24767.20	15013.01
2050	11579.80	32117.50	20537.7
Packaging Industry			
Time (Year)	**Secondary Resource Expenditure (million dollars)**	**Primary Resource Expenditure (million dollars)**	**Avoided Cost (million dollars)**
2030	0.65	5.54	4.89
2031	0.90	7.58	6.68
2032	1.22	10.36	9.14
2033	1.68	14.17	12.50
2034	2.29	19.38	17.09
2035	3.14	26.51	23.37
2036	4.29	36.25	31.96
2037	5.87	49.58	43.72
2038	8.03	67.82	59.79
2039	10.98	92.76	81.78

2040	15.02	126.88	111.86
2041	20.55	173.56	153.01
2042	28.11	237.40	209.29
2043	38.45	324.73	286.28
2044	52.60	444.20	391.60
2045	71.95	607.62	535.66
2046	98.43	831.17	732.74
2047	134.66	1136.98	1002.33
2048	184.21	1555.31	1371.10
2049	251.99	2127.57	1875.58
2050	344.73	2910.41	2565.69
Health and Medical Industry			
Time (Year)	**Secondary Resource Expenditure (million dollars)**	**Primary Resource Expenditure (million dollars)**	**Avoided Cost (million dollars)**
2030	85.55	88.68	3.13
2031	97.59	101.87	4.28
2032	111.35	117.20	5.85
2033	127.06	135.06	8.00
2034	145.02	155.96	10.94
2035	165.55	180.51	14.95
2036	189.05	209.50	20.45
2037	215.95	243.92	27.96
2038	246.78	285.02	38.24
2039	282.14	334.44	52.30
2040	322.75	394.29	71.53
2041	369.46	467.30	97.84
2042	423.27	557.08	133.82
2043	485.37	668.40	183.03
2044	557.22	807.57	250.35
2045	640.57	983.00	342.44
2046	737.54	1205.94	468.40
2047	850.77	1491.48	640.71
2048	983.52	1859.94	876.42
2049	1139.88	2338.74	1198.86
2050	1325.01	2964.94	1639.93
Automotive Industry			
Time (Year)	**Secondary Resource Expenditure (million dollars)**	**Primary Resource Expenditure (million dollars)**	**Avoided Cost (million dollars)**
2030	317.44	336.88	19.44
2031	362.47	389.06	26.60
2032	414.02	450.40	36.38
2033	473.09	522.85	49.76
2034	540.83	608.89	68.06

2035	618.61	711.72	93.11
2036	708.04	835.40	127.36
2037	811.03	985.25	174.22
2038	929.86	1168.18	238.32
2039	1067.27	1393.27	326.00
2040	1226.57	1672.53	445.96
2041	1411.83	2021.88	610.05
2042	1627.99	2462.52	834.53
2043	1881.23	3022.83	1141.60
2044	2179.24	3740.92	1561.68
2045	2531.72	4668.05	2136.33
2046	2950.99	5873.43	2922.44
2047	3452.80	7450.65	3997.85
2048	4057.51	9526.49	5468.98
2049	4791.51	12273.00	7481.49
2050	5689.35	15923.90	10234.55

Total of All Sectors (High Price Scenario)

Table 37. Model results: The total cost to be avoided by using secondary resources in lieu of primary resources (High Price Scenario)

Time (Year)	Avoided Cost (million dollars)
2030	66.46
2031	90.90
2032	124.34
2033	170.08
2034	232.64
2035	318.22
2036	435.30
2037	595.45
2038	814.53
2039	1.11E+03
2040	1.52E+03
2041	2.08E+03
2042	2.85E+03
2043	3.90E+03
2044	5.34E+03
2045	7.30E+03
2046	9.99E+03
2047	1.37E+04
2048	1.87E+04
2049	2.56E+04
2050	3.50E+04

APPENDIX 11 - SECONDARY RESOURCE USE AS A RESULT OF BUSINESS AS USUAL, INCREASED PRICE AND PRICE FIXATION

Table 38. Model result: The effects of fixed price policy for secondary resource use as a result of Business as usual, Increased price and Price Fixation

	Secondary Sources Use in the Construction Industry (Tons)	**Secondary Sources Use in the Packaging Industry (Tons)**	**Secondary Sources Use in the Health and Medical Industry (Tons)**	**Secondary Sources Use in the Automotive Industry (Tons)**
Business as Usual (BAU)	21391.28	2671.64	2841.98	10495.10
Increased Price	14973.90	1870.15	1989.39	7346.57
Fixed-Price	17219.98	2150.67	2287.79	8448.55

APPENDIX 12 - EIA OF RECYCLING AND LANDFILL OPTIONS FOR C-SI SOLAR PANELS FOR ALL IMPACT CATEGORIES, SIMAPRO RESULTS

Table 39. EIA of recycling and landfill options for c-Si PV for all impact categories, SimaPro results

Impact category	**Unit**	**Landfill, c-Si PV module**	**Recycling, c-Si PV module** (Singh et al., 2023)
Global warming	kg CO2 eq	5.35E-05	-1.03E+00
Stratospheric ozone depletion	kg CFC11 eq	1.08E-06	-1.26E-07
Ionizing radiation	kBq Co-60 eq	5.79E-05	1.45E-02
Ozone formation. Human health	kg NOx eq	3.51E-05	-4.64E-03
Fine particulate matter formation	kg PM2.5 eq	8.43E-06	-5.28E-03
Ozone formation. Terrestrial ecosystems	kg NOx eq	4.13E-05	-4.67E-03
Terrestrial acidification	kg SO2 eq	1.41E-05	-1.01E-02
Freshwater eutrophication	kg P eq	0.000151	-4.07E-03
Marine eutrophication	kg N eq	8.09E-07	5.50E-05
Terrestrial ecotoxicity	kg 1.4-DCB	0.00029	-7.75E+01
Freshwater ecotoxicity	kg 1.4-DCB	0.009252	-7.07E-01
Marine ecotoxicity	kg 1.4-DCB	0.011656	-1.01E+00
Human carcinogenic toxicity	kg 1.4-DCB	0.865126	-3.58E-01
Human non-carcinogenic toxicity	kg 1.4-DCB	0.009192	-2.52E+01
Land use	m^2a crop eq	2.41E-06	-1.20E-03
Mineral resource scarcity	kg Cu eq	6.90E-09	1.22E-02
Fossil resource scarcity	kg oil eq	4.33E-05	-1.77E-01
Water consumption	m^3	8.42E-06	-7.81E-03

APPENDIX 13 - EIA OF ORGANIC AND C-SI SOLAR PANELS FOR ALL IMPACT CATEGORIES, SIMAPRO RESULTS

Table 40. EIA of organic and c-Si solar panels for all impact categories, SimaPro results

Impact category	Unit	c-Si PV Module	Organic Solar Cell
Global warming	kg CO2 eq	0.050802	0.000499
Stratospheric ozone depletion	kg CFC11 eq	0.003143	0.000207
Ionizing radiation	kBq Co-60 eq	0.063458	0.000512
Ozone formation. Human health	kg NOx eq	0.0358	0.000368
Fine particulate matter formation	kg PM2.5 eq	0.025242	0.000234
Ozone formation. Terrestrial ecosystems	kg NOx eq	0.043383	0.000448
Terrestrial acidification	kg SO2 eq	0.027929	0.000348
Freshwater eutrophication	kg P eq	0.323107	0.002243
Marine eutrophication	kg N eq	0.004579	0.000364
Terrestrial ecotoxicity	kg 1.4-DCB	6.041656	0.006207
Freshwater ecotoxicity	kg 1.4-DCB	14.01135	0.080185
Marine ecotoxicity	kg 1.4-DCB	24.04866	0.072732
Human carcinogenic toxicity	kg 1.4-DCB	34.95844	2.104982
Human non-carcinogenic toxicity	kg 1.4-DCB	21.74745	0.063662
Land use	m^2a crop eq	0.001546	0.000178
Mineral resource scarcity	kg Cu eq	4.11E-05	5.97E-08
Fossil resource scarcity	kg oil eq	0.081128	0.000911
Water consumption	m^3	0.032253	0.001009