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An integrated model for designing a bi-objective closed-loop solar photovoltaic supply chain network considering environmental impacts: a case study in Iran

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Abstract

Recently, renewable energy resources such as solar energy have been significantly utilized in various sectors, regarding world population growth and the increasing use of fossil fuel and non-renewable resources, and consequently, the increased rate of environmental pollution. Implementing photovoltaic systems is regarded as one of the methods of using solar energy, which countries have highly considered in recent years. With the limited lifetime of photovoltaic systems, addressing the forward and reverse supply chain of these systems plays a significant role in increasing their efficiency. To this end, the present study seeks to develop a two-objective mixed-integer non-linear model, including minimizing total costs and minimizing the negative environmental impacts, aiming to design a closed-loop supply chain network for photovoltaic systems. In this study, the augmented ε-constraint method was employed to convert the current two-objective programming model into a single-objective one. Finally, the proposed model was implemented in a case study in Iran to evaluate the model's efficiency. The results indicated that solar power plants should be built in areas with higher solar energy and lower cost. Also, the model dynamics could increase the number of constructed solar power plants and their electricity generation capacity over the time horizon, followed by increased demand for annual electricity generated by solar energy.

Keywords: Renewables energy, photovoltaic systems, closed-loop supply chain network design, augmented ε-constraint method

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List of abbreviations	
IEA	International energy agency
PV	Photovoltaic
CSP	Concentrated solar power
SC	Supply chain
SCN	Supply chain network
SCND	Supply chain network design
PVSC	Photovoltaic supply chain
PVSCN	Photovoltaic supply chain network
PVSCND	Photovoltaic supply chain network design
DEA	Data envelopments analyses
MCDM	Multi-criteria decision making
GIS	Geographical information system
AHP	Analytical hierarchy process
FAHP	Fuzzy analytical hierarchy process
ISM	Interpretive Structural Modeling
VIKOR	Vlse Kriterijumska Optimizacija I Kompromisno
WLC	Weighted Linear Combination
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WLA	weighted Linear Addition
OWA	Ordered Weighted Averaging
ELECTRE	Elimination et choice translating reality
LCA	Life cycle assessment

1- Introduction

Renewable energy refers to a type of energy that can be regenerated by nature in a short period, contrary to the non-renewable energy resources (Rathore and Panwar, 2007). Nowadays, renewable energy resources have been widely utilized as a suitable alternative to non-renewable energy sources such as oil and gas, running out and cause a high-level of pollution. In this regard, as the output of most renewable sources, electricity provides several advantages such as converting electricity into heat (which generates more heat than fossil fuels), and mechanical energy, which has high efficiency and does not pollute the environment during consumption.

Solar energy is considered as one of the cleanest, economical, and most sustainable renewable energy sources in the world (Al-Shamisi et al., 2013), as it generates electricity without producing greenhouse gases such as carbon monoxide (CO) and carbon dioxide (CO_2). On the other hand, solar energy sources can be found all around the world, unlike other energy sources. Converting only 0.1% of the solar energy transmitted on Earth to electricity generates 3000 gigawatts of energy, which is about four times the world's annual energy demand (Thirugnanasambandam et al., 2010). According to the International Energy Agency (IEA), the power generated by solar energy absorption systems will reach 9000 TWh by 2050, resulting in reducing annual CO_2 gas emissions to 6 billion tons per year (Charabi and Gastli, 2011).

Regarding the high density of solar energy (approximately 170 w/m^2) and its intermittent nature, the process of converting solar energy into electricity involves its concentration and storage, which is performed through two main mechanisms of thermal conversion and photovoltaic (PV) conversion. Concerning thermal conversion, which is generally implemented using concentrated solar power (CSP) technologies, solar radiation is concentrated through reflectors to a receiver. The heat transfer fluid circulates. The temperature of this fluid should be increased to be used in the thermodynamic cycle to generate power. In the second approach, solar radiation is converted directly into electricity through the photoelectric effect by utilizing PV panels (Desideri and Campana, 2014). By comparing PV and CSP technologies, it can be observed that CSP uses more water to cool and wash reflectors. For this reason, PV technology is more suitable and economical for countries with water shortages. On the other hand, PV plants can be installed and implemented significantly faster than those of CSP, increasing their flexibility (Charabi and Gastli, 2011).

Evaluating energy generation costs through PV systems and fossil fuels indicates that PV systems are not economical. In this way, designing a supply chain network (SCN) is considered an efficient way to reduce PV systems' costs (Dehghani et al., 2018a). Moreover, SCN design (SCND) is a prerequisite for emerging industries and increases their competitive advantage (Mohseni and Pishvaee, 2016).

Considering the approximately 20 to 30 years lifetime of modules, as the essential part of PV systems, we will face a large number of worn-out solar panels soon (Kim and Jeong, 2016), necessitating the recycling of PV panels. It should be noted that the recycling of PV systems is of great importance from two environmental and economic aspects. Since a large body of recycling PV system research has been conducted on the recycling methods and their economic and environmental analysis, designing a reverse supply chain (SC) plays a significant role in reducing costs and increasing system efficiency.

For covering the gaps in the literature, this research first attempts to review and categorize articles on the PV SC (PVSC) and then addresses the design of the closed-loop solar PV SCN (PVSCN). Therefore, a two-objective mathematical model with the objective functions of minimizing SC's costs and minimizing adverse environmental impacts is used to design a multi-level and multi-period SCN.

The remaining content of the paper is organized as follows. Section 2 reviews and categorizes the recent studies conducted on the PVSC and the location of PV systems. Section 3 first describes the problem and then proposes a mixed-integer non-linear programming model for designing the closed-loop PVSCN. The solution method developed in this research is explained in section 4. Section 5 shows the model implementation on a case study of PVSC in Iran and provides the computational results and sensitivity analysis. Finally, Section 6 presents a summary of the research and provides suggestions for future research.

2- Literature review

This section addresses recent studies conducted in the field of PVSC. A few research has studied the PV SCND (PVSCND), the most important of which are presented. (Dehghani et al., 2018b) proposed an optimization model for designing the PVSCN under different risks with an objective function of minimizing total costs. They utilized a scenario-based robust approach to deal with all the risks in the chain. In another study, (Dehghani et al., 2018a) developed a two-stage approach, including robust optimization and data envelopment analysis (DEA), to design an SC for PV systems under uncertainty conditions. In the first stage, DEA was employed along with technical, geographical, and social criteria to find suitable candidate locations. The robust optimization approach was also utilized in the second stage to find the tactical and strategic decision variables of the PVSC. (Dehghani et al., 2020) conducted a two-objective mathematical model with the objective functions of minimizing the SC's total costs and minimizing the negative environmental impacts. The uncertainty was addressed in the parameters of this problem and was controlled through a robust optimization approach.

(Chen and Su, 2018) examined PVSCs from a competitive perspective. They argued the existence of intense competition among the PVSCs due to the global PV industry's excess supply problem. In another study, (Chen and Su, 2019) evaluated the equilibrium and coordination strategies for the PVSC, aiming to maximize subsidized social welfare. (Manouchehrabadi et al., 2019) investigated the competition in the multi-period SC for two types of solar cells with two suppliers, an assembler and a solar cell power plant.

However, most researchers have worked on the optimal location of PV cells, solar farms (connecting PV arrays in one area, which belong to different investors (Carrión et al., 2008)), solar power plants, and wind-solar hybrid power plants. Researchers have used mathematical modeling and various types of multi-criteria decision-making (MCDM) methods, geographic information system (GIS) software, and DEA or combining these methods in these studies. In general, the facilities should be established in unused areas with low fertility and in grasslands and barren lands (Graebig et al., 2010, Tsoutsos et al., 2005).

Among the studies carried out to evaluate the optimal location of solar power plants using mathematical modeling, we can mention the studies of (Gómez et al., 2010), (Arnette and Zobel, 2012), (Kim and Jeong, 2016), and (Castellanos et al., 2018).

Kim and Jeong (2016) have studied and compared the three different recycling policies applied by Deutsche Solar, First Solar, and PV cycle companies. For this purpose, they have presented three mathematical programming models of the closed-loop SC to help manufacturers choose the most appropriate recycling policy by minimizing the cost objective function. They have investigated the performance of the proposed models in different numerical examples. Castellanos et al. (2018) have proposed an integrated economic-technical framework for PV systems by considering different tariffs and transportation systems to optimize the SC of PV systems production. They have conducted case studies in Mexico, China, United States, and Brazil.

In the last few years, there has been a growing trend in using various MCDM methods to select the locations of PV facilities and solar farms. These methods have been applied to choose the best alternative from the available alternatives by considering different criteria and decision-makers' preferences (Mateo, 2012). Meanwhile, researchers have utilized various MCDM methods, such as the analytical hierarchy analysis (AHP) method. The studies carried out by (Jun et al., 2014), (Yunna et al., 2014), (Lee et al., 2017), (Liu et al., 2017), (Zoghi et al., 2017), (Fang et al., 2018), and (Rezaei et al., 2018) are among the researches using the MCDM methods.

Lee et al. (2017) have used MCDM methods to find suitable locations for PV systems in Taiwan. In this study, the Interpretive Structural Modeling (ISM) method has been used to determine the relation between criteria and sub-criteria and the Fuzzy Analytical Network Process (FANP) method to calculate the weight of sub-criteria. Finally, the Vlse Kriterijumska Optimizacija I Kompromisno (VIKOR) method has been applied to find suitable locations for these systems. Liu et al. (2017) implemented an MCDM method called Grey cumulative prospect theory to find the sustainable location of solar power plants. Zoghi et al. (2017) conducted an investigation to find a suitable location for solar power plants in Isfahan province. To this end, they have applied the AHP method, fuzzy logic, and Weighted Linear Combination (WLC) to weighting criteria and conducting the feasibility study for the location of solar energy systems. Fang et al. (2018) presented a novel approach based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method, prospect theory, and variable precision rough number to find the PV systems location. Rezaei et al. (2018) have employed the decision-making methods to find a wind-solar hybrid power plant in Fars province. For this purpose, seven Fars province regions have been examined in terms of economic, social, and geological conditions and natural disasters. The analysis and ranking of regions have been conducted with the fuzzy TOPSIS technique.

In the last decade, GIS software has been widely used in renewable energies, especially solar energy. GIS is computer software that works with geographic databases and uses it to analyze, maintain, manage, and prepare geographical maps (Yanar and Akyürek, 2006). Some of the articles performed in this field are the studies made by (Carrión et al., 2008), (Stoms et al., 2013), (Janke, 2010), (Brewer et al., 2015), (Charabi et al., 2016), (Jahangiri et al., 2016), (Merrouni et al., 2016), and (Maleki et al., 2017).

Charabi et al. (2016) evaluate the feasibility of considering inclined terrains for locating the PV cells in the vicinity of urban areas. In this study, the GIS and numerical weather prediction software were used to find proper locations of PV cells. To this end, they have performed a case study in Muscat, Oman. Jahangiri et al. (2016) have attempted to find suitable locations for wind-solar power plants in the Middle East by implementing the Boolean logic in GIS software. In this study, the eastern, central, south-west Iran, southern Oman, all regions of Iraq and Yemen, southern Jordan, and Israel, and a small region in the south-east of Turkey have been selected as suitable locations for constructing these facilities. Merrouni et al. (2016) have investigated suitable locations for large-scale PV power plants using GIS software. An extensive database of the Earth map with a "high spatial resolution" has been built to this end. Finally, they have implemented their proposed method in the eastern regions of Morocco. Maleki et al. (2017) have focused on finding the optimal location and capacity of stand-alone PV systems. They have utilized GIS software to find optimal locations of these systems and the Artificial Bee Swarm optimization method to find the associated optimal capacity. Finally, to evaluate the model's efficiency, they have implemented their proposed model in Iran's eastern regions.

According to previous research, combining MCDM methods with GIS software is a suitable tool for finding the optimal locations of facilities. For finding an optimal location for PV systems and solar farms, many studies have utilized a combination of MCDM methods and GIS software. In this case, we can mention the studies conducted by (Charabi and Gastli, 2011), (Aydin, 2009), (Uyan, 2013), (Sánchez-Lozano et al., 2014), (Borgogno Mondino et al., 2015), (Tahri et al., 2015), (Watson and

Hudson, 2015), (Castillo et al., 2016), (Sánchez-Lozano et al., 2016), (Noorollahi et al., 2016), (Al Garni and Awasthi, 2017), (Asakereh et al., 2017), (Hafeznia et al., 2017), (Suuronen et al., 2017), and (Yousefi et al., 2018).

Castillo et al. (2016) have evaluated the potential zones for solar power generation in Europe and provided a sustainable map for PV systems based on biophysical and socio-economic factors using GIS software and the weighted Linear Addition (WLA) method. The results have been compared with solar energy facilities in France, Italy, Spain, Germany, and Portuguese to validate the obtained map. Sánchez-Lozano et al. (2016) have used both MCDM and GIS models to find the potential locations for solar farms on the Murcia beach in southeastern Spain. In this study, the authors first use GIS to determine potential regions for establishing these systems and the AHP method to calculate different criteria' weights. Then, TOPSIS and ELECTRE-TRI methods have been used to find the most appropriate locations. Noorollahi et al. (2016) have proposed an algorithm based on MCDM and GIS software to find suitable locations for establishing solar farms in Iran. The most suitable solar farms locations were Kerman, Yazd, Fars, Sistan and Baluchestan, South Khorasan, and Isfahan provinces. Al Garni and Awasthi (2017) have used a combination of MCDM and GIS to locate the suitable location of grid-connected PV power plants in Saudi Arabia. First, they have utilized GIS maps to find inappropriate locations. Then AHP method has been used to weigh the various effective criteria. Asakereh et al. (2017) have applied GIS software and FAHP method to find solar farms in Shadiravan, Iran. The results obtained from the analysis showed that 13.98 percent of the total land area has a high potential for constructing these plants. Hafeznia et al. (2017) have proposed a framework for assessing the suitable locations for PV solar power plants using GIS, fuzzy logic models, and Boolean logic. They have selected Birjand county because of its appropriate weather condition. Also, they have designed and simulated a PV power plant of a given capacity in Birjand. Suuronen et al. (2017) have combined the AHP and Ordered Weighted Averaging (OWA) methods to find suitable sites for solar power plants in the Atacama Desert in Chile. This study aims to find regions with high potential for solar energy, determine the areas with the least impact on the environment and a small social impact. Yousefi et al. (2018) have utilized GIS software accompanied by Boolean-Fuzzy logic to find the proper locations for the solar power plants in Markazi province. The results show that the regions near Mahalat and Zarandieh cities are the most suitable places for establishing these facilities.

DEA, which is another method used in articles to determine the most appropriate location for PV cells, is defined as an optimization approach for calculating the efficiency of suitable locations for placing solar cells in a given period by comparing the values of inputs and outputs (Özpeynirci and Köksalan, 2007). Some of the studies conducted with the DEA method are Azadeh et al. (2008), (Azadeh et al., 2011, Azadeh et al., 2008, Yokota and Kumano, 2013), (Khanjarpanah et al., 2018), and (Mastrocinque et al., 2020).

Khanjarpanah et al. (2018) have proposed a new DEA algorithm named Network DEA (NDEA) to rank and find the optimal location of the hybrid wind-PV power plants. They have implemented the proposed algorithm in Fars, Sistan and Baluchestan, Lorestan, and Mazandaran provinces to evaluate its effectiveness. Mastrocinque et al. (2020) have proposed a framework for assessing the three sustainability dimensions in the SC of renewable energies using the AHP method. To this end, they have implemented their proposed model on the PVSC. As a result, suitable locations have been determined for the construction of PV system production centers.

Also, (Lee et al., 2015) proposed a two-stage assessment method to evaluate the efficiency of the suitable location of PV systems. In the first stage, to obtain appropriate locations for these systems, a fuzzy AHP (FAHP) method was used to evaluate quantitative variables and obtain their confidence zone. Then, the DEA method was used in the second stage for assessing the performance of the proposed locations.

In table 1, the codes of categories for classifying the reviewed articles are presented. The types of modeling approaches such as optimization, MCDM, GIS, and DEA, as well as the type of objective functions used in the problem, the different types of flow in the chain such as forward and backward flows, the various types of decision variables as the problem outputs, and problem properties, including capacity and budget limitation, are among the features addressed in the classification of review articles. Table 2 categorizes all the reviewed articles in the form of important properties. According to the reviewed articles categorized in table 2, it can be seen the issues that have been less or not addressed in the literature:

- The optimization approach has been less used in the location of PV systems.
- A few research has studied the field of PVSCND.
- The reverse and closed-loop SC have been less considered for PV systems.
- The number of studies with multi-objective functions is significantly low.
- Multi-period and multi-product models are less considered.
- Sustainability aspects in the PVSC studies are less mentioned.

Based on previous research and observation of the research gaps, the main contributions of this paper is as follows:

- Proposing a new mathematical model for PVSCND
- Considering both forward and reverse flow in designing the PVSC
- Minimizing negative environmental impacts in addition to minimizing total costs to achieve sustainability goals and using the ReCiPe 2008 method and SimaPro software to determine the environmental parameters
- Considering the dynamic capacity for different facilities during the planning horizon
- Providing a case study in Iran to illustrate the application of the proposed model in real life

Table 1. Codes of classifying the PVSC properties

Category	Code
Modeling approach	
Optimization	Op
Decision making	MCDM
DEA	DEA
GIS	GIS
Objective functions	
Minimization of costs, maximization of profits	MC
Minimization of environmental impacts	ME
Maximization of social impacts	MaS
Maximization of utility	MaU
Maximization of efficiency	MaE
Network flow	
Forward	Fw
Backward	Bw
Problem outputs	
Facility location	FL
Network structure	NS
Capacity	Ca
Product flow volume	PF
Inventory	In
Problem properties	
Single-period	SPr
Multi-period	MPr
Single-product	SPd
Multi-product	MPd
Budget limitation	B
Capacity limitation	C
MCDM methods	
Analytical hierarchy process	AHP
Ordered weighted average	OWA
Fuzzy analytical hierarchy process	FAHP
Elimination et choice translating reality	ELECTRE
Artificial neural network	ANN
weighted linear addition	WLA
Interpretive structural modeling	ISM
Vlse kriterijumsk optimizacija kompromisno resenje	VIKOR
Technique for order of preference by similarity to ideal solution	TOPSIS

Table 2. Review of PVSC articles

Reference	Modeling approach	Objective functions	Network flow	Problem outputs	Problem properties	Case study
(Azadeh et al., 2008)	DEA	MaE	Fw	FL	SPr-SPd	Solar farms in Iran
(Carrión et al., 2008)	GIS	-	Fw	FL-Ca	SPr-SPd -C	Solar power plants in Andalusia-Spain
(Gómez et al., 2010)	Op-GIS	MC	Fw	FL	SPr-SPd-B	PV grid-connected system in Spain
(Janke, 2010)	GIS	-	Fw	FL	SPr-SPd-B	Wind and solar farms in Colorado-USA
(Azadeh et al., 2011)	DEA	MaE	Fw	FL	SPr-SPd	Solar power plants in Iran
(Charabi and Gastli, 2011)	MCDM (AHP, OWA)-GIS	MaU	Fw	FL	SPr-SPd	PV solar farms in Oman
(Arnette and Zobel, 2012)	Op-GIS	ME	Fw	FL-Ca	SPr-SPd-B-C	Wind and Solar farms in the greater southern Appalachian Mountain in the USA
(Aydin et al., 2013)	MCDM (OWA)-GIS	MaU	Fw	FL	SPr-SPd	Solar-wind power plants in Turkey
(Stoms et al., 2013)	GIS	-	Fw	FL	SPr-SPd	Solar energy development in California desert-USA
(Uyan, 2013)	MCDM (AHP)-GIS	MaU	Fw	FL	SPr-SPd	Solar farms in Karapinar-Turkey
(Yokota and Kumano, 2013)	DEA	MaE	Fw	FL	SPr-SPd	Mega solar sites in Shizuoka-Japan
(Jun et al., 2014)	MCDM (ELECTRE-II)	MaU	Fw	FL	MPr-SPd	Wind/solar hybrid station in China
(Sánchez-Lozano et al., 2014)	MCDM (ELECTRE-TRI)-GIS	MaU	Fw	FL	SPr-SPd	PV solar farms in Torre Pacheco-Murcia, Southeast of Spain
(Yunna et al., 2014)	MCDM (AHP)	MaU	Fw	FL	MPr-SPd-B	Solar-wind hybrid location in China
(Brewer et al., 2015)	GIS	-	Fw	FL	SPr-SPd-C	Solar power site in the southwestern United States
(Lee et al., 2015)	MCDM (FAHP)-DEA	MaU-MaE	Fw	FL	SPr-SPd	Solar power plants in Taiwan

Table 2 (continued)

Reference	Modeling approach	Objective function	Network flow	Problem outputs	Problem properties	Case study
(Borgogno Mondino et al., 2015)	MCDM (ANN)-GIS	MaU	Fw	FL	SPr-SPd	Ground-Mounted PV Plants in Italy
(Tahri et al., 2015)	MCDM (AHP)-GIS	MaU	Fw	FL	SPr-SPd	Solar farms study in southern Morocco
(Watson and Hudson, 2015)	MCDM (AHP)-GIS	MaU	Fw	FL	SPr-SPd-C	Wind and solar farms in England
(Castillo et al., 2016)	MCDM (WLA)-GIS	MaU	Fw	FL	SPr-SPd-B	PV development in Europe
(Charabi et al., 2016)	GIS	-	Fw	FL	SPr-SPd-C	PV power plants in Muscat-Oman
(Jahangiri et al., 2016)	GIS	-	Fw	FL	SPr-SPd-C	Solar-wind power stations in Middle-East
(Kim and Jeong, 2016)	Op	MC	Fw-Bw	FL-Ca	MPr-SPd-C	PV system manufacturer
(Sánchez-Lozano et al., 2016)	MCDM (TOPSIS, ELECTRE-TRI)-GIS	MaU	Fw	FL	SPr-SPd-C	PV solar farms in Spain
(Merrouni et al., 2016)	GIS	-	Fw	FL	SPr-SPd	PV sites in Morocco
(Noorollahi et al., 2016)	MCDM (FAHP)-GIS	MaU	Fw	FL	SPr-SPd-B	Solar farms in Iran
(Al Garni and Awasthi, 2017)	MCDM (AHP)-GIS	MaU	Fw	FL	SPr-SPd-C	PV solar power plants in Saudi Arabia
(Asakereh et al., 2017)	MCDM (FAHP)-GIS	MaU	Fw	FL	SPr-SPd	Solar farms in Khuzestan province-Iran
(Hafeznia et al., 2017)	MCDM (Boolean logic)-GIS	MaU	Fw	FL-Ca	SPr-SPd-C	Solar PV power plants in Birjand-Iran

Table 2 (continued)

Reference	Modeling approach	Objective function	Network flow	Problem outputs	Problem properties	Case study
(Lee et al., 2017)	MCDM (ISM, VIKOR,FANP)	MaU	Fw	LF	SPr-SPd-C	PV solar plant in Taiwan
(Liu et al., 2017)	MCDM (Grey Cumulative Prospect theory)	MaU	Fw	LF	SPr-SPd	PV power plants in Northwest China
(Maleki et al., 2017)	GIS	-	Fw	LF-Ca	SPr-SPd-C	Stand-alone PV systems in Iran
(Suuronen et al., 2017)	MCDM (AHP-OWA)-GIS	MaU	Fw	FL	SPr-SPd	PV solar power plant in northern Chile
(Zoghi et al., 2017)	MCDM (AHP)	MaU	Fw	FL	SPr-SPd-C	Solar power plants in Isfahan-Iran
(Castellanos et al., 2018)	Op	MC	Fw	FL	SPr-SPd-C-B	PV manufacturing in Mexico, China, USA, and Brazil
(Fang et al., 2018)	MCDM (TOPSIS, prospect theory)	MaU	Fw	FL	SPr-SPd	PV power plants in China
(Khanjarpanah et al., 2018)	DEA	MaE	Fw	FL	MPr-SPd	Hybrid wind-PV power plants in Iran
(Rezaei et al., 2018)	MCDM (TOPSIS)	MaU	Fw	FL	MPr-SPd	Wind-solar hybrid plant in Fars province-Iran
(Yousefi et al., 2018)	MCDM (fuzzy Boolean logic)-GIS	MaU	Fw	FL	SPr-SPd	Solar Power Plants in Markazi province-Iran
(Dehghani et al., 2020)	Op-MCDM (Augmented – epsilon constraint)	MC-ME	Fw	FL-NS-Ca-PF-In	MPr-MPd-C	Wafer, cell, and module production centers and solar power plants in Iran
(Mastrocinque et al., 2020)	MCDM (AHP)	MaU	Fw	FL	SPr-SPd	PV energy production centers in Germany, Italy, UK, France, Spain, Belgium, and Greece
This work	Op	MC-ME	Fw-Bw	FL-NS-Ca-PF-In	MPr-MPd-C	Wafer, cell, and module production centers and solar power plants, worn-out panel separation center, silicon recycling center in Iran

3- Problem definition and formulation

As mentioned above, the present study attempts to provide a multi-product, multi-period mathematical model for designing the closed-loop PVSCN by considering two economic and environmental objective functions. Figure 1 illustrates the proposed closed-loop SC. This SC includes raw material suppliers, solar wafer, cell, and module manufacturers, solar power plants, regional electricity distribution companies, worn-out panel separation centers, silicon recycling centers, and waste disposal centers. The following section briefly discusses the connection between these levels.

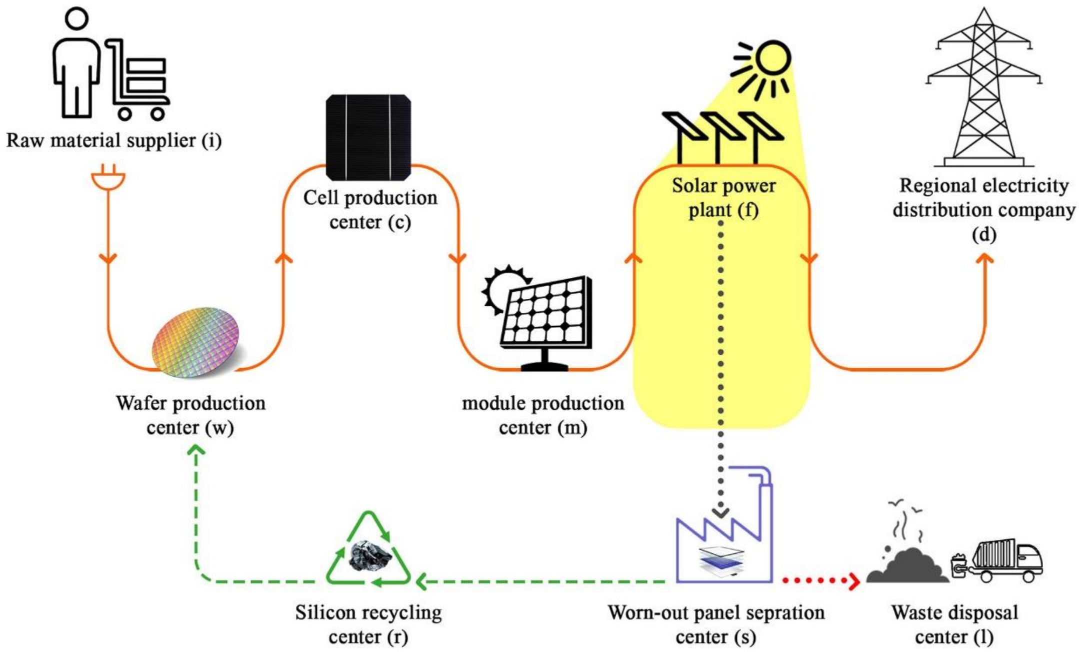

Fig 1. The proposed closed-loop PVSC

Silicon is the most common semiconductor material, which has been used in PV cells due to the abundance of this element in the world. The suppliers supply raw material (electronic-grade silicon) in two forms: monocrystalline and polycrystalline.

The raw electronic-grade silicon has a polycrystalline structure. Polycrystalline silicon is not suitable for making a semiconductor. This silicon should be converted into monocrystalline silicon with a regular atomic structure. The conversion process is usually performed by using the Czochralski process. Accordingly, the raw materials supplied by the suppliers are transported to wafer production centers to be converted into silicon ingots. For cutting these ingots and turn them into silicon wafers, a slurry of silicon is created in which the blades are continually moving. Silicon wafers are transported to solar cell production centers. After a wet chemical operation and emitter making in these centers, an anti-reflective coating covers the cell space to minimize waste. The generated cells are transported to module production centers. PV modules are generally made by connecting several separate cells to achieve an acceptable current and voltage level. For protecting solar cells stacked together, a glass cover and an aluminum frame are used for the surface and around of cells. Next, the solar modules are equipped with a by-pass diode and junction box and sent for installation in solar power plants. Finally, the electricity generated by solar power plants is transmitted to demand areas (regional electricity distribution companies).

Concerning the reverse SC of these systems, the detected worn-out solar panels are transported to worn-out panel separation centers. Then, the process of separating the panel components is performed by using chemical and mechanics operations. The wastes from the separation of worn-out panels are transported to waste disposal centers. Accordingly, the separated recyclable silicons are transported from worn-out panel separation center to silicon recycling center to obtain electronic-grade silicon with high purity and transport it to silicon wafer production centers for reuse purposes.

The main assumptions of the closed-loop PVSC are as follow:

1. The problem is considered for a five-year time horizon.
2. Electrical energy demand is known for each year.
3. The levels of raw material suppliers, waste disposal centers, and regional electricity distribution companies are considered potential.
4. The location of the wafer, cell, and module production centers, solar power plants, worn-out panel separation centers, and silicon recycling centers are selected from the candidate locations.
5. The capacities of facilities are not constant and can change over time.
6. Raw materials or input products of each level can be supplied in two importing methods from foreign countries and production centers of the previous chain level.

3-1- Mathematical modeling

This section presents the mathematical model for designing the PVSCN. The nomenclatures for PVCSND are presented in Appendix.

3-1-1- Objective functions

This sub-section seeks to present the objective functions considered in the model. The model has two objective functions: minimizing total costs and minimizing the adverse environmental impacts, which are formulated in the following.

3-1-1-1- Economic objective function

This function includes the following terms:

Fixed location costs: this term calculates fixed costs for the construction of wafer, cell, and module production centers, solar power plants, worn-out panel separation centers, and silicon recycling centers.

$$FC = \sum_{w\in W} FCK_w YK_w + \sum_{c\in C} FCL_c YL_c + \sum_{m\in M} FCN_m YN_m + \sum_{f\in F} FCP_f YP_f + \sum_{s\in S} FCQ_s YQ_s + \sum_{r\in R} FCE_r YE_r \tag{1}$$

Creating excess capacity costs: this term calculates the costs of creating excess capacity for producing solar cell components in production centers, creating excess capacity for separating worn-out panels in separation centers, recycling in silicon recycling centers, and installing panels in solar power plants.

$$EC = \sum_{o\in O}\sum_{w\in W}\sum_{t\in T} ECK_{owt} VK_{owt} + \sum_{o\in O}\sum_{c\in C}\sum_{t\in T} ECL_{oct} VL_{oct} + \sum_{o\in O}\sum_{m\in M}\sum_{t\in T} ECN_{omt} VN_{omt} + \sum_{o\in O}\sum_{f\in F}\sum_{t\in T} ECP_{oft} VP_{oft} + \sum_{o\in O}\sum_{s\in S}\sum_{t\in T} ECQ_{ost} VQ_{ost} + \sum_{o\in O}\sum_{r\in R}\sum_{t\in T} ECE_{ort} VE_{ort} \tag{2}$$

Production costs: this term calculates the production costs of wafers, cells, and modules in production centers.

$$PC = \sum_{o\in O}\sum_{w\in W}\sum_{t\in T} PCK_{owt} APK_{owt} + \sum_{o\in O}\sum_{c\in C}\sum_{t\in T} PCL_{oct} APL_{oct} + \sum_{o\in O}\sum_{m\in M}\sum_{t\in T} PCN_{omt} APN_{omt} \tag{3}$$

Separation costs: this term calculates the cost of separating worn-out panels in worn-out panel separation centers.

$$SC = \sum_{o\in O}\sum_{s\in S}\sum_{t\in T} SCQ_{ost} ASQ_{ost} \tag{4}$$

Recycling costs: this term calculates the cost of recycling silicon in silicon recycling centers.

$$RC = \sum_{o\in O}\sum_{r\in R}\sum_{t\in T} RCE_{ort} ARE_{ort} \tag{5}$$

Purchase costs: this term calculates the cost of purchasing raw materials for solar wafer production from raw material suppliers.

$$BC = \sum_{o \in O} \sum_{i \in I} \sum_{t \in T} BCO_{oit} ABO_{oit} \tag{6}$$

Maintenance costs: this term calculates the cost of maintaining PV systems in solar power plants.

$$MC = \sum_{o \in O} \sum_{f \in F} \sum_{t \in T} NEP_{oft} AIP_{oft} \tag{7}$$

Inventory holding costs: this term calculates the cost of inventory holding of raw materials and input products in production centers and inventory holding in worn-out panel separation centers and silicon recycling centers.

$$\begin{aligned} HC = & \sum_{o \in O} \sum_{w \in W} \sum_{t \in T} HCK_{owt} ILK_{owt} + \sum_{o \in O} \sum_{c \in C} \sum_{t \in T} HCL_{oct} ILL_{oct} + \sum_{o \in O} \sum_{m \in M} \sum_{t \in T} HCN_{omt} ILN_{omt} \\ & + \sum_{o \in O} \sum_{s \in S} \sum_{t \in T} HCQ_{ost} ILQ_{ost} + \sum_{o \in O} \sum_{r \in R} \sum_{t \in T} HCE_{ort} ILE_{ort} \end{aligned} \tag{8}$$

System Balance costs: this term calculates the costs for various components of PV systems, except the panel.

$$CS = \sum_{o \in O} \sum_{m \in M} \sum_{f \in F} \sum_{t \in T} CSA_f \left(TNP_{omft} \lambda^3{}_{mf} + QIP_{oft} \right) \tag{9}$$

Transportation costs: this term calculates transportation costs among different levels of SC.

$$\begin{aligned} TC = & \sum_{o \in O} \sum_{i \in I} \sum_{w \in W} \sum_{t \in T} TCK_{oiwt} TOK_{oiwt} \lambda_{iw} + \sum_{o \in O} \sum_{w \in W} \sum_{c \in C} \sum_{t \in T} TCL_{owct} TKL_{owct} \lambda^1{}_{wc} \\ & + \sum_{o \in O} \sum_{c \in C} \sum_{m \in M} \sum_{t \in T} TCN_{ocmt} TLN_{ocmt} \lambda^2{}_{cm} + \sum_{o \in O} \sum_{m \in M} \sum_{f \in F} \sum_{t \in T} TCP_{omft} TNP_{omft} \lambda^3{}_{mf} \\ & + \sum_{o \in O} \sum_{f \in F} \sum_{s \in S} \sum_{t \in T} TCQ_{ofst} TPQ_{ofst} \lambda^5{}_{fs} + \sum_{o \in O} \sum_{s \in S} \sum_{r \in R} \sum_{t \in T} TCE_{osrt} TQE_{osrt} \lambda^6{}_{sr} \\ & + \sum_{o \in O} \sum_{s \in S} \sum_{l \in L} \sum_{t \in T} TCW_{oslt} TQW_{oslt} \lambda^7{}_{sl} + \sum_{o \in O} \sum_{r \in R} \sum_{w \in W} \sum_{t \in T} TCK'_{orwt} TEk'_{orwt} \lambda'_{rw} \end{aligned} \tag{10}$$

Transmission costs: this term calculates the cost of transmitting electrical energy from solar power plants to regional electricity distribution companies.

$$TR = \sum_{f \in F} \sum_{d \in D} \sum_{t \in T} TCH_{fdt} TPH_{fdt} \lambda^4_{fd} \tag{11}$$

Import costs: this term calculates the cost of importing raw materials to wafer production centers, importing wafers and cells to cell and module production centers, and importing panels to solar power plants.

$$\begin{aligned} IC = & \sum_{o \in O} \sum_{w \in W} \sum_{t \in T} ICK_{owt} QIK_{owt} + \sum_{o \in O} \sum_{c \in C} \sum_{t \in T} ICL_{oct} QIL_{oct} \\ & + \sum_{o \in O} \sum_{m \in M} \sum_{t \in T} ICN_{omt} QIN_{omt} + \sum_{o \in O} \sum_{f \in F} \sum_{t \in T} ICP_{oft} QIP_{oft} \end{aligned} \tag{12}$$

Generally, the economic objective function of the model is formulated as follows:

$$\begin{aligned} Min\, objective\ Z_1 = & FC + EC + PC + SC + RC + BC + MC \\ & + HC + CS + TC + TR + IC \end{aligned} \tag{13}$$

3-1-1-2- Environmental objective function

This objective function includes the following terms:

Environmental impacts of creating excess capacity in established facilities: this term calculates the environmental impacts of creating excess capacity for producing solar cell components in production centers, creating excess capacity for separating worn-out panels in separation centers, recycling in silicon recycling centers, as well as installing panels in solar power plants.

$$\begin{aligned} EVC = &\sum_{o\in O}\sum_{w\in W}\sum_{t\in T} EVCK_{owt} YK_w EVK_{owt} + \sum_{o\in O}\sum_{c\in C}\sum_{t\in T} EVCL_{oct} YL_c EVL_{oct} \\ &+ \sum_{o\in O}\sum_{m\in M}\sum_{t\in T} EVCN_{omt} YN_m EVN_{omt} + \sum_{o\in O}\sum_{f\in F}\sum_{t\in T} EVCP_{oft} YP_f EVP_{oft} \\ &+ \sum_{o\in O}\sum_{s\in S}\sum_{t\in T} EVCQ_{ost} YQ_s EVQ_{ost} + \sum_{o\in O}\sum_{r\in R}\sum_{t\in T} EVCE_{ort} YE_r EVE_{ort} \end{aligned} \quad (14)$$

Environmental impacts of production and processing processes in production and processing centers: this term calculates the environmental impacts of various production, separation, and recycling processes of products in different centers in PVSC.

$$\begin{aligned} EVP = &\sum_{o\in O}\sum_{w\in W}\sum_{t\in T} EVPK_{owt} APK_{owt} + \sum_{o\in O}\sum_{c\in C}\sum_{t\in T} EVPL_{oct} APL_{oct} \\ &+ \sum_{o\in O}\sum_{m\in M}\sum_{t\in T} EVPN_{omt} APN_{omt} + \sum_{o\in O}\sum_{s\in S}\sum_{t\in T} EVSQ_{ost} ASQ_{ost} \\ &+ \sum_{o\in O}\sum_{r\in R}\sum_{t\in T} EVRE_{ort} ARE_{ort} \end{aligned} \quad (15)$$

Environmental impacts of purchasing raw materials from suppliers: this term calculates the environmental impacts of supplying raw materials for wafer production from raw material suppliers.

$$EVB = \sum_{o\in O}\sum_{i\in I}\sum_{t\in T} EVBO_{oit} ABO_{oit} \quad (16)$$

Environmental impacts of solar panels' maintenance: this term calculates the environmental impacts of PV panels' maintenance in solar power plants.

$$EVM = \sum_{o\in O}\sum_{f\in F}\sum_{t\in T} EVMP_{oft} AIP_{oft} \quad (17)$$

Environmental impacts of inventory holding of raw materials and input products in production and processing centers: this term calculates the environmental impacts of inventory holding of raw materials and input products in production centers and inventory holding in worn-out panel separation centers and silicon recycling centers.

$$\begin{aligned} EVH = &\sum_{o\in O}\sum_{w\in W}\sum_{t\in T} EVHK_{owt} ILK_{owt} + \sum_{o\in O}\sum_{c\in C}\sum_{t\in T} EVHL_{oct} ILL_{oct} \\ &+ \sum_{o\in O}\sum_{m\in M}\sum_{t\in T} EVHN_{omt} ILN_{omt} + \sum_{o\in O}\sum_{s\in S}\sum_{t\in T} EVHQ_{ost} ILQ_{ost} \\ &+ \sum_{o\in O}\sum_{r\in R}\sum_{t\in T} EVHE_{ort} ILE_{ort} \end{aligned} \quad (18)$$

Environmental impacts of system balance: this term calculates the environmental impacts of PV panels' balance in solar power plants.

$$EVS = \sum_{o\in O}\sum_{m\in M}\sum_{f\in F}\sum_{t\in T} EVSA_f \left(TNP_{omft} \lambda^3_{mf} + QIP_{oft} \right) \quad (19)$$

Environmental impacts of transportation between different SC levels: this term calculates the environmental impact of transport between various centers and solar power plants.

$$
\begin{aligned}
EVT = & \sum_{o\in O}\sum_{i\in I}\sum_{w\in W}\sum_{t\in T} EVTK_{oiwt} TOK_{oiwt} \lambda_{iw} \quad + \sum_{o\in O}\sum_{w\in W}\sum_{c\in C}\sum_{t\in T} EVTL_{owct} TKL_{owct} \lambda^{1}{}_{wc} \\
& + \sum_{o\in O}\sum_{c\in C}\sum_{m\in M}\sum_{t\in T} EVTN_{ocmt} TLN_{ocmt} \lambda^{2}{}_{cm} + \sum_{o\in O}\sum_{m\in M}\sum_{f\in F}\sum_{t\in T} EVTP_{omft} TNP_{omft} \lambda^{3}{}_{mf} \\
& + \sum_{f\in F}\sum_{d\in D}\sum_{t\in T} EVTH_{fdt} TPH_{fdt} \lambda^{4}_{fd} \quad + \sum_{o\in O}\sum_{f\in F}\sum_{s\in S}\sum_{t\in T} EVTQ_{ofst} TPQ_{ofst} \lambda^{5}{}_{fs} \\
& + \sum_{o\in O}\sum_{s\in S}\sum_{r\in R}\sum_{t\in T} EVTE_{osrt} TQE_{osrt} \lambda^{6}{}_{sr} \quad + \sum_{o\in O}\sum_{s\in S}\sum_{l\in L}\sum_{t\in T} EVTW_{oslt} TQW_{oslt} \lambda^{7}{}_{sl} \\
& + \sum_{o\in O}\sum_{r\in R}\sum_{w\in W}\sum_{t\in T} EVTK'_{orwt} TEk'_{orwt} \lambda'{}_{rw}
\end{aligned} \tag{20}
$$

Environmental impacts of imports: this term calculates the environmental impact of importing raw materials to wafer production centers, and importing wafers and cells to cell and modules production centers and importing panels to solar power plants.

$$
\begin{aligned}
EVI = & \sum_{o\in O}\sum_{w\in W}\sum_{t\in T} EVIK_{owt} QIK_{owt} \quad + \sum_{o\in O}\sum_{c\in C}\sum_{t\in T} EVIL_{oct} QIL_{oct} \\
& + \sum_{o\in O}\sum_{m\in M}\sum_{t\in T} EVIN_{omt} QIN_{omt} + \sum_{o\in O}\sum_{f\in F}\sum_{t\in T} EVIP_{oft} QIP_{oft}
\end{aligned} \tag{21}
$$

The environmental objective function is the sum of all the terms mentioned above, which are formulated as follows:

$$
Min\, objective\; Z_2 = EVC + EVP + EVB + EVM + EVH + EVS + EVT + EVI \tag{22}
$$

3-1-2- Constraints

Model constraints are formulated as follows:

$$
\begin{aligned}
& \sum_{o\in O}\sum_{m\in M} EF_o\, CS_o\, YR_f\, PR_f\, TNP_{omft}\, \lambda^{3}_{mf} \\
& + \sum_{o\in O} EF_o\, CS_o\, YR_f\, PR_f\, QIP_{oft} = EP_{ft}
\end{aligned} \qquad \forall f \in F, \forall t \in T \tag{23}
$$

$$
\sum_{f\in F} EP_{ft} \geq De_t \qquad \forall t \in T \tag{24}
$$

$$
AIP_{oft} = AIP_{oft-1} + \sum_{m\in M} TNP_{omft} \lambda^{3}{}_{mf} + QIP_{oft} \qquad \forall o \in O, \forall f \in F, \forall t \in T \tag{25}
$$

$$
ABO_{oit} = \sum_{w\in W} TOK_{oiwt} \lambda_{iw} \qquad \forall o \in O, \forall i \in I, \forall t \in T \tag{26}
$$

$$
APK_{owt} \leq COK_o (QIK_{owt} + \sum_{i\in I} TOK_{oiwt} \lambda_{iw} + \sum_{r\in R} TEK'_{orwt} \lambda'_{rw} + ILK_{owt-1}) \qquad \forall o \in O, \forall w \in W, \forall t \in T \tag{27}
$$

$$
APL_{oct} \leq CKL_o (QIL_{oct} + \sum_{w\in W} TKL_{owct} \lambda^{1}_{wc} + ILL_{oct-1}) \qquad \forall o \in O, \forall c \in C, \forall t \in T \tag{28}
$$

$$
APN_{omt} \leq CLN_o (QIN_{omt} + \sum_{c\in C} TLN_{ocmt} \lambda^{2}_{cm} + ILN_{omt-1}) \qquad \forall o \in O, \forall m \in M, \forall t \in T \tag{29}
$$

$$
ARE_{ort} \leq \vartheta E_o (\sum_{s\in S} TQE_{osrt} \lambda^{6}_{sr}) \qquad \forall o \in O, \forall r \in R, \forall t \in T \tag{30}
$$

$$
APK_{owt} = \sum_{c\in C} TKL_{owct} \lambda^{1}_{wc} \qquad \forall o \in O, \forall w \in W, \forall t \in T \tag{31}
$$

$$APL_{oct} = \sum_{m \in M} TLN_{ocmt} \lambda_{cm}^{2} \qquad \forall o \in O, \forall c \in C, \forall t \in T \qquad (32)$$

$$APN_{omt} = \sum_{f \in F} TNP_{omft} \lambda_{mf}^{3} \qquad \forall o \in O, \forall m \in M, \forall t \in T \qquad (33)$$

$$\alpha p_{oft} AIP_{oft} W_{O} = \sum_{s \in S} TPQ_{ofst} \lambda_{fs}^{5} \qquad \forall o \in O, \forall f \in F, \forall t \in T \qquad (34)$$

$$ASQ_{ost} \frac{1}{w_{o}} AS_{o} = \sum_{r \in R} TQE_{osrt} \lambda_{sr}^{6} \qquad \forall o \in O, \forall s \in S, \forall t \in T \qquad (35)$$

$$ASQ_{ost} \frac{1}{w_{o}} AW_{o} = \sum_{l \in L} TQW_{oslt} \lambda_{sl}^{7} \qquad \forall o \in O, \forall s \in S, \forall t \in T \qquad (36)$$

$$ARE_{ort} = \sum_{w \in W} TEK_{orwt}^{'} \lambda_{rw}^{'} \qquad \forall o \in O, \forall r \in R, \forall t \in T \qquad (37)$$

$$EP_{ft} = \sum_{d \in D} TPH_{fdt} \lambda_{fd}^{4} \qquad \forall f \in F, \forall t \in T \qquad (38)$$

$$ILK_{owt} = ILK_{owt-1} + \sum_{i \in I} TOK_{oiwt} \lambda_{iw} + \sum_{r \in R} TEK_{orwt}^{'} \lambda_{rw}^{'} - \frac{1}{COK_{o}} APK_{owt} \qquad \forall o \in O, \forall w \in W, \forall t \in T \qquad (39)$$

$$ILL_{oct} = ILL_{oct-1} + \sum_{w \in W} TKL_{owct} \lambda_{wc}^{1} - \frac{1}{CKL_{o}} APL_{oct} \qquad \forall o \in O, \forall c \in C, \forall t \in T \qquad (40)$$

$$ILN_{omt} = ILN_{omt-1} + \sum_{c \in c} TLN_{ocmt} \lambda_{cm}^{2} - \frac{1}{CLN_{o}} APN_{omt} \qquad \forall o \in O, \forall m \in M, \forall t \in T \qquad (41)$$

$$ILQ_{ost} = ILQ_{ost-1} + \sum_{f \in F} TPQ_{ofst} \lambda_{fs}^{5} - ASQ_{ost} \qquad \forall o \in O, \forall s \in S, \forall t \in T \qquad (42)$$

$$ILE_{ort} = ILE_{ort-1} + \sum_{s \in S} TQE_{osrt} \lambda_{sr}^{6} - \frac{1}{\vartheta E_{o}} ARE_{ort} \qquad \forall o \in O, \forall r \in R, \forall t \in T \qquad (43)$$

$$VK_{owt} = VK_{owt-1} + EVK_{owt} \qquad \forall o \in O, \forall w \in W, \forall t \in T \qquad (44)$$

$$VL_{oct} = VL_{oct-1} + EVL_{oct} \qquad \forall o \in O, \forall c \in C, \forall t \in T \qquad (45)$$

$$VN_{omt} = VN_{omt-1} + EVN_{omt} \qquad \forall o \in O, \forall m \in M, \forall t \in T \qquad (46)$$

$$VP_{oft} = VP_{oft-1} + EVP_{oft} \qquad \forall o \in O, \forall f \in F, \forall t \in T \qquad (47)$$

$$VQ_{ost} = VQ_{ost-1} + EVQ_{ost} \qquad \forall o \in O, \forall s \in S, \forall t \in T \qquad (48)$$

$$VE_{ort} = VE_{ort-1} + EVE_{ort} \qquad \forall o \in O, \forall r \in R, \forall t \in T \qquad (49)$$

$$APK_{owt} \leq VK_{owt} \qquad \forall o \in O, \forall w \in W, \forall t \in T \qquad (50)$$

$$APL_{oct} \leq VL_{oct} \qquad \forall o \in O, \forall c \in C, \forall t \in T \qquad (51)$$

$$APN_{omt} \leq VN_{omt} \qquad \forall o \in O, \forall m \in M, \forall t \in T \qquad (52)$$

$$AIP_{oft} \leq VP_{oft} \qquad \forall o \in O, \forall f \in F, \forall t \in T \qquad (53)$$

$$ASQ_{ost} \leq VQ_{ost} \qquad \forall o \in O, \forall s \in S, \forall t \in T \qquad (54)$$

$$ARE_{ort} \leq VE_{ort} \qquad \forall o \in O, \forall r \in R, \forall t \in T \qquad (55)$$

$$EP_{ft} \leq VPP_{ft} \qquad \forall f \in F, \forall t \in T \qquad (56)$$

$$TPH_{fdt} \lambda_{fd}^{4} \leq VPH_{fdt} \qquad \forall f \in F, \forall d \in D, \forall t \in T \qquad (57)$$

$$\sum_{o \in O} ABO_{oit} \leq MCO_{i} \qquad \forall i \in I, \forall t \in T \qquad (58)$$

$$\sum_{o \in O} VK_{owt} \leq MCK_{w} YK_{w} \qquad \forall w \in W, \forall t \in T \qquad (59)$$

$$\sum_{o \in O} VL_{oct} \leq MCL_{C} YL_{c} \qquad \forall c \in C, \forall t \in T \qquad (60)$$

$$\sum_{o \in O} VN_{omt} \leq MCN_{m} YN_{m} \qquad \forall m \in M, \forall t \in T \qquad (61)$$

$$\sum_{o \in O} VP_{oft} \leq MCP_{f} YP_{f} \qquad \forall f \in F, \forall t \in T \qquad (62)$$

$$\sum_{o \in O} VQ_{ost} \leq MCQ_{s} YQ_{s} \qquad \forall s \in S, \forall t \in T \qquad (63)$$

$$\sum_{o \in O} VE_{ort} \leq MCE_{r} YE_{r} \qquad \forall r \in R, \forall t \in T \qquad (64)$$

$$VPP_{ft} \leq \delta_{f} YP_{f} \qquad \forall f \in F, \forall t \in T \qquad (65)$$

$$\sum_{o \in O} VW_{olt} \leq MCW_{l} \qquad \forall l \in L, \forall t \in T \qquad (66)$$

$$VPH_{fdt} \leq MPH_{fd} \qquad \forall f \in F, \forall d \in D, \forall t \in T \qquad (67)$$

$$YK_{w}, YL_{c}, YN_{m}, YP_{f}, YN_{m}, YQ_{s}, YE_{r} \in \{0,1\} \qquad \forall w, c, m, f, s, r \qquad (68)$$

$$\begin{aligned} &TOK_{oiwt}, TKL_{owct}, TLN_{ocmt}, TNP_{omft}, TPQ_{ofst}, TQE_{osrt}, TQW_{oslt}, TEK'_{orwt}, TPH_{fdt} \\ &ABO_{oit}, APK_{owt}, APL_{oct}, APN_{omt}, AIP_{oft}, ASQ_{ost}, ARE_{ort}, EP_{ft}, \\ &VK_{owt}, VL_{oct}, VN_{omt}, VP_{oft}, VPP_{ft}, VPH_{fdt}, VQ_{ost}, VE_{ort}, VW_{olt} \\ &EVK_{owt}, EVL_{oct}, EVN_{omt}, EVP_{oft}, EVQ_{ost}, EVE_{ort}, \\ &QIK_{owt}, QIL_{oct}, QIN_{omt}, QIP_{oft}, \\ &ILK_{owt}, ILL_{oct}, ILN_{omt}, ILQ_{ost}, ILE_{ort} \geq 0 \end{aligned} \qquad \forall i, w, c, m, f, s, r, d, l, o, t \qquad (69)$$

Constraint (23) indicates the amount of electrical energy generated by radiation to solar panels at each solar power plant, in each period. Constraint (24) shows that the amount of electrical energy generated by solar panels in all solar power plants should be more than the total demand to meet all required electrical energy demand. Constraint (25) calculated the total number of installed panels at each solar power plant and in each period. This amount is equal to the sum of the total number of installed panels up to the previous period, the total number of imported panels, and the number of produced panels transported from solar module production centers to the solar power plant. Constraint (26) states that the amount of raw materials purchased from each raw material supplier is equal to the amount of raw materials entered into wafer production centers. Constraints (27)-(29) illustrate the relation between the number of products produced at production centers and the amount of raw material and input products transported to production centers.

Constraint (30) implies that only a percentage of silicons separated from worn-out panels can be recycled. Constraints (31)-(33) indicate the balance between the number of products produced in production centers and the transported amount to the next level in each production center. Constraint

(34) demonstrates the balance between the number of worn-out panels in the solar power plant and the number of worn-out panels transported to worn-out panel separation centers. Constraints (35) and (36) display the balance between wastes and recyclable silicons separated from worn-out panels in each worn-out panel separation center and the amount of these separated components transported to waste disposal centers and silicon recycling centers. Constraint (37) states that after recycling silicon at each silicon recycling center, the recycled silicons are transported to wafer production centers for reuse in the silicon wafer production. Constraint (38) indicates that the amount of electrical energy generated in each solar power plant is equal to the total electrical energy distributed among regional electricity distribution companies. Constraints (39)-(41) show the amount of raw materials or input products inventory in each wafer, cell, and module production center. This amount in each period is equal to the sum of the raw materials or input products inventory in the previous period and the amount of raw materials or input products transported from the prior level to these levels. This amount should be subtracted by the total raw materials or products required for product production in the current period. Constraints (42) and (43) illustrate the amount of separable and recyclable product inventory in separation and recycling centers in each period. This amount is equal to the sum of the total product inventory in the previous period and the total number of products transported to these centers in this period, from which the amount of separated or recycled products should be subtracted. Constraints (44)-(49) indicate the capacity of wafer, cell, and module production centers, as well as solar power plants, worn-out panel separation centers, and silicon recycling centers in each period. This amount is equal to the total capacity of each center in the previous period and the excess capacity created in this period. Constraints (50)-(55) restricted the maximum production, panels installation, worn-out panels separation, and recycling capacity in the relevant centers in each period. Constraint (56) indicates the capacity of electrical energy generated by each solar power plant in each period.

Constraint (57) depicts the maximum electrical energy transmission capacity to regional electricity distribution companies in each period. Constraint (58) expresses the maximum raw material supply capacity for each raw material supplier. Constraints (59)-(65) reveal that the amount of activated capacity for each established center should not exceed the maximum defined capacity. Constraint (66) implies that wastes from worn-out panel separation transported to each waste disposal center should not exceed the maximum defined capacity for waste acceptance. Constraint (67) shows that the amount of electrical energy transmission from the solar power plant to each regional electricity distribution company should not exceed the maximum defined transmission capacity. Finally, Constraints (68) and (69) indicate binary and non-negative decision variables.

4- Solution method

In the process of solving the problem, there are some complexities in the model. Hence some methods should be provided to cope with them. These complexities can be mentioned as follows:

1. The proposed model includes a non-linear term in eq. (14), which increases the model's complexity, and therefore, the non-linear term should be converted to a linear form by using a suitable method.
2. A suitable method should be used for data collection to determine the environmental parameters.
3. Since the proposed model is a two-objective model, it should be converted into a single-objective one to be solved. Thus, a multi-objective solution method is required to obtain Pareto optimal solutions.

4-1- Linearization

As mentioned before, the proposed model has a non-linear term in eq. (14), which is the result of the multiplication of a binary variable into a continuous one. The linearization process of this term is presented in the following.

Assume that $Z = X \times Y$ is the multiplication of a binary variable (X) into a continuous variable (Y). In this case, the variable Z can be equal to the continuous variable if the binary variable takes the value one. Otherwise, the variable Z will be equal to zero. Constraints (70)-(72) are added to linearize the model (Glover and Woolsey, 1974). It should be noted that $BigM$ is a non-negative number whose value should not be assumed too large but to be determined depending on the problem's characteristics.

$$Z \le Y \tag{70}$$

$$Z \le BigM \ X \tag{71}$$

$$Z \ge Y - BigM\,(1 - X) \tag{72}$$

4-2- Determining environmental parameters using SimaPro software

As noted, the proposed model seeks to minimize adverse environmental effects while minimizing the total costs. Since each product has different environmental impacts during its life cycle, it is appropriate to utilize the product life cycle assessment to quantify and evaluate its environmental effects (Pishvaee et al., 2014). Life cycle assessment (LCA) is a tool for analyzing the environmental effects of products at all stages of their life cycle, from resource extraction to material production, final product production, and product utilization to post-disposal management, including recycling reuse and final disposal. However, the direct use of life cycle assessment requires a large amount of time and cost, and its results cannot be used directly (Chiu et al., 2008). In this study, SimaPro software is used to collect, evaluate, and monitor the environmental efficiency of products and processes throughout their life cycle stages. SimaPro software is the latest version of LCA software, which has been widely used recently. ReCiPe 2008 is one of the SimaPro software methods employed in this study to determine the environmental parameters.

This method has many advantages that can be mentioned as follows:

1. This method evaluates the environmental impacts using both the effects of Mid- and end-point impacts
2. One of the most important advantages of this method is utilizing the latest environmental sciences advances.
3. This method is a broad-scale assessment method that mainly considers the mid- and end-point impacts.
4 - This method has been developed based on two other techniques of Simapro software, namely CML2001 and Echo Indicator 99, and benefits from the advantages of both approaches.

4-3- Converting model into a single-objective one using the augmented ε-constraint method

So far, various methods have been proposed to transform multi-objective problems into single-objective models, among which the ε-constraint method is one of the most well-known methods. However, the ε-constraint method has two main issues: 1) not optimizing the range of each objective over the efficient set, and 2) lack of guarantee for the efficiency of Pareto optimal solutions (Aghaei et al., 2011). The present study aims to implement the augmented ε-constraint method proposed by (Mavrotas, 2009) to cope with these issues. This method only generates the Pareto optimal solutions. In the following, the application of this method is described.

Consider the following two-objective model:

$$\begin{aligned} &Max\ (f_1, f_2) \\ &s.t:\ X \in F \end{aligned} \tag{73}$$

The steps of the augmented ε-constraint method are as follows:

1) Selecting one of the functions as the main objective function, for example, f_1
2) Optimizing the problem by considering the main objective function (f_1^*)
3) Optimizing the problem by considering the second objective function (f_2^*)
4) Addressing the problem at the value $f_1 = f_1^*$ and solving it with the second objective function $(f_2^*)'$
5) Calculating the range of the second objective function $r_2 = f_2^* - (f_2^*)'$
6) Main step: converting the objective function to a constraint and changing the model.

$$\begin{aligned} &\max\ f_1 + eps(\frac{s_2}{r_2}) \\ &s.t:\ f_2 - S_2 = e_2 \end{aligned} \tag{74}$$

$S_2 \geq 0$

$X \in F$

7) Determining the number of grid points

8) Repetitive step: Calculating the equation (75) from $i_2 = 0$ to $i_2 = g_2$ and solving the proposed model in each iteration. Equation (75) describes how to perform this step.

$$e_2 = (f_2^*)' + \frac{i_2}{r_2 + g_2} \tag{75}$$

At the end of this section, figure 2 summarizes all the subjects presented in this section and the previous sections.

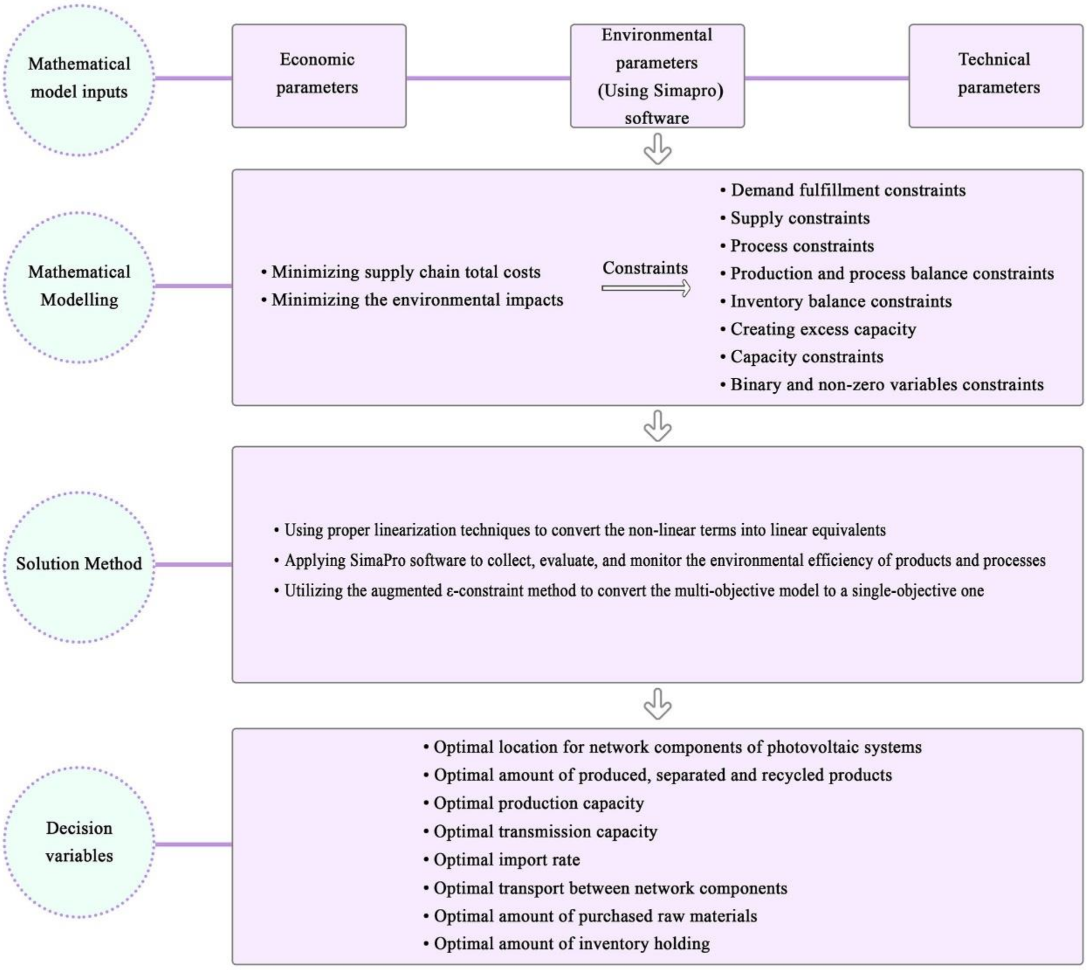

Fig 2. Schematic view of the problem

5- Practical and computational results

This section first provides the case study, collects the related data, and then shows the results of solving the proposed model and presents the sensitivity analysis.

5-1- Case study

This study seeks to examine the problem of designing PVSCN in Iran. According to the statistics, 99% of Iran's energy is supplied from oil and gas resources. In comparison, only 1% of the total energy is provided from renewable resources, despite Iran's high potential in using this type of these resource (Najafi et al., 2015). Iran has 300 sunny days out of 365 days a year, illustrating Iran's high potential for using solar energy in more than two-thirds of its area (Bakhoda et al., 2012). The average amount of solar radiation in Iran is 2200 KWh/m^2 (Najafi et al., 2015). Currently, various solar power plants, such as solar power plants located in Yazd, Sarkavir of Semnan, Darbid of Yazd, and Tehran, are operating, which play a small role in the country's energy supply. However, it is possible to provide a more considerable contribution to the country's required energy through solar energy, considering the high potential of solar radiation in Iran.

The following section describes data collection for the problem derived from valid and cited databases.

According to the sixth development plan, the installed capacity of renewable energy sources should reach 5,000 megawatts, which is almost impossible over the remaining years. Given the country's current situation, Iran aims to achieve the capacity of 5,000 megawatts of renewable energy resources over the next five years. Since 44% of the total capacity of renewable energy belongs to solar power plants, 40% to wind power plants, and the other 16% to other renewable energy sources. Figure 3 shows the amount of required electrical energy generated by solar energy in Iran.

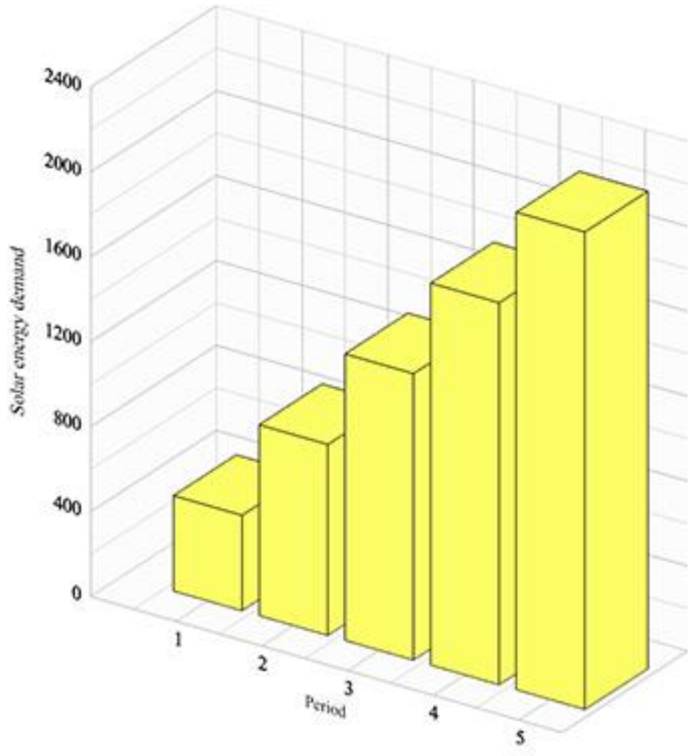

Fig 3. Electrical energy demand made by solar energy in the next five periods

The transportation costs of products and wastes are calculated based on the cost calculated on the site (https://ubaar.ir).

In this research, Meteosyn software is utilized to determine candidate locations for constructing solar power plants. The first 15 cities are chosen from the software output list based on their potential for building a solar power plant, with the condition that only one city was considered from each province. The candidate locations for panel component production centers and worn-out panel separation centers and silicon recycling centers are considered in nearby cities of these candidate areas.

5-2- Results and sensitivity analysis

The current section provides the solving results of the model and implementing it in the case study. The presented model is coded in GAMS software and is solved by CPLEX solver. All experiments in this study are carried out with an Intel Core i7 CPU, 2.4 GHz, and RAM 8GB laptop. Table 3 presents the size of the proposed problem.

Table 3. The problem size for the proposed model

$\|I\|$	$\|W\|$	$\|C\|$	$\|M\|$	$\|F\|$	$\|S\|$	$\|R\|$	$\|L\|$	$\|D\|$	$\|O\|$	$\|T\|$
6	9	10	9	15	12	13	12	16	2	5

Figure 4 depicts the value of all the types of SC's costs. As observed, the facility location costs and transportation costs have the highest values. In the proposed model, the dynamic capacity of facilities in different periods prevents the construction of facilities in unnecessary periods and saves the fixed location costs.

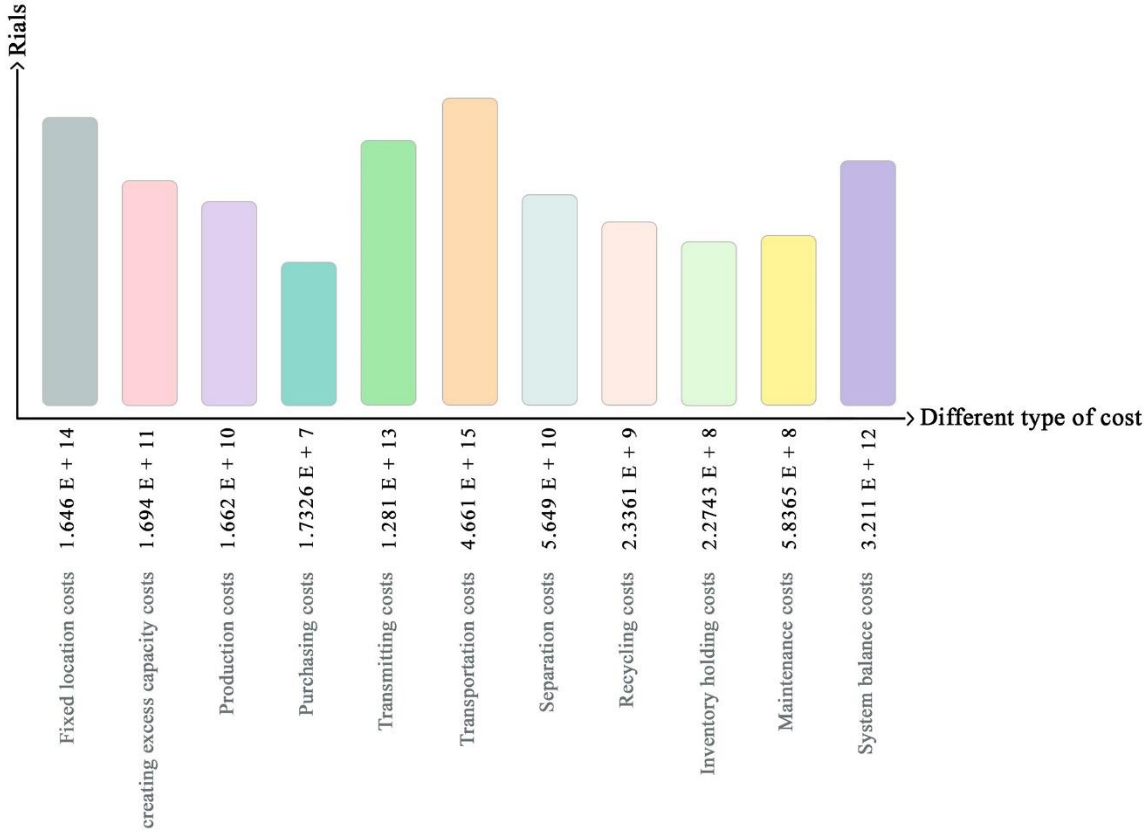

Fig 4. The value of different costs in SC

Figures 5 and 6 illustrate the optimal location of production centers, solar power plants, worn-out panel separation centers, silicon recycling centers, and the allocation of different centers to each other at different levels of the SC. It is observed that solar power plants have been selected in Chabahar, Bandar Lengeh, Urmia, Birjand, Yazd, Semnan, and Shahr-e Kord. In the reverse flow, only one silicon recycling center is activated in Yazd, where worn-out panels from all the separation centers are transported to this center. Then, the recycled silicons are sent to the nearest wafer production centers.

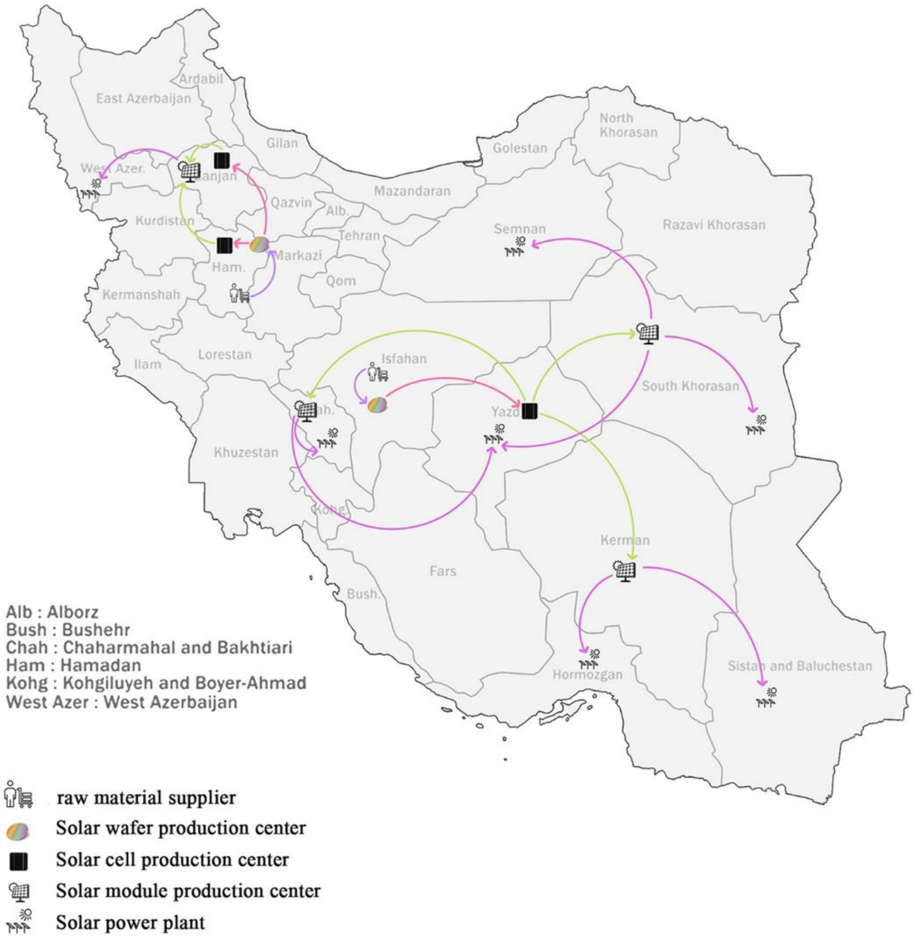

Fig 5. Optimal location and allocation of centers in the forward flow of SC

Fig 6. Optimal location and allocation of centers in the reverse flow of SC

Table 4 reports the created excess capacity of each solar power plant in the five planning periods. Based on the table, cities such as Chabahar and Birjand have been built since the first period because of their high potential for solar energy radiation. Consequently, their capacity is gradually increased in the next periods. However, solar power plants in other cities are built in the subsequent periods in the case of growing electrical energy demand. For example, the solar power plant capacity in Yazd is zero at the first period, and it reaches the values 281, 10180, 1879, and 2244 in the next periods. As mentioned, this issue implies the proposed model dynamics, which significantly saves the SC's costs.

Table 4. The capacity of solar power plants built during the five planning periods

city \ period	1	2	3	4	5
Chabahar	883	1794	2705	3616	3946
Birjand	617	1548	2479	3410	4322
Urmia	0	102	892	1863	2050
Bandar Lengeh	0	849	1824	2799	2799
Yazd	0	281	1080	1879	2244
Semnan	0	0	0	186	186
Shahr-e Kord	0	0	273	273	273

As mentioned before, the model presented in this study is a multi-objective one, in which the objective functions generally conflict with each other. It means that improvement in an objective function worsens the value of the other one. In this case, the Pareto optimal solutions will be presented. In this section, we analyze the trade-off between the model's objective functions. As shown in figure 7, decreasing the destructive environmental impacts increases the total costs because achieving an appropriate level of SC's environmental effects is a costly and time-consuming process.

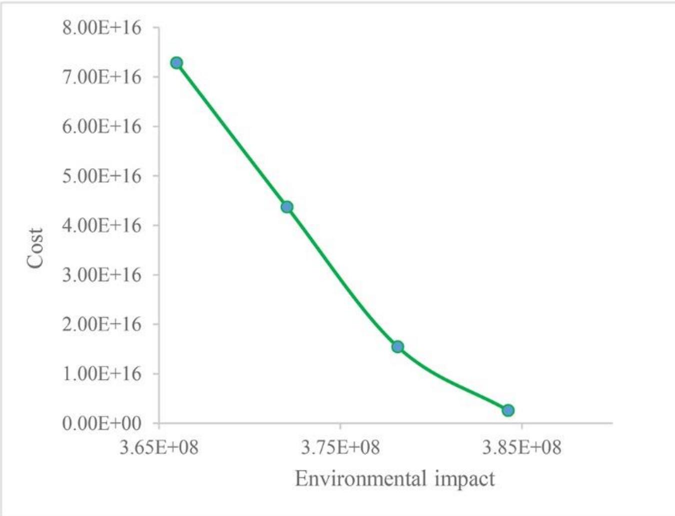

Fig 7. The Pareto optimal curve of the presented two-objective model

As shown in table 5, additional costs should be paid to improve environmental issues, referred to as "environmental protection costs". This indicator is obtained by the difference between the efficient solutions of the Pareto optimal set resulting from solving the model by considering both objective functions and the best value of the economic objective function. The best value of the economic objective function is obtained by solving the model only with the economic objective function, which equals 1.61417E+14. Figure 7 and table 4 help decision-makers of this field reach a balance between the economic and environmental objective functions and make the best decision based on their available resources.

Table 5. Environmental protection cost

iteration	Objective function value	
	Environmental objective function	The cost of reducing negative environmental impacts
1	3.66E+08	7.27E+16
2	3.72E+08	4.37E+16
3	3.78E+08	1.55E+16
4	3.84E+08	2.59E+15

The recycling costs are gradually decreased to evaluate the effectiveness of silicon recycling in the SC's costs and its reuse in solar wafer production. Based on the results, a decrease in recycling costs returns more silicon to chain as raw materials, allowing purchasing less raw materials from suppliers and significantly reducing the raw materials' purchasing costs. Figure 8 demonstrates the results of decreasing raw materials' purchasing costs resulted from reducing recycling costs. Also, due to considering the level of silicon recycling centers in the proposed model, the recycled materials return to the chain as the primary material, leading to a decrease in raw materials' purchasing cost by about 1.58764E+3.

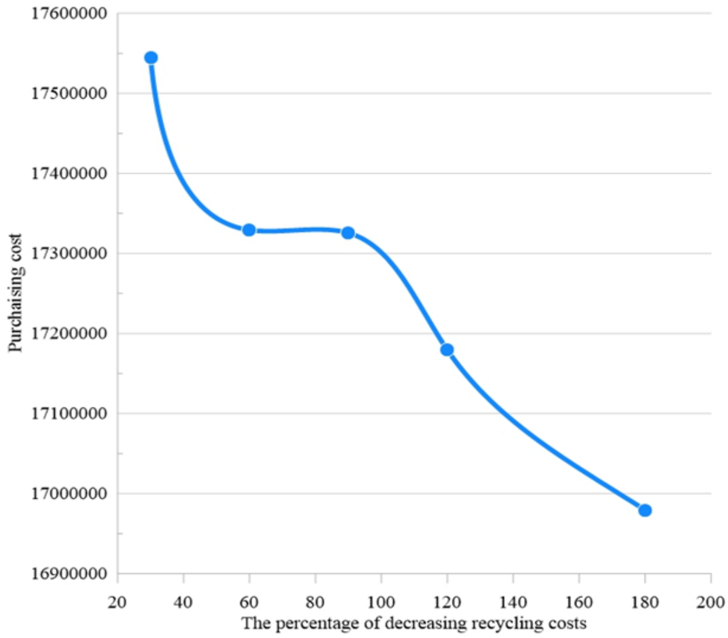

Fig 8. Evaluating the raw material purchasing costs relative to reducing recycling costs

6- Conclusions

Regarding the limited resources of non-renewable energy and various types of environmental pollution caused by these resources, it is necessary to replace them with renewable energy resources such as solar energy. Hence, utilizing a variety of solar energy-absorbing technologies such as PV systems has been highly considered by researchers in different fields. The recycling and reuse of PV panels can lead to economic advantages due to the limited lifetime of PV systems. Regarding the few studies conducted on forward and reverse SCND for PV systems, the present study sought to discuss the closed-loop PVSCND. To this aim, a two-objective, mixed-integer non-linear mathematical model was presented to design the PVSCN while including economic and environmental aspects. Then, the augmented ε-constraint method was applied to solve the two-objective model, which can guarantee the Pareto optimal solutions.

Consequently, the performance of the model was represented in a real-world case in Iran. The results indicated that solar power plants had been built in areas with higher solar energy radiation. In this regard, Chabahar, Birjand, Urmia, Bandar Lengeh, Yazd, Semnan, and Shahr-e Kord were selected for constructing solar power plants. One of the main results of this research is finding the optimal location and capacity for wafer, cell, and module production centers, solar power plants, worn-out panel separation centers, silicon recycling centers, the amount of electricity produced in solar power plants, and the number of products transferred between different levels of the SC. The model dynamics also causes the facilities with different capacities established in different periods, leading to a reduction in the SC's associated costs. Another key result can be pointed to the conflict between the minimization function of the costs and environmental impacts. As expected, reducing the negative environmental impact needs spending more money. On the other hand, the proposed Pareto diagram helps managers balance the two objective functions according to their financial resources and preferences.

For developing the proposed model, future research can focus on utilizing various MCDM methods, GIS software, and the DEA method at different decision-making levels of the SC, such as determining candidate locations for production centers. Also, due to the increasing attention to sustainability, considering social life improvement in SCND and addressing a sustainable PVSCND can be another future research. Given the lack of access or incompleteness of information in the SCND, it is possible to include uncertainty in some model parameters such as demand and capacity and make the model more similar to the real world. The various types of robust, fuzzy, probabilistic, and stochastic approaches can be utilized to deal with these uncertainties. Finally, addressing the risk of disruption at different SC levels and using resilience strategies to control these risks in the chain are other suggestions for future research.

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Appendix:

Sets and indices

I	Set of raw material suppliers, $i=\{1,...,I\}$
W	Set of candidate locations for solar wafer production centers, $w=\{1,...,W\}$
C	Set of candidate locations for solar cell production centers, $c=\{1,...,C\}$
M	Set of candidate locations for solar module production centers, $m=\{1,...,M\}$
F	Set of candidate locations for solar power plants, $f=\{1,...,F\}$
S	Set of candidate locations for worn-out panel separation centers, $s=\{1,...,S\}$
R	Set of candidate locations for silicon recycling centers, $r=\{1,...,R\}$
L	Set of potential locations for waste disposal centers, $l=\{1,...,L\}$
D	Set of potential locations for demand areas (regional electricity distribution companies, $d=\{1,...,D\}$
O	Set of products (solar cell), $o=\{1,...,O\}$
T	Set of periods, $t=\{1,...,T\}$

Parameters

Cost parameters	
FCK_w	Fixed cost of constructing solar wafer production center *w* (Rials)
FCL_c	Fixed cost of constructing solar cell production center *c* (Rials)
FCN_m	Fixed cost of constructing solar module production center *m* (Rials)
FCP_f	Fixed cost of constructing solar power plant *f* (Rials)
FCQ_s	Fixed cost of constructing worn-out panel separation center *s* (Rials)
FCE_r	Fixed cost of constructing silicon recycling center *r* (Rials)
ECK_{owt}	Unit cost of creating excess capacity for producing wafer type *o* in solar wafer production center *w* in period *t* (Rials/unit)
ECL_{oct}	Unit cost of creating excess capacity for producing cell type *o* in solar cell production center *c* in period *t* (Rials/unit)
ECN_{omt}	Unit cost of creating excess capacity for producing module type *o* in solar module production center *m* in period *t* (Rials/unit)
ECP_{oft}	Unit cost of creating excess capacity for installing solar panel type *o* in solar power plant *f* in period *t* (Rials/unit)
ECQ_{ost}	Unit cost of creating excess capacity for separating worn-out panel type *o* in worn-out panel separation center *s* in period *t* (Rials/unit)
ECE_{ort}	Unit cost of creating excess capacity for recycling silicon separated from worn-out panel type *o* in silicon recycling center *r* in period *t* (Rials/unit)

PCK_{owt} Unit cost of wafer type *o* production in solar wafer production center *w* in period *t* (Rials/unit)

PCL_{oct} Unit cost of cell type *o* production in solar cell production center *c* in period *t* (Rials/unit)

PCN_{omt} Unit cost of module type *o* production in solar module production center *m* in period *t* (Rials/unit)

SCQ_{ost} Unit cost of worn-out panel type *o* separation in worn-out panel separation center *s* in period *t* (Rials/unit)

RCE_{ort} Unit cost of recycling silicon separated from worn-out panel type *o* in silicon recycling center *r* in period *t* (Rials/unit)

BCO_{oit} Unit cost of purchasing raw material for producing wafer type *o* from raw material supplier *i* in period *t* (Rials/unit)

NEP_{oft} Unit cost of solar panel type *o* maintenance in solar power plant *f* in period *t* (Rials/unit)

HCK_{owt} Unit cost of raw material inventory holding for producing wafer type *o* in solar wafer production center *w* in period *t* (Rials/unit)

HCL_{oct} Unit cost of wafer inventory holding for producing cells type *o* in solar cell production center *c* in period *t* (Rials/unit)

HCN_{omt} Unit cost of cell inventory holding for producing module type *o* in solar module production center *m* in period *t* (Rials/unit)

HCQ_{ost} Unit cost of worn-out panel type *o* inventory holding in worn-out panel separation center *s* in period *t* (Rials/unit)

HCE_{ort} Unit cost of recyclable silicon inventory holding separated from worn-out panel type *o* in silicon recycling center *r* in period *t* (Rials/unit)

CSA_{f} Unit cost of system balance in solar power plant *f* (Rials/unit)

TCK_{oiwt} Unit cost of raw material transportation for producing wafer type *o* from raw material supplier *i* to solar wafer production center *w* in period *t* (Rials/unit)

TCL_{owct} Unit cost of wafer type *o* transportation from solar wafer production center *w* to solar cell production center *c* in period *t* (Rials/unit)

TCN_{ocmt} Unit cost of cell type *o* transportation from solar cell production center *c* to solar module production center *m* in period *t* (Rials/unit)

TCP_{omft} Unit cost of module type *o* transportation from solar module production center *m* to solar power plant *f* in period *t* (Rials/unit)

TCQ_{ofst} Unit cost of panel type *o* transportation from solar power plant *f* to worn-out panel separation center *s* in period *t* (Rials/unit)

TCE_{osrt} Unit cost of silicon transportation separated from worn-out panel type *o* from worn-out panel separation center *s* to silicon recycling center *r* in period *t* (Rials/unit)

TCW_{oslt} Unit cost of wastes transportation separated from worn-out panel type *o* from worn-out panel separation center *s* to waste disposal center *l* in period *t* (Rials/unit)

TCK'_{orwt} Unit cost of silicon transportation recycled for reuse in wafer type *o* production from silicon recycling center *r* to solar wafer production center *w* in period *t* (Rials/unit)

TCH_{fdt} Unit cost of electrical energy transmission from solar power plant *f* to regional electricity distribution company *d* in period *t* (Rials/unit)

ICK_{owt}	Unit cost of raw material import for producing wafer type *o* to solar wafer production center *w* in period *t* (Rials/unit)
ICL_{oct}	Unit cost of wafer type *o* import for producing cell type *o* to solar cell production center *c* in period *t* (Rials/unit)
ICN_{omt}	Unit cost of cell type *o* import for producing module type *o* to solar module production center *m* in period *t* (Rials/unit)
ICP_{oft}	Unit cost of panel type *o* import to solar power plant *f* in period *t* (Rials/unit)

Environmental parameters

$EVCK_{owt}$	Unit environmental impact of creating excess capacity for producing wafer type *o* in solar wafer production center *w* in period *t* (Pt/unit)
$EVCL_{oct}$	Unit environmental impact of creating excess capacity for producing cell type *o* in solar cell production center *c* in period *t* (Pt/unit)
$EVCN_{omt}$	Unit environmental impact of creating excess capacity for producing module type *o* in solar module production center *m* in period *t* (Pt/unit)
$EVCP_{oft}$	Unit environmental impact of creating excess capacity for installing solar panel type *o* in solar power plant *f* in period *t* (Pt/unit)
$EVCQ_{ost}$	Unit environmental impact of creating excess capacity for separating worn-out panel type *o* in worn-out panel separation center *s* in period *t* (Pt/unit)
$EVCE_{ort}$	Unit environmental impact of creating excess capacity for recycling silicon separated from worn-out panel type *o* in silicon recycling center *r* in period *t* (Pt/unit)
$EVPK_{owt}$	Unit environmental impact of wafer type *o* production in solar wafer production center *w* in period *t* (Pt/unit)
$EVPL_{oct}$	Unit environmental impact of cell type *o* production in solar cell production center *c* in period *t* (Pt/unit)
$EVPN_{omt}$	Unit environmental impact of module type *o* production in solar module production center *m* in period *t* (Pt/unit)
$EVSQ_{ost}$	Unit environmental impact of worn-out panel type *o* separation in worn-out panel separation center *s* in period *t* (Pt/unit)
$EVRE_{ort}$	Unit environmental impact of recycling silicon separated from worn-out panel type *o* in silicon recycling center *r* in period *t* (Pt/unit)
$EVBO_{oit}$	Unit environmental impact of purchasing raw material for wafer type *o* production from raw material supplier *i* in period *t* (Pt/unit)
$EVMP_{oft}$	Unit environmental impact of panel type *o* maintenance in solar power plant f in period *t* (Pt/unit)
$EVHK_{owt}$	Unit environmental impact of raw material inventory holding for producing wafer type *o* in solar wafer production center *w* in period *t* (Pt/unit)
$EVHL_{oct}$	Unit environmental impact of wafer inventory holding for producing cell type *o* in solar cell production center *c* in period *t* (Pt/unit)

$EVHN_{omt}$ Unit environmental impact of cell inventory holding for producing module type *o* in solar module production center *m* in period *t* (Pt/unit)

$EVHQ_{ost}$ Unit environmental impact of worn-out panel type *o* inventory holding in worn-out panel separation center *s* in period *t* (Pt/unit)

$EVHE_{ort}$ Unit environmental impact recyclable silicon inventory holding separated from worn-out panel type *o* in silicon recycling center *r* in period *t* (Pt/unit)

$EVSA_f$ Unit environmental impact of system balance in solar power plant *f* (Pt/unit)

$EVTK_{oiwt}$ Unit environmental impact of raw material transportation for producing wafer type *o* from raw material supplier *i* to solar wafer production center *w* in period *t* (Pt/unit)

$EVTL_{owct}$ Unit environmental impact of wafer type *o* transportation from solar wafer production center *w* to solar cell production center *c* in period *t* (Pt/unit)

$EVTN_{ocmt}$ Unit environmental impact of cell type *o* transportation from solar cell production center *c* to solar module production center *m* in period *t* (Pt/unit)

$EVTP_{omft}$ Unit environmental impact of module type *o* transportation from solar module production center *m* to solar power plant *f* in period *t* (Pt/unit)

$EVTQ_{ofst}$ Unit environmental impact of panel type *o* transportation from solar power plant *f* to worn-out panel separation center *s* in period *t* (Pt/unit)

$EVTE_{osrt}$ Unit environmental impact of silicon transportation separated from worn-out panel type *o* from worn-out panel separation center *s* to silicon recycling center *r* in period *t* (Pt/unit)

$EVTW_{oslt}$ Unit environmental impact of wastes transportation separated from worn-out panel type *o* from worn-out panel separation center *s* to waste disposal center *l* in period *t* (Pt/unit)

$EVTK'_{orwt}$ Unit environmental impact of silicon transportation recycled for reuse in wafer type *o* production from silicon recycling center *r* to solar wafer production center *w* in period *t* (Pt/unit)

$EVTH_{fdt}$ Unit environmental impact of electrical energy transmission from solar power plant *f* to regional electricity distribution company *d* in period *t* (Pt/unit)

$EVIK_{owt}$ Unit environmental impact of raw material import for producing wafer type *o* to solar wafer production center *w* in period *t* (Pt/unit)

$EVIL_{oct}$ Unit environmental impact of wafer type *o* import for producing cell type *o* to solar cell production center *c* in period *t* (Pt/unit)

$EVIN_{omt}$ Unit environmental impact of cell type *o* import for producing module type *o* to solar module production center *m* in period *t* (Pt/unit)

$EVIP_{oft}$ Unit environmental impact of panel type *o* import to solar power plant *f* in period *t* (Pt/unit)

Technical parameters

De_t Electrical energy demand in period *t* (KWh)

W_o	Weight of a solar panel type *o* (Unit)
EF_o	Efficiency of panel type *o* (Percent)
CS_o	Cross-section of panel type *o* (m^2)
YR_f	Annual radiation at solar power plant *f* (KWh/m^2)
PR_f	Performance rate at solar power plant *f* (Percent)
COK_o	Raw material to the wafer conversion factor for product type *o*
CKL_o	Wafer to cell conversion factor for product type *o*
CLN_o	Cell to module conversion factor for product type *o*
αp_{oft}	Percentage of solar panels type *o* installed at solar power plant *f*, which are worn-out in period *t* (Percent)
ϑE_o	Percentage of silicon recycling from silicon scraps separated from worn-out solar panels type *o* (Percent)
AW_o	Amount of waste in a solar panel type *o* (Unit)
AS_o	Amount of recyclable silicon in a solar panel type *o* (Unit)
MCO_i	Maximum capacity of raw material supplier *i* (Unit)
MCK_w	Maximum production capacity of solar wafer production center *w* (Unit)
MCL_c	Maximum production capacity of solar cell production center *c* (Unit)
MCN_m	Maximum production capacity of solar module production center *m* (Unit)
MCP_f	Maximum solar panels installation capacity at solar power plant *f* (Unit)
MCQ_s	Maximum separation capacity of worn-out panel separation center *s* (Unit)
MCE_r	Maximum silicon recycling capacity of silicon recycling center *r* (Unit)
MCW_l	Maximum waste acceptance capacity at waste disposal center *l* (Unit)
δ_f	Maximum electrical energy generation capacity in solar power plant *f* (Unit)
MPH_{fd}	Maximum electrical energy transmission capacity from solar power plant *f* to regional electricity distribution company *d* (Unit)
λ_{iw}	Equal to 1, if it is possible to transport raw material from raw material supplier *i* to solar wafer production center *w*, otherwise 0

λ_{wc}^{1}	Equal to 1, if it is possible to transport products from solar wafer production center *w* to solar cell production center *c*, otherwise 0
λ_{cm}^{2}	Equal to 1, if it is possible to transport products from solar cell production center *c* to solar module production center *m*, otherwise 0
λ_{mf}^{3}	Equal to 1, if it is possible to transport products from solar module production center *m* to solar power plant *f*, otherwise 0
λ_{fd}^{4}	Equal to 1, if it is possible to transmit electrical energy from solar power plant *f* to regional electricity distribution company *d*, otherwise 0
λ_{fs}^{5}	Equal to 1, if it is possible to transport products from solar power plant *f* to worn-out panel separation center *s*, otherwise 0
λ_{sr}^{6}	Equal to 1, if it is possible to transport products from worn-out panel separation center *s* to silicon recycling center *r*, otherwise 0
λ_{sl}^{7}	Equal to 1, if it is possible to transport products from worn-out panel separation center *s* to waste disposal center *l*, otherwise 0
$\lambda_{rw}^{'}$	Equal to 1, if it is possible to transport products from silicon recycling center *r* to solar wafer production center *w*, otherwise 0

Decision variables

YK_{w}	Equal to 1, if solar wafer production center *w* is established, otherwise 0
YL_{c}	Equal to 1, if solar cell production center *c* is established, otherwise 0
YN_{m}	Equal to 1, if solar module production center *m* is established, otherwise 0
YP_{f}	Equal to 1, if solar power plant *f* is established, otherwise 0
YQ_{s}	Equal to 1, if worn-out panel separation center *s* is established, otherwise 0
YE_{r}	Equal to 1, if silicon recycling center *r* is established, otherwise 0
VK_{owt}	Total capacity of wafer type *o* production in solar wafer production center *w* in period *t*
VL_{oct}	Total capacity of cell type *o* production in solar cell production center *c* in period *t*
VN_{omt}	Total capacity of module type *o* production in solar module production center *m* in period *t*
VP_{oft}	Total capacity of panel type *o* installation in solar power plant *f* in period *t*
VPP_{ft}	Total capacity of electrical energy generation in solar power plant *f* in period *t*
VPH_{fdt}	Electrical energy transmission capacity from solar power plant *f* to regional electricity distribution company *d* in period *t*

VQ_{ost} — Total capacity of worn-out panel type *o* separation in worn-out panel separation center *s* in period *t*

VE_{ort} — Total capacity of recycling silicon separated from worn-out panel type *o* in silicon recycling center *r* in period *t*

VW_{olt} — Total acceptance capacity of waste separated from worn-out panel type *o* at waste disposal center *l* in period *t*

ABO_{oit} — Amount of raw materials purchased for producing wafer type *o* from raw material supplier *i* in period *t*

APK_{owt} — Amount of wafer type *o* produced in solar wafer production center *w* in period *t*

APL_{oct} — Amount of cell type *o* produced in solar cell production center *c* in period *t*

APN_{omt} — Amount of module type *o* produced in solar module production center *m* in period *t*

AIP_{oft} — Amount of panel type *o* installed in solar power plant *f* in period *t*

ASQ_{ost} — Amount of worn-out panel type *o* separated in worn-out panel separation center *s* in period *t*

ARE_{ort} — Amount of recycled silicon separated from worn-out panels type *o* in silicon recycling center *r* in period *t*

EP_{ft} — Amount of electrical energy generated by solar power plant *f* in period *t*

ILK_{owt} — Amount of raw materials inventory for producing wafer type *o* in solar wafer production center *w* in period *t*

ILL_{oct} — Amount of wafer type *o* inventory in solar cell production center *c* in period *t*

ILN_{omt} — Amount of cell type *o* inventory in solar module production center *m* in period *t*

ILQ_{ost} — Amount of worn-out panel type *o* inventory in worn-out panel separation center *s* in period *t*

ILE_{ort} — Amount of recyclable silicon inventory separated from worn-out panel type *o* in silicon recycling center *r* in period *t*

TOK_{oiwt} — Amount of raw materials transportation for producing wafer type *o* from raw material supplier *i* to solar wafer production center *w* in period *t*

TKL_{owct} — Amount of wafer type *o* transportation from solar wafer production center *w* to solar cell production center *c* in period *t*

TLN_{ocmt} — Amount of cell type *o* transportation from solar cell production center *c* to solar module production center *m* in period *t*

TNP_{omft} — Amount of module type *o* transportation from solar module production center *m* to solar power plant *f* in period *t*

TPQ_{ofst} — Amount of worn-out panel type *o* transportation from solar power plant *f* to worn-out panel separation center *s* in period *t*

TQE_{osrt}	Amount of recyclable silicon transportation separated from worn-out panel type *o* from worn-out panel separation center *s* to silicon recycling center *r* in period *t*
TQW_{oslt}	Amount of waste transportation separated from worn-out panel type *o* from worn-out panel separation center *s* to waste disposal center *l* in period t
TEK'_{orwt}	Amount of silicon transportation recycled for reuse in wafer type *o* production from silicon recycling center *r* to solar wafer production center *w* in period *t*
TPH_{fdt}	Amount of electrical energy transmitted from solar power plant *f* to regional electricity distribution company *d* in period *t*
QIK_{owt}	Amount of raw materials imported for producing wafer type *o* to solar wafer production center *w* in period *t*
QIL_{oct}	Amount of wafer type *o* imported for producing cell type *o* to solar cell production center *c* in period *t*
QIN_{omt}	Amount of cell type *o* imported for producing module type *o* to solar module production center *m* in period *t*
QIP_{oft}	Amount of panel type *o* imported to solar power plant *f* in period *t*
EVK_{owt}	Amount of excess capacity created for producing wafer type *o* in solar wafer production center *w* in period *t*
EVL_{oct}	Amount of excess capacity created for producing cell type *o* in solar cell production center *c* in period *t*
EVN_{omt}	Amount of excess capacity created for producing module type *o* in solar module production center *m* in period *t*
EVP_{oft}	Amount of excess capacity created for installing panel type *o* in solar power plant *f* in period *t*
EVQ_{ost}	Amount of excess capacity created for separating worn-out panel type *o* in worn-out panel separation center *s* in period *t*
EVE_{ort}	Amount of excess capacity created for recycling silicon separated from worn-out panel type *o* in silicon recycling center *r* in period *t*