

Article

Decision-Making Approach to Design a Sustainable Photovoltaic Closed-Loop Supply Chain Considering Market Share for Electric Vehicle Energy

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Abstract: This study aims to develop a model for the closed-loop supply chain of photovoltaic (PV) systems. The primary objective addresses strategic and tactical decision-making using a two-stage approach. To pinpoint suitable locations for solar power plants, the PROMETHEE II method is utilized, which is a component of multi-attribute decision making (MADM) approaches. Next, a multi-objective modeling of the closed-loop PV supply chain is conducted. This model aims to minimize total supply chain costs, reduce environmental impacts, mitigate adverse social effects, maximize the on-time delivery (OTD) of manufactured products, and maximize market share. Additionally, a robust fuzzy mathematical model is introduced to examine the model's sustainability under various uncertainties. An evaluation of the effectiveness and utility of this model is conducted in Tehran city. Furthermore, a comprehensive analysis of various supply chain costs indicates that production centers have the highest costs, while separation centers have the lowest costs.

Keywords: energy supply; photovoltaic; sustainability; on-time delivery; market share



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1. Introduction

In today's global business landscape, supply chain processes wield a significant influence [1]. Thus, a supply chain network (SCN) must be strategically designed to establish a reliable and robust network for the production of finished goods and the timely delivery of those goods to the customers [2]. Within these processes, markets strive to satisfy the needs of customers while taking into account the enhancement of product quality, expedited delivery of products, and fluctuations in customer demand levels. Markets are fiercely competitive, with numerous companies competing for market share and making significant investments in research and development in order to optimize efficiency and reduce costs. Simultaneously, driven by factors such as the scarcity of valuable resources, escalating customer demands, economic conditions, and the growing influence of environmental and social concerns, the design of reverse logistics networks is gaining traction among supply chain professionals [3]. The formulation of a closed-loop supply chain yields benefits by fulfilling customer demands in diverse markets, both through direct product flows and through the reverse flow of returned products [4].

Currently, with a steadily growing global population, worldwide energy consumption has increased significantly, and after the Paris Climate Agreement was adopted and the global commitment to achieving carbon neutrality was made, the transition to renewable energy has become essential worldwide [5]. Among the primary motivations for the growing adoption of renewable energy sources is the desire to reduce reliance on fossil fuels and mitigate their environmental impacts. The term “renewable energy” refers to energy that can be naturally replenished or restored within a relatively short period of time. Notable examples of recognized renewable energy sources include solar energy, wind,

waves, geothermal, and biomass. Using renewable energy sources is widely regarded as the most economically viable, secure, and sustainable approach to meeting our energy requirements [6]. Considering the importance of this issue, there has been a surge of interest in designing and implementing efficient and practical supply chain networks within the renewable energy sector.

Over the past few years, solar energy has emerged as one of the most promising sources of renewable energy for meeting the energy needs of a number of countries. This is due to the fact that it is a naturally abundant resource, widely available and economical. Solar energy accounts for 60% of total renewable energy production [7]. In the future, solar energy, particularly PV systems, will play a significant role in energy provision for convincing reasons [8]. These include the virtually limitless availability of solar energy resources, minimal water-cooling requirements, environmental sustainability considerations, the ease of implementation, rapid deployment capabilities, a high potential for reducing greenhouse gas emissions, and efficiency in regions where the economic feasibility of electric grid distribution is limited [9]. Despite these numerous advantages, the high costs associated with PV systems remain a primary concern.

The electrification of vehicles has gained momentum in several countries around the world in recent years. Electric vehicles (EVs) represent a crucial avenue for fostering an environmentally conscious evolution and low-carbon metamorphosis within the global automotive industry. The latest report from the International Energy Agency (IEA) reveals that global EV sales surpassed 14 million units in 2023 [10]. This shift has created a surging demand for electrical energy to power these vehicles. In 2022, electric vehicles (EVs) constituted 14% of all new car purchases, and it is anticipated that this number will surge to roughly 35% by 2030 [11]. The expanding presence of EVs has unlocked new possibilities for their utilization as adaptable energy resources.

The global cumulative installed capacities for solar energy, significant as of 2020, are expected to increase substantially by 2050, underscoring the growing reliance on this sustainable energy source [12]. The resulting annual growth underscores the necessity for a well-designed photovoltaic supply chain network (PVSCN) to ensure efficient cost reduction within the supply chain.

By addressing three key aspects simultaneously, the World Commission on Environment and Development has adopted a holistic approach to sustainability. Photovoltaic (PV) systems in particular are poised for continued growth as the world moves toward a more sustainable, low-carbon energy system. Due to this, it is necessary that sustainability considerations are included in the design of the photovoltaic supply chain network.

Furthermore, the dynamic and intricate nature of supply chains introduces considerable uncertainties that have a significant impact on their overall performance. It is important to note that in the real world, a multitude of factors can introduce uncertainty into the data, such as inflation, which has an impact on production and product maintenance costs. Therefore, decision-makers should place a high priority on addressing various uncertainty factors within the photovoltaic supply chain (PVSC) to ensure enhanced adaptability.

Several approaches have been explored in recent years in order to optimize supply chains under uncertain conditions. These approaches encompass random, fuzzy, and robust optimization techniques. In the robust approach, ensuring the optimal solution's resilience against existing uncertainties leads to finding a robust solution that simultaneously considers both feasibility robustness and optimality robustness. For instance, researchers have employed a data-driven, robust approach to address uncertainties within the problem at hand [13].

There is a significant challenge associated with the construction of solar power plants due to their high costs. This underscores the need to meticulously assess potential locations based on economic and environmental factors, ensuring that they meet efficient criteria before embarking on the design of a supply chain model. Therefore, multi-criteria decision-making (MCDM) models offer optimal solutions for this purpose [14].

This research delves into the impact of the aforementioned factors on the PVSCND. The primary objective of this study is to develop an optimal supply chain model for PV systems, recognizing that decision-makers grapple with inherent uncertainties related to solar power plant demands and production and repair costs across different network layers. Throughout the work, a fuzzy robust optimization approach has been employed to mitigate the adverse effects of unexpected events stemming from parameter uncertainties. This study proposes an approach to partially address the growing demand for electrical energy by establishing solar power plants. The key to maximizing the benefits of these power plants lies in ensuring timely product delivery within the various layers of the PVSC systems. Additionally, this research underscores the importance of safeguarding the supply chain against competing systems, with the primary objective of enhancing market share and reducing lost sales.

This section outlines the structure of the present study. In Section 2, an overview of PV system studies is presented. Section 3 is initiated with a discussion on the optimal locations for solar power plants and their integration with electric vehicle charging stations. Subsequently, a novel closed-loop supply chain for PV systems is introduced. Section 4 involves the utilization of a multi-objective mathematical model designed for shaping a multi-period and multi-level supply chain network. Three core elements are considered by this network: sustainability, on-time delivery targets, and market share acquisition. Additionally, the fuzzy robust approach and an exact solution method are introduced. Section 5 showcases the practical application of the model through a real case study and its subsequent analysis. In Section 6, practical and managerial insights gleaned from the results are provided. Lastly, in Section 7, conclusions are drawn, and avenues for future research are outlined.

2. Literature Review

In this section, an exploration of the existing literature related to PV systems will be initiated. The research gaps in the field will first be identified and discussed. Subsequently, the findings of previous studies will be consolidated into a summary table, and the innovative contributions of this research will be presented.

In the deployment of PV systems, optimization methods play a crucial role in improving production efficiency and minimizing costs. Several optimization methodologies have been applied within this context. For instance, these techniques were harnessed by Hartner et al. [15] to determine the optimal tilt angle for PV modules. Similarly, uncertainties in PV system electricity generation were addressed through the utilization of a mixed-integer non-linear programming model [16]. This model, in turn, facilitated the adjustment of operational schedules for conventional generators while considering operational costs and available storage. Bousselamti et al. [17] implemented an optimization study of the PV-concentrated solar power system under different dispatch strategies. The purpose of the first objective was to minimize the levelized cost of electricity (LCOE) and to maximize the capacity factor simultaneously. For the second objective, they added reducing the dumped energy as a criterion. The results of their study indicate that the dispatch strategy that maintains the power block operation at minimum rated power is more suitable and results in a high capacity factor, low LCOE, and low dumped energy.

A recurring theme in the discourse on PVSC issues is the concept of competition. For instance, Chen and Su [18] argued that a surplus in supply had intensified competition within the PVSC. To shed light on the dynamics of this competition, they conducted a comprehensive theoretical and numerical investigation of trade within the PVSC. This research effort aimed to yield deeper insights and propose pertinent policies. In a subsequent study, Chen and Su [19] sought to address the prevailing gaps in the literature concerning PVSC studies. They specifically focused on the identification of effective mechanisms for balance and coordination within the PVSC, particularly in the context of government subsidy policies. Their primary objective was to enhance

overall social welfare. Furthermore, Chen et al. [20] contended that government subsidy policies, while instrumental in fostering the growth of the PV industry, also precipitated overcapacity problems. To tackle this challenge, they employed game theory models to formulate more effective government subsidy policies for the PV industry. Their findings underscored the importance of governmental control over market entry into the PV industry and the promotion of healthy competition among multiple PV supply chains to optimize the performance of both the PVSC and government subsidy policies. In a separate study, an integrated framework was introduced for the development of a flexible solar energy management system under three distinct scenarios [21]. This framework delved into the competitive dynamics of the multi-period PV cell supply chain, considering factors such as domestic and foreign competitors, as well as government tariffs. The overarching objective was to enhance the efficiency of the PVSC. Chen and Sun [22] introduced a dual competing PV supply chains in terms of cooperative research and development (R&D) of generic technology. They believed that, collaborative R&D around generic technologies among module suppliers across PV supply chains will help create complementary synergies and accelerate breakthroughs in generic technologies. The results indicated that in all scenarios, the adoption of a centralized operational strategy is more effective in terms of government subsidies and the operational performance of the PV supply chains than a hybrid or decentralized operational strategy.

Numerous past studies have employed various methodologies, including MCDM, Data Envelopment Analysis (DEA), geographic information systems (GISs), and their combinations, to identify optimal locations for solar power plants. Several of these studies are highlighted below.

Zoghi et al. [23] employed a combination of the Analytic Hierarchy Process (AHP), fuzzy logic models, and Weighted Linear Combination (WLC) to evaluate criteria and determine suitable locations for solar power plants. Azadeh et al. [24] utilized the DEA method, with a focus on population density and proximity to the power distribution network as crucial factors in their analysis of solar power plant locations. Sánchez et al. [25] integrated ELECTRE-TRI within a GIS to identify appropriate sites for solar power plants. Fang et al. [26] introduced a two-stage approach based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), prospect theory, and variable precision rough number theory to pinpoint ideal locations for solar power plants. Maleki et al. [27] leveraged GIS software (version 10.5.1) to ascertain optimal sites for PV systems, taking into consideration socio-economic, environmental, and technical criteria. Ernesto et al. [28] proposed an MCDM framework rooted in the AHP to prioritize factors within sustainable supply chains for PV systems. They subsequently ranked various energy production locations based on their proposed methodology. Francisco et al. [29] employed data-driven tools to evaluate the placement of PV installations in urban areas, with the overarching goal of mitigating climate change and enhancing urban sustainability. Hosseini and Firoozabadi [30] presented a new four stage comprehensive framework based on a geographic information system (GIS) and fuzzy SWARA to identify suitable areas for developing solar power plants (SPPs) in one of the dust-prone areas of Iran, Yazd province. Also Ding et al. [31] provided an effective strategy for identifying suitable locations for solar power plants and other production centers, which can be referred to as the Nash negotiation model to maximize the profits of all participants. The literature review on PV systems demonstrates that many previous studies have focused on determining suitable locations for PV facilities.

Additionally, some researchers have focused on the development of integrated supply chains for PV systems in addition to the optimal locations for solar power plants. These networks encompass not only strategic but also tactical decision-making considerations. As an illustrative example, Chen et al. [32] introduced a deterministic optimization model for the design of the PVSC. To solve this model efficiently, they devised a Particle Swarm Optimization (PSO) algorithm. Through this approach, they aimed to obtain optimal

values for various operational aspects such as transportation, procurement from recycling units, and waste disposal. Their analytical findings demonstrated that a company can enhance its economic efficiency by adhering to carbon emission regulations and implementing an appropriate recycling strategy or energy-saving technologies. Albrecht and Steinrücke [33] have delved into the development of mixed-integer linear programming models to optimize various facets of the PVSCN. Their model encompasses production, distribution, and transportation considerations, with a particular focus on determining the optimal time for sales. The objective of their research is to maximize the overall profit within the supply chain network. Wang et al. [34] proposed a dual-objective model for a solar concentrator system in which a trade-off between maximizing the manufacturer's profit and the community's energy collected is achieved when designing and allocating this system. Experiments indicated that their proposed method significantly improves both energy collection efficiency and profits earned.

In a separate study conducted by Dehghani et al. [35], a two-stage approach for designing a resilient PVSC under conditions of uncertainty was explored. The initial stage involved the identification of suitable locations for various supply chain components, incorporating factors such as technical, geographical, and social aspects through the Data Envelopment Analysis (DEA) method. The second stage of their investigation centered on the modeling of a robust supply chain capable of addressing inherent uncertainties. Tactical decisions in this research encompass the determination of production and import quantities at production centers, inventory levels at these centers, transportation volumes between different tiers, and the quantity of electricity generated at solar power plants. The analysis put forth by Dehghani et al. suggests that the proposed robust model exhibits superior performance compared to the expected value model, considering both the average and standard deviation of economic objective function values. Furthermore, they introduced a combined model that integrates robust and scenario-based approaches for designing a flexible PV supply chain, thereby enhancing its resilience in the face of various risks. This research also explored the implementation of flexible strategies aimed at bolstering the PV supply chain's capabilities and reducing its vulnerability to the negative consequences of unforeseen events.

In another study conducted by Dehghani et al. [9], the focus was on a solar PV supply chain. This research uniquely considered the interplay between economic factors and environmental impacts while applying a robust approach to confront the inherent uncertainties within the system. The results of this research underscored the significant impact and effectiveness of their proposed model.

Gilani et al. [13] demonstrated the reduction in conservatism and overall costs through the optimization of robust data-driven models in comparison to classical sets of uncertainties. This approach has the potential to enhance the attractiveness of investing in PV systems. Tactical decisions explored in this work encompass purchase decisions, transportation considerations, inventory management at production centers, electricity generation levels from solar power plants, optimal procurement strategies for transport trucks, and the augmentation of production capacity.

Through the NSGA-II genetic algorithm, Yuan et al. [36] obtained the Pareto optimal solution with the minimum environmental pollution and the lowest economic cost in the whole life cycle of solar PV technology. The results of their research demonstrated that toxic environmental impacts are the primary categories of crystalline silicon PV panels' potential environmental impacts, and monocrystalline silicon PV technology is the more advantageous choice when considering environmental impact and electricity supply cost. Wu et al. [37] presented a co-design model for combined heat and power-based microgrids. They formulated an MIP model to minimize the total installation cost of all components in the microgrid. The comparison between the case study results with and without disruptions indicates that the proposed co-design model is able to flexibly optimize the configuration of the microgrid as well as the schedule of operation to minimize overall cost.

In the present research, the foundational work of Dehghani et al. [35], which focused on a forward PVSC and an economic objective function, serves as the basis for our study. The findings of Dehghani et al. [9], which introduced two objective functions encompassing economic and environmental considerations, are further extended. Additionally, considerations are made regarding a solar power plant as the ultimate customer, and relevant adjustments and improvements are explored. The literature review, as summarized in Table 1, highlights six key aspects that are intended to be collectively investigated for the first time:

- 1- Identifying suitable sites for solar power plants and the associated electric vehicle charging stations using the PROMETHEE II method.
- 2- Designing a closed-loop PVSCN while considering both tactical and strategic decisions.
- 3- Formulating a multi-objective mathematical model for the PVSC, integrating three essential sustainability dimensions.
- 4- Incorporating product delivery lead times into the modeling of PVSC systems.
- 5- Including market share acquisition as a factor within the modeling of PVSCs to minimize lost sales.
- 6- Addressing uncertainties associated with certain input data within the PVSC model.

Table 1. Summary of literature review.

Case Study	Uncertainty	MADM	MODM	Considering Market Share	Considering Delivery Time	Sustainability (3 Aspects)	Articles
*		TOPSIS- ELE. TRI					Sanchez et al. (2016) [25]
*		AHP					Zoghi et al. (2017) [23]
			*				Chen et al. (2017) [32]
*		TOPSIS, prospect theory					Fang et al. (2018) [26]
*			*				Chen and Su (2018) [18]
*	*		*				Dehghani et al. (2018) [35]
*	*		*				Chen and Su (2019) [19]
*	*		*				Dehghani et al. (2020) [9]
*	*		*				Manouchehrabadi et al. (2020) [21]
*	*	Robust-BWM	*				Gilani et al. (2022) [13]
*	*	PROMETHEE II-Fuzzy AHP					Almasad et al. (2023) [14]
*	*		*	*			Chen and Sun. (2024) [22]
*	*	Fuzzy SWARA					Hosseini and Firoozabadi (2023) [30]
*	*		*				Yuan et al. (2023) [36]
*	*	PROMETHEE II	*	*	*	*	This Paper

Note: * means that the table column is applied to the related papers.

This research begins with the initial focus on the identification of suitable solar power plant sites. Subsequently, the formulation of a closed-loop PVSC is addressed, taking into account economic, environmental, and social objectives, as well as the optimization of on-time product delivery and the maximization of market share. Uncertainties in certain input data are accommodated by the mathematical model presented. In the case study section, a comprehensive explanation of the data required for the environmental objective function is provided. Furthermore, to transform the multi-objective model into a single-objective one, the proposed exact solution method is employed, ensuring the attainment of optimal Pareto solutions. As a result, significant advancements across various dimensions of sustainability are achieved by the model. The practical applicability of the proposed model is assessed by conducting a case study in Tehran to evaluate its performance.

3. Problem Statement

In this section, the PROMETHEE II method will first be introduced for the prioritization of candidate locations for solar power plants and their associated electric vehicle charging stations. After that, the closed loop supply chain of PV systems for electric vehicle energy supply will be described. The deterministic model includes the assumptions that will be presented in the rest of this section.

3.1. PROMETHEE II (Preference Ranking Organization Method for Enrichment)

The MCDM family constitutes a subset of decision-making methods within the broader framework of operations research. MCDM problems are characterized by the decision-makers quest for an optimal solution among available options, often entailing conflicting and diverse quantitative and qualitative criteria. MCDM problems are typically categorized into two primary classes: the first category employs utility functions, while the second category resorts to outranking methods, with PROMETHEE being a notable member of this category. Among the various PROMETHEE methods, PROMETHEE II provides a comprehensive ranking approach, and comprehensive details about this method can be found in various references (e.g., Brans and Vincke, 1985 [38]).

In the context of this work, appropriate criteria for the selection of sites for solar power plants and their associated electric vehicle charging stations have been identified. These criteria, along with their respective impacts, are outlined in Table 2. Subsequently, the ranking of the proposed areas is explored using the Visual PROMETHEE software (version 1.4). It should be noted that the higher the net flow value assigned to a region, the higher its level of preference.

Table 2. Effective criteria in decision-making.

Criterion	Criterion Effect
Environmental factors	The possibility of initial construction and the construction of larger power plants in the future
Geology (existence of faults)	Reducing renovation and repair costs
Population and vehicle density	Reducing urban traffic
Safety and security	Protection of infrastructure and equipment against risks
Economic factors	Reducing construction costs

In this study, specific regions within Tehran, namely 1, 2, 4, 5, 7, 10, 12, 15, 16, 18, and 21, were designated as primary candidates for ranking. Following the application of these options, along with their associated criteria and weights, within the Visual PROMETHEE software (version 1.4), based on the opinions of experts and specialists, regions 18, 10, 2, 7, 16, and 21 were chosen as the preferred sites for the establishment of solar power plants and their associated electric vehicle charging stations. The complete ranking of these regions is presented in Figure 1.

3.2. Description of the Model

The solar energy production process encompasses several stages, including the supply of raw materials, wafer production, cell manufacturing, module production, and, ultimately, solar energy generation at a solar power plant. When considering the power plant as the ultimate customer, a three-layer supply chain is involved. The first layer includes the supplier of crystalline ingot, the second layer comprises wafer, cell, and module manufacturers, and the third layer represents solar power plants. The proposed closed-loop PVSC process is depicted in Figure 2. This research endeavors to present a sustainable PVSC model that incorporates considerations of social and environmental factors.

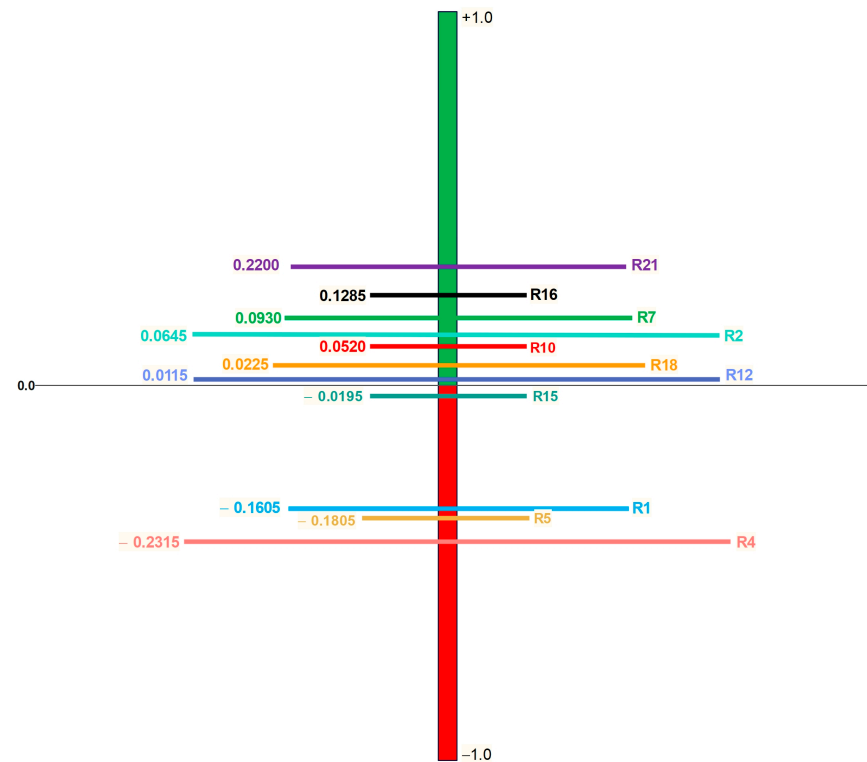


Figure 1. PROMETHEE II.

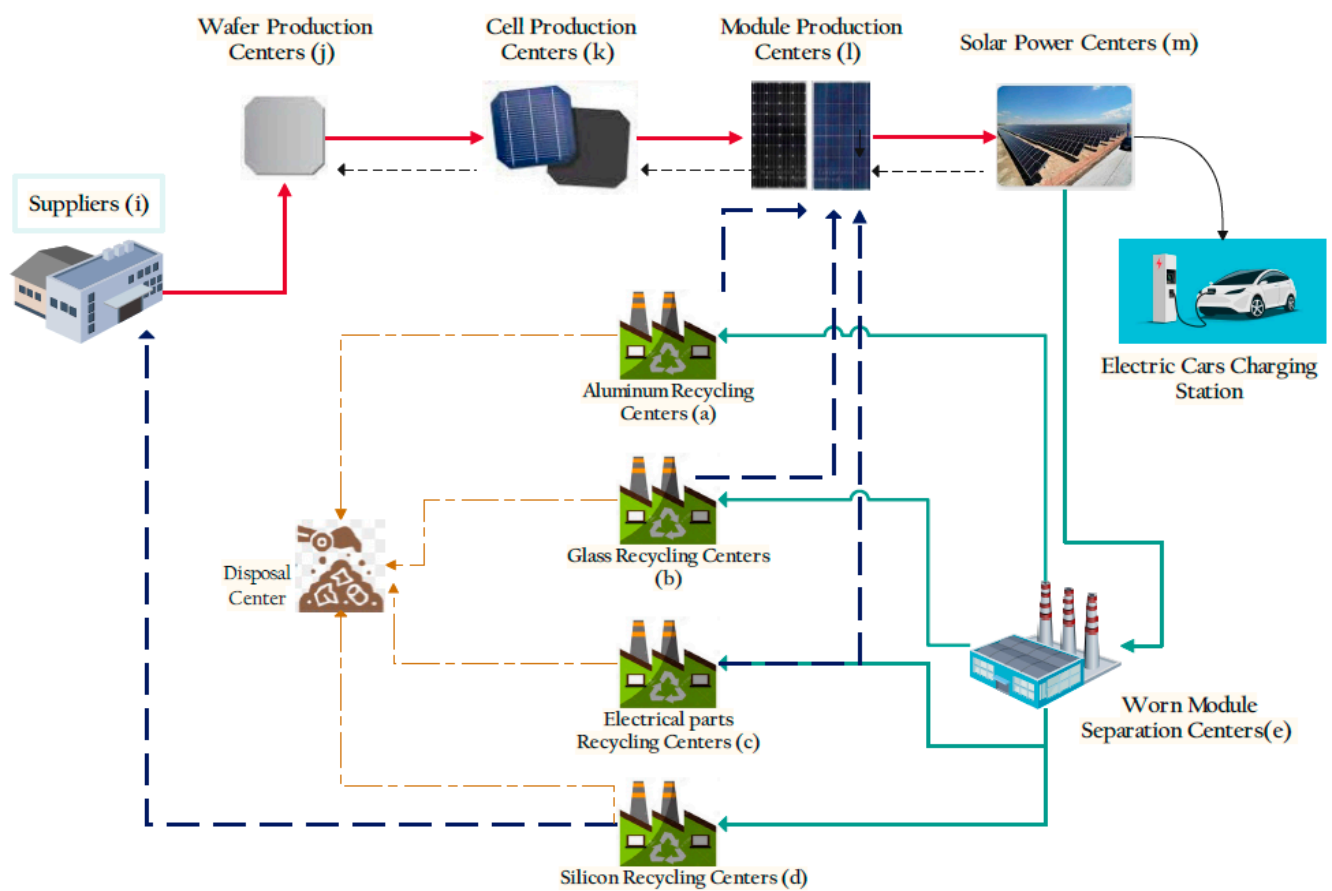


Figure 2. The proposed photovoltaic closed-loop supply chain.

The assumptions underlying the mathematical model are as follows:

- 1- Uncertainties exist in certain parameters.
- 2- Costs encompass a range of elements, including construction, production, maintenance, repairs, transportation, recycling, disposal, and potential revenue losses.
- 3- The possibility of product returns due to defects is acknowledged.
- 4- Manufacturers with lower return rates are perceived as having higher social responsibility.
- 5- Environmental considerations pertaining to manufacturers are taken into account.

4. Mathematical Modeling

4.1. The Proposed Mathematical Model

In this section, the model's objective functions and constraints will be elucidated. All parameters and variables are explained in Appendix A. The first objective function (z1) is formulated by examining revenue and supply chain costs:

$$FC = \sum_j FCJ_j \cdot XJ_j + \sum_k FCK_k \cdot XK_k + \sum_l FCL_l \cdot XL_l \quad (1)$$

Equation (1) signifies the fixed costs associated with establishing production centers.

$$\begin{aligned} TC = & \sum_i \sum_j \sum_t TCIJ_{ijt} \cdot \sum_n QIJ_{ijnt} + \sum_j \sum_k \sum_t TCJK_{jkt} \cdot \sum_n QJK_{jknt} \\ & + \sum_k \sum_l \sum_t TCKL_{klt} \cdot \sum_n QKL_{klnt} \\ & + \sum_l \sum_m \sum_t TCLM_{lmt} \cdot \sum_n QLM_{lmnt} \\ & + \sum_m \sum_e \sum_t TCME_{met} \cdot \sum_n QME_{ment} \\ & + \sum_e \sum_a \sum_t TCEA_{eat} \cdot \sum_n QEA_{eant} \\ & + \sum_e \sum_b \sum_t TCEB_{ebt} \cdot \sum_n QEB_{ebnt} \\ & + \sum_e \sum_c \sum_t TCEC_{ect} \cdot \sum_n QEC_{ecnt} \\ & + \sum_e \sum_d \sum_t TCED_{edt} \cdot \sum_n QED_{ednt} \\ & + \sum_a \sum_l \sum_t TCAL_{alt} \cdot \sum_n QAL_{alnt} \\ & + \sum_b \sum_l \sum_t TCBL_{blt} \cdot \sum_n QBL_{blnt} \\ & + \sum_c \sum_l \sum_t TCCL_{clt} \cdot \sum_n QCL_{clnt} + \\ & + \sum_d \sum_i \sum_t TCDI_{dit} \cdot \sum_n QDI_{dint} \end{aligned} \quad (2)$$

Equation (2) incorporates transportation costs between various layers of the supply chain.

$$LC = \sum_m \sum_n \sum_t LSM_{mnt} \cdot CLSM_{mnt} \quad (3)$$

Equation (3) accounts for costs related to lost sales.

$$\begin{aligned} PC = & \sum_i \sum_n \sum_t MCI_{int} \cdot MQIJ_{int} + \sum_j \sum_n \sum_t MCJ_{jnt} \cdot MQJK_{jnt} \\ & + \sum_k \sum_n \sum_t MCK_{knt} \cdot MQKL_{knt} + \sum_l \sum_n \sum_t MCL_{lnt} \cdot MQLM_{lnt} \end{aligned} \quad (4)$$

Equation (4) represents the production costs of wafers, cells, and modules at the production centers.

$$\begin{aligned} HC = & \sum_j \sum_n \sum_t SCJ_{jnt} \cdot INVJK_{jnt} + \sum_k \sum_n \sum_t SCK_{knt} \cdot INVKL_{knt} \\ & + \sum_l \sum_n \sum_t SCL_{lnt} \cdot INVLM_{lnt} \end{aligned} \quad (5)$$

Equation (5) includes product holding costs at production centers.

$$MC = \sum_j \sum_k \sum_n \sum_t RQJK_{jkn} \cdot CRJ_{jnt} + \sum_k \sum_l \sum_n \sum_t RQKL_{kln} \cdot CRK_{knt} + \sum_l \sum_m \sum_n \sum_t RQLM_{lmn} \cdot CRL_{lnt} \quad (6)$$

Equation (6) encompasses the expenses associated with repairing returned products at production centers.

$$RI = \sum_e \sum_a \sum_n \sum_t QEA_{eant} \cdot PEA_{ent} + \sum_e \sum_b \sum_n \sum_t QEB_{ebnt} \cdot PEB_{ent} + \sum_e \sum_c \sum_n \sum_t QEC_{ecnt} \cdot PEC_{ent} + \sum_e \sum_d \sum_n \sum_t QED_{ednt} \cdot PED_{ent} + \sum_a \sum_l \sum_n \sum_t QAL_{alnt} \cdot PAL_{ant} + \sum_b \sum_l \sum_n \sum_t QBL_{blnt} \cdot PBL_{bnt} + \sum_c \sum_l \sum_n \sum_t QCL_{clnt} \cdot PCL_{cnt} + \sum_d \sum_i \sum_n \sum_t QDI_{dint} \cdot PDI_{dnt} \quad (7)$$

Equation (7) encompasses the revenue generated from the sale of recoverable products from end-of-life modules, such as aluminum, glass, electronic components, and solar cells, to various recycling centers, as well as the sales of recovered aluminum, glass, electronic components, and silicon to module production centers and suppliers.

$$SC = \sum_m \sum_e \sum_n \sum_t QME_{ment} \cdot CE_{ent} \quad (8)$$

Equation (8) represents the costs associated with the separation of end-of-life modules at separation centers.

$$RC = \sum_e \sum_a \sum_n \sum_t QEA_{eant} \cdot CA_{ant} + \sum_e \sum_b \sum_n \sum_t QEB_{ebnt} \cdot CB_{bnt} + \sum_e \sum_c \sum_n \sum_t QEC_{ecnt} \cdot CC_{cnt} + \sum_e \sum_d \sum_n \sum_t QED_{ednt} \cdot CD_{dnt} \quad (9)$$

Equation (9) includes the overall recycling costs at recycling centers.

$$\text{Minimize}z1 = (FC + TC + LC + PC + HC + MC + SC + RC) - RI \quad (10)$$

Equation (10), representing $z1$, is designed to minimize the total supply chain costs.

$$\text{Minimize}z2 = \sum_i \sum_n \sum_t ECI_{int} \cdot \frac{MQIJ_{int}}{UD} + \sum_j \sum_n \sum_t ECJ_{jnt} \cdot \frac{MQJK_{jnt}}{UA} + \sum_k \sum_n \sum_t ECK_{knt} \cdot \frac{MQKL_{knt}}{UB} + \sum_l \sum_n \sum_t ECL_{lnt} \cdot \frac{MQLM_{lnt}}{UC} \quad (11)$$

Equation (11), representing $z2$, aims to minimize energy consumption at production centers.

$$\text{Minimize}z3 = \sum_j \sum_k \sum_n \sum_t RQJK_{jkn} + \sum_k \sum_l \sum_n \sum_t RQKL_{kln} + \sum_l \sum_m \sum_n \sum_t RQLM_{lmn} \quad (12)$$

Equation (12), is geared toward maximizing social welfare by minimizing the total number of returned products.

$$\begin{aligned} \text{Maximize } z_4 = & \sum_i \sum_j \sum_n \sum_t \text{POTIJ}_{ijt} \cdot \text{QIJ}_{ijnt} \\ & + \sum_j \sum_k \sum_n \sum_t \text{POTJK}_{jkt} \cdot \text{QJK}_{jknt} \\ & + \sum_k \sum_l \sum_n \sum_t \text{POTKL}_{klt} \cdot \text{QKL}_{klnt} \\ & + \sum_l \sum_m \sum_n \sum_t \text{POTLM}_{lmt} \cdot \text{QLM}_{lmnt} \end{aligned} \quad (13)$$

Equation (13) (z4) strives to maximize the on-time delivery of products shipped between production centers.

$$\text{Maximize } z_5 = \sum_l \sum_m \sum_n \sum_t \text{QLM}_{lmnt} / \sum_m \sum_n \sum_t \text{DM}_{mnt} \quad (14)$$

Equation (14) (z5) endeavors to maximize the attained market share.

$$\begin{aligned} \text{INVJK}_{jnt} = & (\text{INVJK}_{jnt-1} + \text{MQJK}_{jnt} + \sum_k \text{RQJK}_{jknt}) - \sum_k \text{QJK}_{jknt} \\ & \forall j \in J, \forall n \in N, \forall t \in T \end{aligned} \quad (15)$$

Equation (15) represents the inventory of wafers.

$$\begin{aligned} \text{INVKL}_{knt} = & (\text{INVKL}_{knt-1} + \text{MQKL}_{knt} + \sum_l \text{RQKL}_{klnt}) - \sum_l \text{QKL}_{klnt} \\ & \forall k \in K, \forall n \in N, \forall t \in T \end{aligned} \quad (16)$$

Equation (16) represents the inventory of cells.

$$\begin{aligned} \text{INVLM}_{lnt} = & (\text{INVLM}_{lnt-1} + \text{MQLM}_{lnt} + \sum_k \text{RQLM}_{lmnt}) - \sum_m \text{QLM}_{lmnt} \\ & \forall l \in L, \forall n \in N, \forall t \in T \end{aligned} \quad (17)$$

Equation (17) indicates the inventory of modules.

$$\text{INVJK}_{jnt} \leq \text{CAPJ}_{jn} \forall j \in J, \forall n \in N, \forall t \in T \quad (18)$$

Equation (18) represents the constraint on wafer inventory capacity.

$$\text{INVKL}_{knt} \leq \text{CAPK}_{kn} \forall k \in K, \forall n \in N, \forall t \in T \quad (19)$$

Equation (19) represents the constraint on cell inventory capacity.

$$\text{INVLM}_{lnt} \leq \text{CAPL}_{ln} \forall l \in L, \forall n \in N, \forall t \in T \quad (20)$$

Equation (20) represents the constraint on module inventory capacity.

$$H \cdot \sum_k \text{QJK}_{jknt} \leq \sum_k \text{RQJK}_{jknt} \leq HP \cdot \sum_k \text{QJK}_{jknt} \quad \forall j \in J, \forall n \in N, \forall t \in T \quad (21)$$

$$H \cdot \sum_l \text{QKL}_{klnt} \leq \sum_l \text{RQKL}_{klnt} \leq HP \cdot \sum_l \text{QKL}_{klnt} \quad \forall k \in K, \forall n \in N, \forall t \in T \quad (22)$$

$$H \cdot \sum_m \text{QLM}_{lmnt} \leq \sum_m \text{RQLM}_{lmnt} \leq HP \cdot \sum_m \text{QLM}_{lmnt} \quad \forall l \in L, \forall n \in N, \forall t \in T \quad (23)$$

Equations (21)–(23) depict the volume or flow of returned products to a manufacturer.

$$\sum_j \text{QIJ}_{ijnt} = \text{MQIJ}_{int} \quad \forall i \in I, \forall n \in N, \forall t \in T \quad (24)$$

Equation (24) indicates that due to the lack of storage capacity at suppliers, all produced crystalline wafers are sent from suppliers to wafer manufacturers.

$$DJ_{jnt}.XJ_j \leq \sum_i QIJ_{ijnt} \leq M.XJ_j \quad \forall j \in J, \forall n \in N, \forall t \in T \quad (25)$$

$$DK_{knt}.XK_k \leq \sum_j QJK_{jknt} \leq M.XK_k \quad \forall k \in K, \forall n \in N, \forall t \in T \quad (26)$$

$$DL_{lnt}.XL_l \leq \sum_k QKL_{klnt} \leq M.XL_l \quad \forall l \in L, \forall n \in N, \forall t \in T \quad (27)$$

$$\sum_l QLM_{lmnt} + LSM_{mnt} = DM_{mnt} \quad \forall m \in M, \forall n \in N, \forall t \in T \quad (28)$$

Equations (25)–(28) express that the minimum requirements of production centers must be met if established, and the demand of the solar power plant can be fulfilled either through the proposed supply chain or competitors.

$$MQJK_{jnt} = NTA \cdot \sum_i QIJ_{ijnt} \quad \forall j \in J, \forall n \in N, \forall t \in T \quad (29)$$

$$MQKL_{knt} = NTB \cdot \sum_j QJK_{jknt} \quad \forall k \in K, \forall n \in N, \forall t \in T \quad (30)$$

$$MQLM_{lnt} = NTC \cdot \sum_k QKL_{klnt} \quad \forall l \in L, \forall n \in N, \forall t \in T \quad (31)$$

Equations (29)–(31) denote the number of productions in production centers.

$$MQIJ_{int} \leq CAPII_{int} \quad \forall i \in I, \forall n \in N, \forall t \in T \quad (32)$$

$$MQJK_{jnt} \leq CAPMJ_{jnt} \quad \forall j \in J, \forall n \in N, \forall t \in T \quad (33)$$

$$MQKL_{knt} \leq CAPMK_{knt} \quad \forall k \in K, \forall n \in N, \forall t \in T \quad (34)$$

$$MQLM_{lnt} \leq CAPML_{lnt} \quad \forall l \in L, \forall n \in N, \forall t \in T \quad (35)$$

Equations (32)–(35) illustrate that production capacity exists for each product and period.

$$\sum_e QME_{ment} = NFM \cdot \left(\sum_l QLM_{lmnt} + LSM_{mnt} \right) \quad \forall m \in M, \forall n \in N, \forall t \in T \quad (36)$$

Equation (36) represents the flow of sending end-of-life modules to separation centers.

$$\sum_a QEA_{eant} = \sum_m QME_{ment} \quad \forall e \in E, \forall n \in N, \forall t \in T \quad (37)$$

$$\sum_b QEB_{ebnt} = \sum_m QME_{ment} \quad \forall e \in E, \forall n \in N, \forall t \in T \quad (38)$$

$$\sum_c QEC_{ecnt} = \sum_m QME_{ment} \quad \forall e \in E, \forall n \in N, \forall t \in T \quad (39)$$

$$\sum_d QED_{ednt} = \sum_m QME_{ment} \quad \forall e \in E, \forall n \in N, \forall t \in T \quad (40)$$

Equations (37)–(40) represent the flow of products separated from separation centers to recycling centers.

$$\sum_l QAL_{alnt} = NBA \cdot \sum_e QEA_{eant} \quad \forall a \in A, \forall n \in N, \forall t \in T \quad (41)$$

$$\sum_l QBL_{blnt} = NBB \cdot \sum_e QEB_{ebnt} \quad \forall b \in B, \forall n \in N, \forall t \in T \quad (42)$$

$$\sum_l QCL_{clnt} = NBC \cdot \sum_e QEC_{ecnt} \quad \forall c \in C, \forall n \in N, \forall t \in T \quad (43)$$

$$\sum_i QDI_{dint} = NBD \cdot WM \cdot \sum_e QED_{ednt} \quad \forall d \in D, \forall n \in N, \forall t \in T \quad (44)$$

Equations (41)–(44) describe the flows from recycling centers to module production centers and suppliers.

4.2. Fuzzy Robust Model

To address the uncertain parameters, present in the objective function and constraints, various methodologies have been developed, with one notable approach being Fuzzy Robust Programming (e.g., Pishvae et al., 2012 [39]). Fuzzy robust modeling does not require precise probability distributions for uncertain parameters; it only requires knowledge of parameter bounds. Consequently, the application of these models for modeling uncertainty becomes more straightforward. In this research, this approach is employed to manage the uncertainties in our input data. Trapezoidal fuzzy numbers will be used to represent the bounds of uncertain parameters. The initial mathematical model can be expressed as follows:

$$\tilde{a} = \{\tilde{a}_1, \tilde{a}_2, \tilde{a}_3, \tilde{a}_4\}$$

$$\min Z = fy + cx \quad (45)$$

s.t :

$$Ax \geq d \quad (46)$$

$$Bx = 0 \quad (47)$$

$$Sx \leq Ny \quad (48)$$

$$Tx \leq 1 \quad (49)$$

$$y \in \{0, 1\}; x \geq 0 \quad (50)$$

Given that f , c , d , and N are uncertain parameters, the fuzzy robust model assumes a non-linear form, necessitating the implementation of linearization procedures.

$$\begin{aligned} \text{Min} \frac{1}{4} * (\tilde{f}_1 + \tilde{f}_2 + \tilde{f}_3 + \tilde{f}_4)y + \frac{1}{4} * (\tilde{c}_1 + \tilde{c}_2 + \tilde{c}_3 + \tilde{c}_4)x + \gamma(Z_{\max} - Z_{\min}) + \\ \delta \left(\tilde{d}_4 - (1 - \alpha)\tilde{d}_3 - \alpha\tilde{d}_4 \right) + \lambda(\beta\tilde{N}_1 + (1 - \beta)\tilde{N}_2 - \tilde{N}_1)y \end{aligned} \quad (51)$$

$$Ax \geq (1 - \alpha)\tilde{d}_3 + \alpha\tilde{d}_4 \quad (52)$$

$$Bx = 0 \quad (53)$$

$$Sx \leq \left[(1 - \beta)\tilde{N}_2 + \beta\tilde{N}_1 \right] y \quad (54)$$

$$Tx \leq 1 \quad (55)$$

$$y \in \{0, 1\}; x \geq 0 \quad (56)$$

4.3. Proposed Exact Solution Method

This method can be viewed as a fusion of the lexicographic method and the evolved epsilon-constraint method. It is presumed that the initial model is formulated as follows:

$$\text{Maximize} \{f_1(x)\} \quad (57)$$

$$\text{Minimize} \{f_2(x), \dots, f_i(x)\} \quad (58)$$

$$\text{s.t: } x \in X \quad (59)$$

The method progresses through the following stages:

Step 1: Selection of a primary objective function.

Step 2: Independent optimization of each objective function and calculation of their optimal values.

Step 3: Calculation of the value of each objective function for the optimal values of the variables identified in step 1.

Step 4: Determination of weights for each objective function (with the constraint that the sum of all weights equals 1) to adjust the relative importance of each objective function.

Step 5: Solving the model below utilizing the augmented epsilon constraint method with two objective functions.

5. Case Study

5.1. Solar Energy in Tehran City

An evaluation of the practical applicability of a mathematical model is presented in this section. The case study examines a PVSC under uncertain conditions in Tehran, the capital city of Iran. Tehran, as the most populous city in Iran, holds strategic importance in the country's energy landscape. It is worth noting that Iran possesses approximately 10% of the world's crude oil reserves, contributing to its significant reliance on fossil fuels. The current energy consumption in Iran is predominantly fueled by fossil resources (over 99%), with renewable energy sources accounting for less than 1% of the total consumption. This heavy dependence on fossil fuels has been associated with high economic costs, resource depletion, and environmental pollution. Furthermore, the estimated lifespan of Iran's remaining oil resources is limited to approximately 93 years [40]. Iran is geographically endowed with abundant sunlight, with two-thirds of its land area experiencing an average of 300 sunny days per year [40]. Consequently, Iran, including Tehran, possesses a significant potential for harnessing solar energy. The current population of Tehran stands at over 9 million residents and continues to grow annually. The adoption of electric vehicles (EVs) in Iran is in its early stages, but government reports indicate that mass EV adoption, particularly in Tehran, is anticipated by 2024. This shift towards electric mobility is expected to drive an increase in the demand for electrical energy in the region.

Considering the increasing demand for energy and environmental concerns, the Iranian government has implemented policies and strategies to assist the private sector in installing solar power plants. Additionally, they have supported research centers in the field of solar energy to advance technologies. This case study presents an approach to address a portion of the electrical energy requirements for EV charging through the utilization of solar power plants.

5.2. Data Collection

For the purpose of data collection, well-established databases were used to gather the necessary information. Additionally, certain assumptions were applied in the data collection process, and these assumptions will be elaborated in the following. The standard size of each solar cell is 156×156 mm, and each solar module is considered to contain 60 cells. The conversion rates from one product to another are detailed in Table 3.

Table 3. Conversion rate values.

Process	Conversion Rate
Converting crystal ingots to wafers	10
Convert wafer to cell	1
Convert cell to module	0.01666

The concept of embodied energy refers to the total energy consumed in the manufacturing, operation, and maintenance of products. This energy consumption has a direct correlation with greenhouse gas emissions and air pollution in the production of goods

and services [41]. A breakdown of the energy consumption at various stages of the PVSC is presented in Table 4 [42]. Furthermore, the area of each cell or wafer is estimated to be 0.024336 m^2 . This estimation serves as the basis for calculating the area of other products used. Thus, the area of a 60-cell module can be calculated as follows: $60 \times 0.024336 \text{ m}^2$. For the estimation of transportation costs, the proposed approach on the website [<https://irits.ir>, accessed on 27 July 2023] was utilized, with costs varying depending on the product type.

Table 4. Amount of energy consumption (MJ/m^2).

Process	Monocrystalline	Multicrystalline
Purification of silicon	1231.6	1222.8
Czochralski process	1436.8	-
Wafer manufacturing process	307	658.4
Cell manufacturing process	308.8	339
Module	615.8	790
Total	3900	3010

5.3. Computational Results and Analysis

This section presents the results of the analysis and the applications of the model. In this work, specific regions in Tehran have been designated for various stages of the PVSC.

Regions 5 and 17 in Tehran are designated as locations for crystalline ingot suppliers. Six regions in Tehran serve as candidate locations for wafer manufacturers. Another six regions in Tehran are candidate locations for cell manufacturers. Additionally, six regions in Tehran are considered candidate locations for module manufacturers. The model also includes one separation unit, one aluminum recycling unit, one glass recycling unit, one electronic component recycling unit, and one silicon recycling unit. Moreover, solar power plant locations and associated electric vehicle charging stations have been selected in regions 18, 10, 2, 7, 16, and 21 in Tehran, using the PROMETHEE II method. Furthermore, the analysis involves two time periods and two types of solar panels to determine the strategic and tactical variables of the problem. The proposed model is solved using the CPLEX solver in GAMS. It is worth noting that all of the results have been obtained on a laptop equipped with an Intel Core i7 2.4 GHz CPU and 8 GB of RAM.

In Table 5, the computational results are provided, which are crucial for decision-makers. These results enable the identification of the most desirable solution among the Pareto solutions. Factors such as the total cost of the supply chain, energy consumption at production centers, social impacts, the on-time delivery of products, and the attained market share play a significant role in influencing the decision-making process.

Table 5. Set of Pareto solutions.

Objective Functions					Epsilon	No.
(z5)	(z4)	(z3)	(z2)	(z1)		
0.89	7,243,118	82,557	3.26×10^8	1.34×10^{13}	0.182	1
0.913	7,470,430	89,742	3.58×10^8	1.32×10^{13}	0.201	2
0.894	7,038,148	106,053	3.57×10^8	1.32×10^{13}	0.22	3
0.914	7,274,918	175,293	3.52×10^8	1.31×10^{13}	0.239	4
0.913	7,248,245	220,136	3.49×10^8	1.31×10^{13}	0.258	5
0.914	7,024,565	250,595	3.47×10^8	1.30×10^{13}	0.277	6
0.909	6,834,101	284,781	3.45×10^8	1.30×10^{13}	0.296	7
0.914	6,826,060	336,169	3.41×10^8	1.30×10^{13}	0.316	8
0.913	6,789,613	379,735	3.39×10^8	1.30×10^{13}	0.335	9
0.914	6,778,991	424,624	3.37×10^8	1.30×10^{13}	0.354	10

In Figure 3, the optimal locations for wafer, cell, and solar module production centers, solar power plants, a module separation center, a silicon recycling center, an aluminum recycling center, a glass recycling center, and an electronic component recovery center are illustrated. Notably, regions 21, 16, and 18 in Tehran have been selected for solar wafer production, regions 22, 15, and 18 for solar cell production, and regions 22, 7, 20, and 19 for solar module production. These selections are made while considering all relevant costs in the supply chain and the specific constraints set for this analysis.

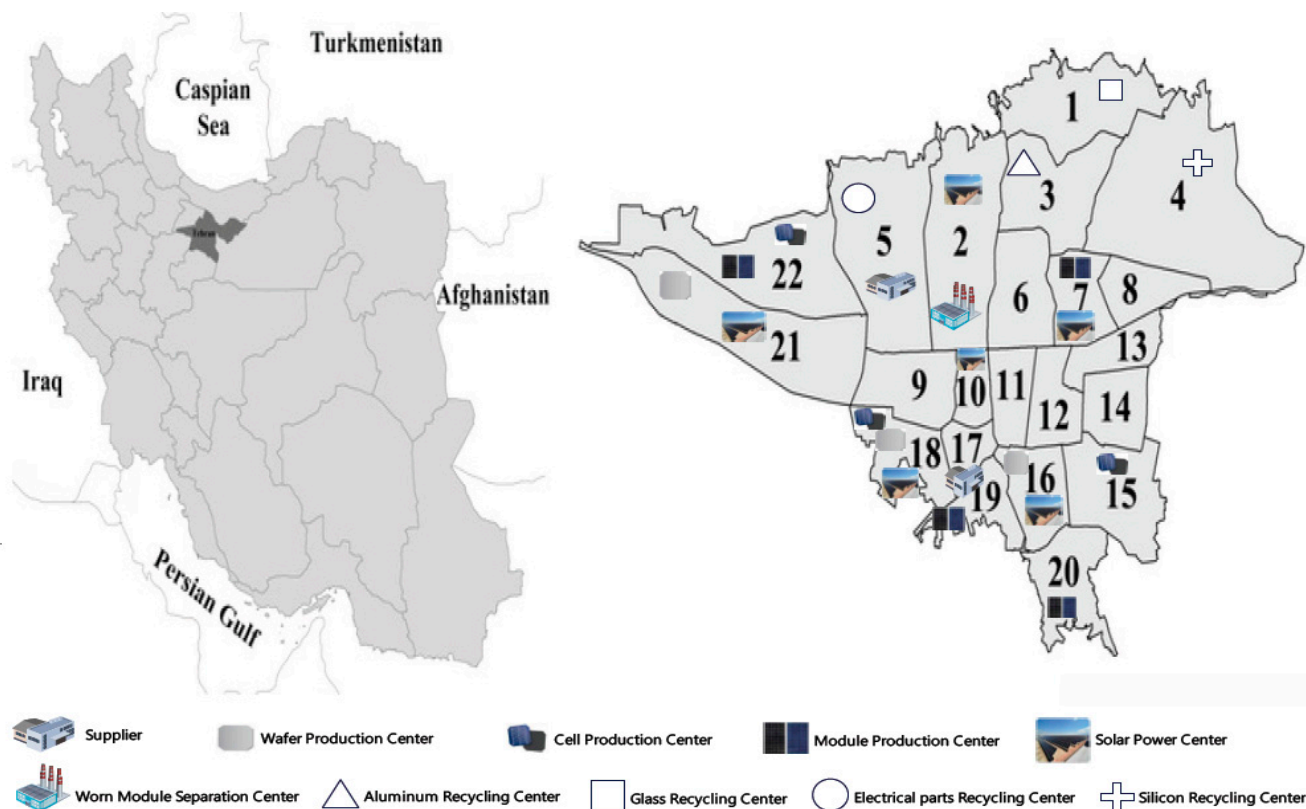


Figure 3. Optimal location of production centers, solar power plants, and recycling centers.

To analyze the interactions between the objective functions, the first objective function (minimizing the total cost) is solved first, and its optimal value (1.29640×10^{13} Rials) is calculated. Subsequently, the model is solved separately with the first objective function along with the other four objective functions. In Figure 4, an inverse relationship is observed between the total cost of the supply chain and energy consumption, indicating that reducing energy consumption at production centers to decrease greenhouse gas emissions results in higher costs in the supply chain. Figure 5 illustrates a generally inverse relationship between the first objective function and the third objective function. This suggests that reducing defective return products and, consequently, improving social conditions lead to higher costs in the supply chain. Figure 6 suggests that ensuring an on-time delivery of products to demand points requires higher costs in the supply chain. Figure 7 also demonstrates that achieving a higher market share imposes higher costs on the supply chain.

In Figure 8, a histogram displays the various cost components of the supply chain. According to the results, the highest costs are associated with the total production costs at the production centers, while the lowest costs are associated with the total production costs at the separation centers.

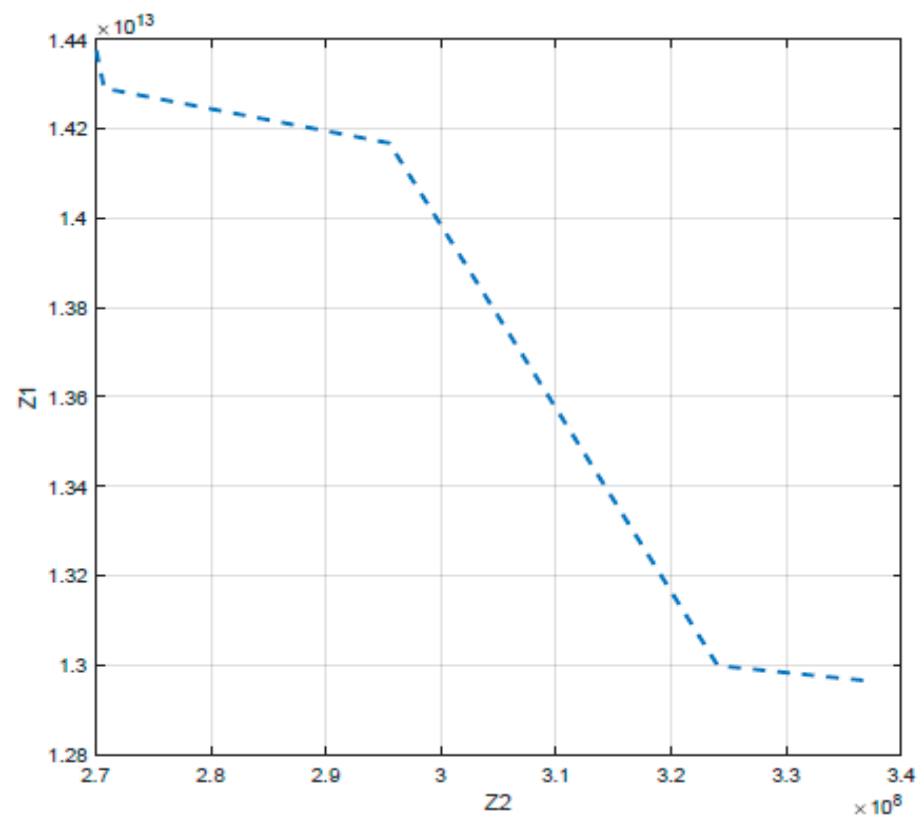


Figure 4. Trade-off between z_1 (Rial) and z_2 (MJ).

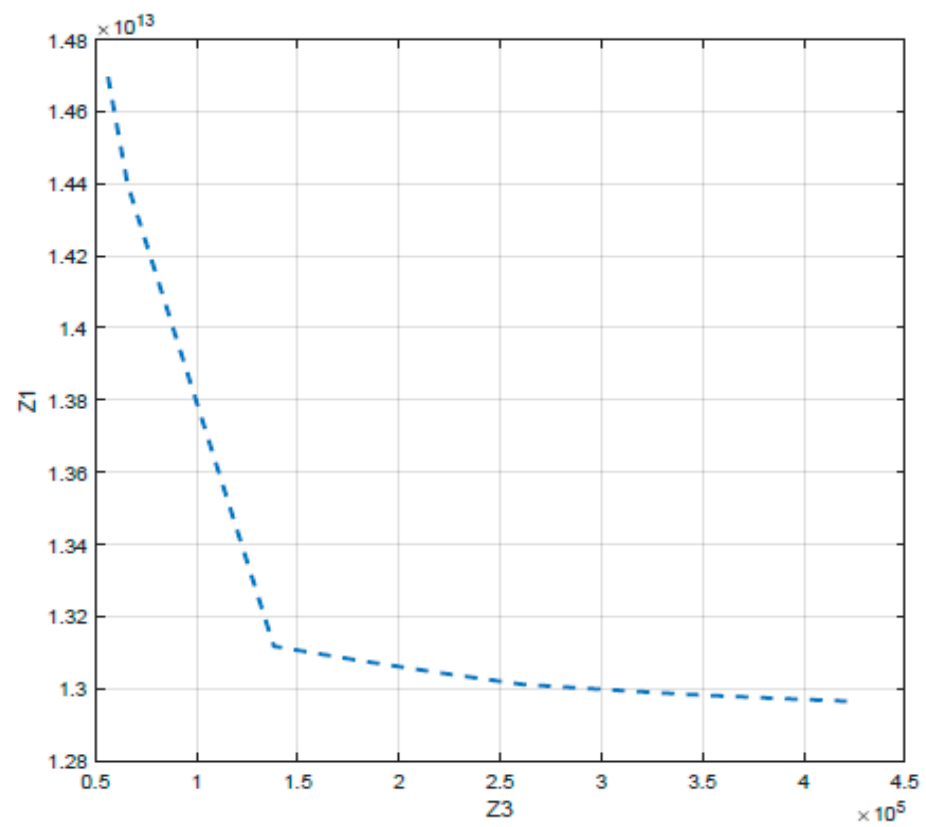


Figure 5. Trade-off between z_1 (Rial) and z_3 (Units).

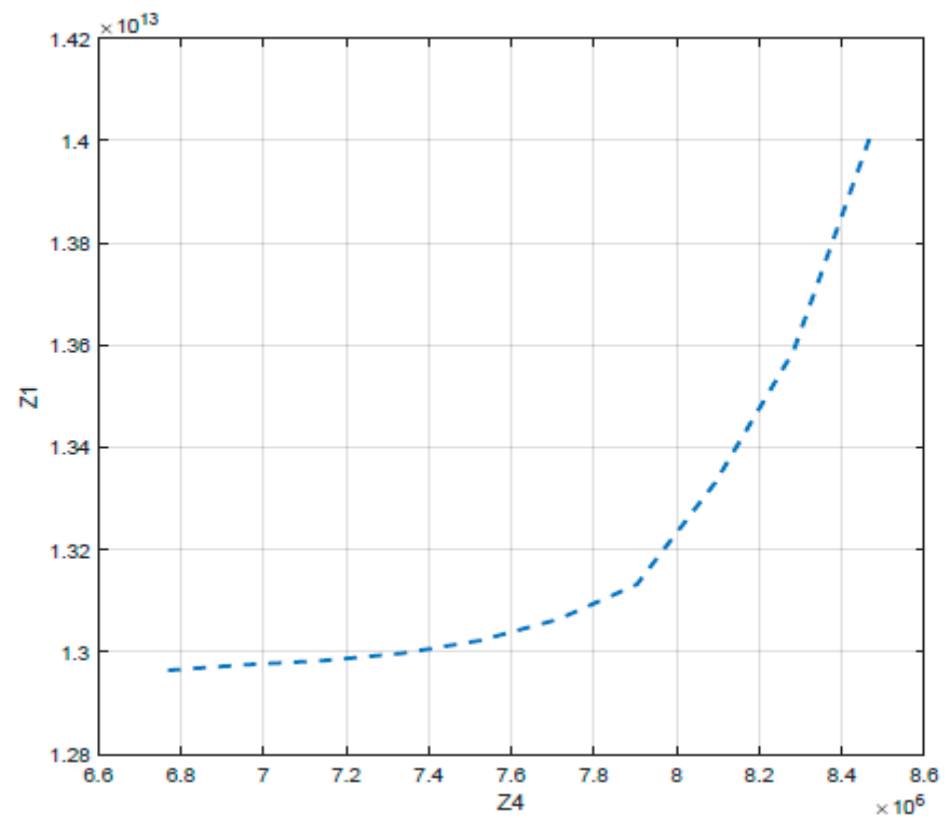


Figure 6. Trade-off between z_1 (Rial) and z_4 (Units).

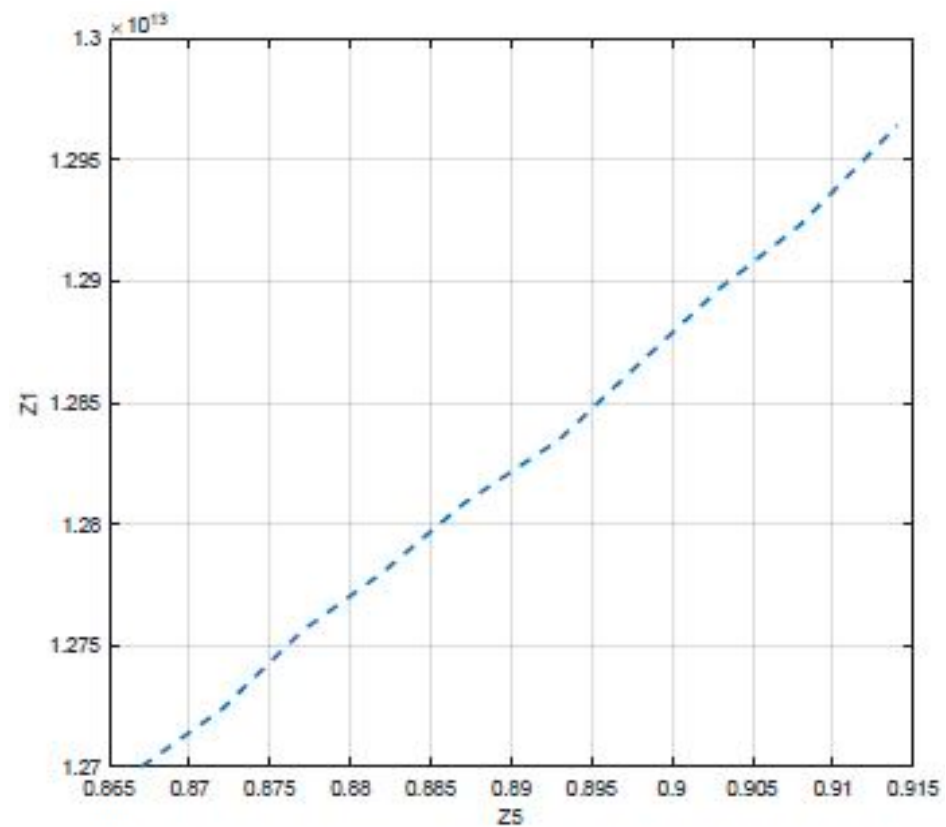


Figure 7. Trade-off between z_1 (Rial) and z_5 (Units).

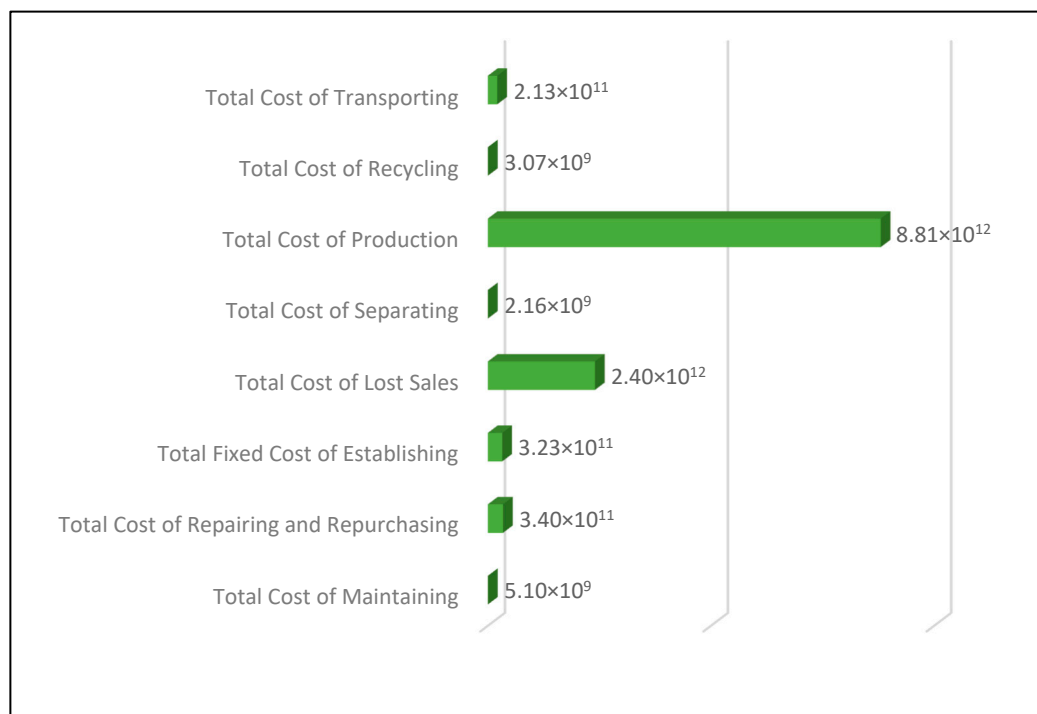


Figure 8. Histogram of supply chain costs.

6. Managerial Insights

- A. Utilizing MCDM for Solar Power Plants: The investigation presents a comprehensive framework for the establishment of solar power plants aimed at providing electric energy for electric vehicles. It employs an MCDM approach to optimize the decision process.
- B. Development of a Robust Multi-Objective Model for Sustainable PVSC: The study introduces a robust multi-objective model designed for the analysis of sustainable PVSC. It takes into account factors such as delivery time and market share while addressing the uncertainties inherent in such operations.
- C. Mitigating Defective Return Products to Safeguard Company Reputation: This work proposes an effective strategy to uphold the reputation and credibility of manufacturing companies by minimizing the occurrence of defective return products.
- D. Embracing Reverse Logistics in Supply Chains: The research not only explores the forward supply chain but also delves into the intricacies of reverse logistics, including material and product recycling in end-of-life stages. Such practices can significantly reduce supply chain costs and energy consumption at production facilities.
- E. Efficient Solution Selection from the Pareto Set: Through the utilization of the proposed exact solution method, the study empowers decision-makers to select the most optimal solutions from the efficient Pareto set.
- F. Balancing Environmental, Social, and Economic Objectives: The results highlight the complex relationship between the overall cost of the supply chain and environmental and social objectives. Simultaneously, it identifies a harmonious alignment of the overall supply chain cost with objectives related to on-time product delivery and market share.
- G. Dynamic Modeling of the PVSC: In contrast to conventional literature models designed for specific time periods, this model offers adaptability to accommodate diverse time frames, enhancing flexibility in supply chain planning.
- H. Cost Analysis Insights: The findings underscore the production cost as the primary cost driver in the PVSC, with the separation center being associated with the lowest

cost. This critical insight equips managers and decision-makers with the knowledge to innovate in product manufacturing and make informed decisions.

- I. Real-world Adaptation: This study assures managers that in the presence of any uncertainties, the developed model will demonstrate the best response and alleviate concerns regarding any real and natural issues existing in the market.
- J. Effective Collaboration Across Different Departments: This approach encourages managers of various supply chain sections to coordinate, make decisions, and efficiently utilize resources to reduce overall supply chain costs and promote other objective functions.

7. Conclusions and Future Research

Renewable energy sources, particularly solar energy, are considered suitable alternatives to non-renewable energy resources such as fossil fuels due to their easy accessibility, reduced pollution, and minimal environmental impact. This inclination is shaped by a variety of factors, such as the ease of accessibility, diminished environmental pollution, and minimal depletion of natural resources. Consequently, PV systems, a subset of solar energy systems, have gained increasing attention. In this research, an approach to harnessing a portion of the electrical energy required for charging electric vehicles through PV systems is presented. As PV systems have a limited useful operational lifespan, attention to the recycling of their constituent parts and their reuse becomes crucial. In the initial phase, a comprehensive review of PV system-related literature was conducted. According to the review, most studies focus on optimizing the locations of solar power plants, while relatively few examine the integrated design of a sustainable PVSC. Moreover, only a limited number of research works consider closed-loop and reverse supply chain mechanisms, as well as sustainability aspects. Therefore, in the present work, suitable locations for the establishment of solar power plants were initially identified using the PROMETHEE II method, considering influential factors. Subsequently, a mixed-integer linear supply chain model was developed, encompassing all sustainability dimensions, with the objectives of minimizing supply chain costs, energy consumption at production sites, and adverse social impacts, while simultaneously maximizing on-time product delivery and market share. To address uncertainties in input data, a robust fuzzy optimization approach has been adopted. This fuzzy multi-objective model has been solved using an exact solution approach that provides a Pareto optimal solution. This facilitates the striking of a balance among these five objective functions by managers and decision-makers, according to their assets and preferences. A case study was conducted in Tehran city to examine the performance of the proposed model, resulting in significant insights. One of the major findings underscores the interplay among economic, environmental, social, delivery time, and market share objectives. The results illustrate that the following:

- 1- The endeavor to reduce energy consumption at production centers for greenhouse gas emission mitigation comes at the expense of increased supply chain costs.
- 2- The pursuit of minimizing returned defective products, thereby enhancing social conditions, also incurs higher supply chain costs.
- 3- Ensuring an on-time delivery of products to meet demand necessitates increased supply chain costs.
- 4- Striving for a larger market share imposes higher costs on the supply chain.
- 5- The examination of different cost elements within the PVSC indicates that, in terms of scale, the most significant costs are linked to production centers, while the least significant costs are related to separation centers.

In summary, this study introduces several noteworthy achievements and innovations:

- An MCDM approach has been introduced to identify optimal regions for solar power plant placement.
- A fuzzy, robust multi-objective planning model tailored for the PVSC is presented. This model incorporates sustainability principles.

- Three primary sustainability aspects within the PVSC are addressed. These include cost optimization, energy consumption reduction at production centers, and the management of the rate of returned defective products to ensure customer satisfaction.
- Three main sustainability aspects have been considered by optimizing PVSC costs, energy consumption at production centers, and the rate of returned defective products to ensure customer satisfaction.
- Maximizing on-time product delivery between different layers of PVSC has been considered to enhance the benefits of solar power plants and increase electricity production.
- Maximizing the market share obtained for reducing the amount of lost sales has been incorporated into the PVSC modeling.
- A recommended precise solution method is presented that yields an efficient Pareto solution set.
- To showcase the practicality and effectiveness of the model, a comprehensive case study has been conducted, evaluating its performance and capabilities.

Finally, a set of managerial insights were presented, offering interpretations or recommendations from a management perspective to guide decision-makers in this field.

For future research, the utilization of GIS software (version 10.5.1) and Data Envelopment Analysis (DEA) methods at various decision-making levels can offer more effective strategies for identifying suitable locations for solar power plants and other production centers. Researchers can integrate scenario-based stochastic programming into the developed model to explain uncertainty in the PVSC. Furthermore, investigating the risk of disruption and developing resilience strategies may offer promising research directions in the future.

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Data Availability Statement: All data are available within the paper.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Notation of indices and sets.

Notation	Description	
I	Suppliers of crystalline ingot	$i \in I$
J	Candidate locations for wafer production centers	$j \in J$
K	Candidate locations for cell production centers	$k \in K$
L	Candidate locations for module production centers	$l \in L$
M	Solar power plants	$m \in M$
E	End-of-life module separation centers	$e \in E$
A	Aluminum recycling centers	$a \in A$
B	Glass recycling centers	$b \in B$
C	Electrical component recycling centers	$c \in C$
D	Silicon recycling centers	$d \in D$
N	Product type	$n \in N$
T	Time period	$t \in T$

Table A2. Notation of parameters.

Notation	Description
TCI_{ijt}	Cost of transferring raw materials from supplier i to wafer manufacturer j in time period t .
$TCJK_{jkt}$	Cost of transferring a wafer from wafer manufacturer j to cell manufacturer k in time period t .
$TCKL_{klt}$	Cost of transferring cells from cell manufacturer k to module manufacturer l in time period t .
$TCLM_{lmt}$	Cost of transferring modules from module manufacturer l to solar power plant m in time period t .
$TCME_{met}$	Cost of transferring end-of-life modules from solar power plant m to separation center e in time period t .
$TCEA_{eat}$	Cost of transferring separated aluminum from separation center e to aluminum recycling center a in time period t .
$TCEB_{ebt}$	Cost of transferring separated glass from separation center e to glass recycling center b in time period t .
$TCEC_{ect}$	Cost of transferring separated electrical components from separation center e to electrical components recycling center c in time period t .
$TCED_{edt}$	Cost of transferring separated solar cells from separation center e to silicon recycling center d in time period t .
$TCAL_{alt}$	Cost of transferring recycled aluminum from recycling center a to module production center l in time period t .
$TCBL_{blt}$	Cost of transferring recycled glass from recycling center b to module production center l in time period t .
$TCCL_{clt}$	Cost of transferring recycled electrical components from recycling center c to module production center l in time period t .
$TCDI_{dit}$	Cost of transferring recycled silicon from recycling center d to supplier i in time period t .
$\tilde{MCI}_{int}$	Cost of producing crystalline ingots type n by supplier i in time period t .
$\tilde{MCJ}_{jnt}$	Cost of producing wafer type n by wafer manufacturer j in time period t .
$\tilde{MCK}_{knt}$	Cost of producing cells type n by cell manufacturer k in time period t .
$\tilde{MCL}_{lnt}$	Cost of producing modules type n by module manufacturer l in time period t .
SCJ_{jnt}	Cost for storing wafer type n by wafer manufacturer j in time period t .
SCK_{knt}	Cost for storing cell type n by cell manufacturer k in time period t .
SCL_{lnt}	Cost for storing module type n by module manufacturer l in time period t .
ECl_{int}	Amount of energy consumption for producing crystalline ingots type n by supplier i in time period t .
ECJ_{jnt}	Amount of energy consumption for producing wafer type n by wafer manufacturer j in time period t .
ECK_{knt}	Amount of energy consumption for producing cell type n by cell manufacturer k in time period t .
ECL_{lnt}	Amount of energy consumption for producing module type n by module manufacturer l in time period t .
$CAPJ_{jn}$	Capacity for storing wafer type n by wafer manufacturer j .
$CAPK_{kn}$	Capacity for storing cell type n by cell manufacturer k .
$CAPL_{ln}$	Capacity for storing module type n by manufacturer l .
$CAPII_{int}$	Capacity for producing crystalline ingot type n by supplier i .
$CAPMJ_{jnt}$	Capacity for producing wafer type n by wafer manufacturer j in time period t .
$CAPMK_{knt}$	Capacity for producing cell type n by cell manufacturer k in time period t .
$CAPML_{lnt}$	Capacity for producing module type n by module manufacturer l in time period t .
$\tilde{CRJ}_{jnt}$	Cost of repairing and repurchasing returned wafer type n by wafer manufacturer j in time period t .
$\tilde{CRK}_{knt}$	Cost of repairing and repurchasing returned cell type n by cell manufacturer k in time period t .
$\tilde{CRL}_{lnt}$	Cost of repairing and repurchasing returned module type n by module manufacturer l in time period t .

Table A2. Cont.

Notation	Description
CE_{ent}	Cost of separating end-of-life module type n by recycling center e in time period t.
CA_{ant}	Cost of recycling separated aluminum from end-of-life module type n by recycling center a in time period t.
CB_{bnt}	Cost of recycling separated glass from end-of-life module type n by recycling center b in time period t.
CC_{cnt}	Cost of recycling separated electrical components from end-of-life module type n by recycling center c in time period t.
CD_{dnt}	Cost of recycling separated solar cells from end-of-life module type n by recycling center d in time period t.
PEA_{ent}	Selling price of separated aluminum from end-of-life module type n by recycling center e in time period t.
PEB_{ent}	Selling price of separated glass from end-of-life module type n by recycling center e in time period t.
PEC_{ent}	Selling price of separated electrical components from end-of-life module type n by recycling center e in time period t.
PED_{ent}	Selling price of separated solar cells from end-of-life module type n by recycling center e in time period t.
PAL_{ant}	Selling price of recycled aluminum type n by recycling center a in time period t.
PBL_{bnt}	Selling price of recycled glass type n by recycling center b in time period t.
PCL_{cnt}	Selling price of recycled electrical component type n by recycling center c in time period t.
PDI_{dnt}	Selling price of recycled silicon type n by recycling center d in time period t.
DJ_{jnt}	Demand for crystalline ingot type n by wafer manufacturer j in time period t.
DK_{knt}	Demand for wafer type n by cell manufacturer k in time period t.
DL_{lnt}	Demand for cell type n by module manufacturer l in time period t.
$\tilde{DM}_{mnt}$	Demand for module type n by the solar power plant m in time period t.
$POTIJ_{ijt}$	On-time delivery percentage of crystalline ingots sent from supplier i to wafer manufacturer j in time period t.
$POTJK_{jkt}$	On-time delivery percentage of wafer sent from wafer manufacturer j to cell manufacturer k in time period t.
$POTKL_{klt}$	On-time delivery percentage of cells sent from cell manufacturer k to module manufacturer l in time period t.
$POTLM_{lmt}$	On-time delivery percentage of modules sent from module manufacturer l to solar power plant m in time period t.
$CLSM_{mnt}$	Cost of one unit of lost sales for type n modules at the solar power plant m in time period t.

Table A3. Notation of technical parameters.

Notation	Description
H	Minimum percentage of returned products from demand centers to manufacturers
HP	Maximum percentage of returned products from demand centers to manufacturers
UA	Number of wafers per square meter
UB	Number of cells per square meter
UC	Number of modules per square meter
UD	Number of crystalline ingots per square meter
NTA	Conversion rate from crystalline ingot to solar wafer
NTB	Conversion rate from solar wafer to solar cell
NTC	Conversion rate from solar cell to solar module
NFM	Percentage of module degradation in solar power plants in each period
NBA	Percentage of aluminum recycling
NBB	Percentage of glass recycling
NBC	Percentage of electronic components recycling
NBD	Percentage of silicon recycling
WM	Weight of silicon in each module

Table A4. Notation of decision variables.

Notation	Description
XJ_j	If wafer manufacturer j builds, then it equals 1, otherwise 0.
XK_k	If cell manufacturer k builds, then it equals 1, otherwise 0.
XL_l	If module manufacturer l builds, then it equals 1, otherwise 0.
QIJ_{ijnt}	Flow of transferring crystalline wafer type n from supplier i to wafer manufacturer j in time period t.
QJK_{jknt}	Flow of transferring wafer type n from wafers manufacturer j to cell manufacturer k in time period t.
QKL_{klnt}	Flow of transferring cell type n from cell manufacturer k to module manufacturer l in time period t.
QLM_{lmnt}	Flow of transferring module type n from module manufacturer l to solar power plant m in time period t.
QME_{ment}	Flow of transferring end-of-life module type n from solar power plant m to separation center e in time period t.
QEA_{eant}	Flow of transferring recycled aluminum type n from separation center e to aluminum recycling center a in time period t.
QEB_{ebnt}	Flow of transferring recycled glass type n from separation center e to glass recycling center b in time period t.
QEC_{ecnt}	Flow of transferring recycled electrical component type n from separation center e to electrical components recycling center c in time period t.
QED_{ednt}	Flow of transferring recycled solar cell type n from separation center e to silicon recycling center d in time period t.
QAL_{alnt}	Flow of transferring recycled aluminum type n from aluminum recycling center a to module manufacturer l in time period t.
QBL_{blnt}	Flow of transferring recycled glass type n from glass recycling center b to module manufacturer l in time period t.
QCL_{clnt}	Flow of transferring recycled electrical component type n from electrical components recycling center c to module manufacturer l in time period t.
QDI_{dint}	Flow of transferring recycled silicon of type n from silicon recycling center d to supplier i in time period t.
$INVJK_{jnt}$	Inventory of wafer type n produced by manufacturer j in time period t.
$INVKL_{knt}$	Inventory of cell type n produced by manufacturer k in time period t.
$INVM_{lnt}$	Inventory of module type n produced by manufacturer l in time period t.
$RQJK_{jknt}$	Return flow of wafer type n from cell manufacturer k to wafer manufacturer j in time period t.
$RQKL_{klnt}$	Return flow of cell type n from module manufacturer l to cell manufacturer k in time period t.
$RQIM_{lmnt}$	Return flow of module type n from solar power plant m to module manufacturer l in time period t.
$MQIJ_{int}$	Amount of crystalline ingot type n produced by supplier i in time period t.
$MQJK_{jnt}$	Amount of wafer type n produced by wafer manufacturer j in time period t.
$MQKL_{knt}$	Amount of cell type n produced by cell manufacturer k in time period t.
$MQIM_{lnt}$	Amount of module type n produced by module manufacturer l in time period t.
LSM_{mnt}	Demand for solar power plant m for module type n in time period t, which is supplied by competitors.

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