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Optimal scenarios for solar cell supply chain considering degradation in powerhouses

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ABSTRACT

In recent years, the sun has been used as one of the main sources of renewable energy and supplying energy through solar cells has been quickly increased. This paper develops a two-echelon multi-period multi-product solar cell supply chain (SCSC) with three scenarios including (1) The presence of domestic supplier in a monopoly market, (2) The arrival of a foreign rival to the competitive market, and (3) The government intervention in a competitive market. Three scenarios under non-cooperative Nash game are modeled and formulated for two types of solar cells, dye-sensitized and perovskite. The obtained solutions of three scenarios from the game models are put in a mathematical model for a solar cell powerhouse. In this multi-period multi-product mathematical model, the degradation of the solar cells is considered. In the meantime, solar cell powerhouse as one of the end-users of solar energy deals with the degradation by substitution solar panels. The proposed model determines how many solar panels/modules from two kinds of it should be installed and substituted in each period and which scenario to be selected. Finally, it is represented a numerical example, sensitive analysis, and management insights for the proposed model.

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1. Introduction

Owing to the environmental problems driven by fossil fuels, it is better to use renewable energies [1]. Solar energy as one of the clean energies is able to convert solar energy into electrical energy directly [2]. Solar cells are known based on the different characteristics and kinds of material employed within them. The use of different materials within cells influences the improvement of efficiency [3]. Efficiency plays an important role in improving the electricity output of the solar cells [4] and each of the solar cells has a different efficiency. In addition to efficiency, considering the new technologies in manufacturing cells is also significant. Also, one of the important points of producing solar cells is the availability of materials and the use of safe material without environmental impacts in manufacturing cells [5]. Regarding a 20-year lifetime for solar cells, the efficiency of solar systems should maintain during these years through used methods in manufacturing cells, initial materials, and the installation of solar systems in a good environmental situation [6]. On the other hands, the photovoltaic (PV) technologies have positive impacts on efficiency, stability, the decline in the costs of balanced solar systems, and the reduction in modules costs [7]. In other words, the effect of production technology, used material, reliability, and device design enhance efficiency [8].

In solar cells market, there are different types of cells, for example, organic photovoltaic cells, dye-sensitized solar cells, thin film cells, silicon cells, perovskites, etc. Solar cells are introduced based on the kinds of the generation that the third generation of solar cells is dye-sensitized solar cells, and perovskite solar cells are also considered as the fourth generation. By developing technology, the researchers try to produce solar cells with low manufacturing cost, high efficiency, low initial cost, etc. Domestic and foreign suppliers produce these cells and compete with together on the different kinds of cells, their efficiency, and technologies R&D in manufacturing cells [9].

Initial material suppliers, solar module suppliers, and solar system assemblers are members of an SCSC. Solar module suppliers manufacture cells and then produce solar modules/panels. Solar modules suppliers sell modules/panels to the assemblers. Solar modules are assembled to devices by the assemblers and are sold to the customers [10].

The lifetime of the solar cells is long, but degradation dependent

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on temperature, dust, humidity, and solar radiation influences the lifetime of the cells and decreases the efficiency of cells. When the efficiency of cells is not suitable for consumers (powerhouses), they can substitute solar panels and install new panels [11]. By considering the point that the efficiency and performance of the solar cells decrease in periods, it is a good idea to substitute solar panels in every couple of periods. The customers of solar cells are the powerhouses, residential areas, and industrial units [12].

In the real world, the members of the SCSC compete with together. Competition between domestic and foreign suppliers to increase efficiency and stay at the competitive market helps to improve trend in the SCSC [13]. The domestic and foreign suppliers compete in efficiency which they can raise the customer's demand and obtain more profit.

To speed developing and growing in the SCSC, the government helps players to cooperate with together [14,15]. The government's tariffs (tax or subsidy) not only increase the government's profit, but members' profit also goes up [16,17]. Indeed, the government's policies cause to develop solar energy technologies, decrease the use of fossil fuels, and increase using domestic solar cell producers [18]. The high installation of solar systems depends on the government's policy [19]. The government's subsidy leads to a reduction in solar systems price for end-user [10]. Furthermore, the government's tariffs induce to develop energy-saving technologies and sustainable objectives [20]. On the other hand, the government's tax and subsidy decrease costs of environmental pollution [21,22]. Additionally, the government has an important effect on competition between members [23]. Moreover, the government considers the demand-side policies and the supply-side policies for the SCSC to have a healthier solar cell industry [24]. Also, the supply-side policies should move to the demand-side policies [25]. The domestic suppliers are supported by the government's subsidy due to the government willing to support domestic solar cells [26]. The government even intends to export domestic solar cells and their electricity to the other countries, whereas the foreign suppliers pay government tax to export their solar cells. The government as the main leader plays an important role in the SCSC because it can reduce high manufacturing and assembling costs, by its policies. Also, the subsidy can be considered for diminishing the retailing price of domestic solar systems. This way, the customers are encouraged to buy domestic products. Additionally, the government's tax causes to augment the retailing price of foreign system that persuades the final customers to use domestic products. The foreign suppliers want to remain in the competitive market. For this reason, they intend to decrease the final price and overcome competitors. On the other hand, the tax prevents foreign suppliers from exporting more foreign solar systems. The government's supportive policies assist members in extending technologies for improving the efficiency and developing the SCSC [9,27,28].

The differences between our research and mentioned papers are demonstrated as follows:

- Two kinds of solar cells are considered (dye-sensitized and perovskite solar cell)
- The government is considered as the leader and the other members as the followers.
- The efficiency has an important role in generating more electricity.
- The impact of degradation is seen in the life time of the solar cells and their efficiency. If the efficiency falls, the powerhouse can substitute solar panels.
- The substitution of solar panels/modules is considered in a multi-period time horizon. Regarding kinds of the solar cells (domestic and foreign), the powerhouses can replace panels in each period.
- The final consumers of solar cells are the powerhouses.
- The domestic and foreign suppliers compete with together where this competition enhances efficiency as a factor of quality.
- The competition between the suppliers is formulated and modeled by non-cooperative Nash game, and after that, a mixed-integer linear programming for supplying energy.
- The important effect of the government on competition between the suppliers is investigated.

In fact, the main goal of this paper is considering both downstream and upstream members. It is investigated the upstream members including the foreign and domestic suppliers and the assembler in the presence of the government in this theme. In addition to upstream members, the downstream members such as powerhouses also are noticed. In other words, the mathematical model for solar cell powerhouse selects which scenario (market) is the optimal scenario to satisfy powerhouse demand with respect to the efficiency and price of solar systems in the non-cooperative Nash game. Furthermore, the proposed model determines how many domestic and foreign solar panels should be installed in each period and each scenario. It specifies which kinds of solar panels (dye-sensitized and perovskite) should be selected and which period chosen. It indicates how much energy is generated in each period and each scenario. Also, it expresses how many solar panels should be collected in each period and each scenario.

The rest of the paper is investigated as follows: The literature review is examined in section 2. The scenarios of the SCSC are explained in section 3. The mathematical model for the solar cell powerhouse is expressed in section 4. The case study and sensitivity analysis are mentioned in section 5. The managerial insights are indicated in section 6. The conclusion of the paper is displayed in section 7.

2. Literature review

Goetzberger and Hoffmann [27] have presented the existence of government for improvement and development of the solar PV industry. The government supports chain members with giving tariffs. Moreover, they have investigated the cases such as costs of manufacturing modules, cost of technology and materials, generating electricity through solar PV in houses, powerhouses, and industrial plants, improving the efficiency of solar PV, installation, and recycling of solar PV, etc. Sheu [17] has studied the issue that the government intervention influences bargaining power among chain members, profit of members, and social welfare. Solangi et al. [18] have investigated the solar energy policies in different countries. Indeed, enough incentive for the growth and applying technologies R&D for renewable energies is provided by the policies such as feed-in-tariff (FIT), tax, subsidy,and grant. The FIT has included both subsidy and tax.

Parida et al. [8] have considered new technologies, environmental aspects, using materials with a high absorption coefficient of light, performance, reliability, applications, and the efficiency of solar PV. The technologies applied for manufacturing cells caused to develop the efficiency. Sheu and Chen [23] have used a game theory for competition of green supply chains that the financial intervention of government influences competition of these chains. Sawhney et al. [19] have asserted motivations (government's policies) such as grants are more effectual than the tax and policies cause to sustain Tennessee solar value chain (TNSVC) and increase demand and revenue. Iqbal et al. [2] have studied renewable energies are good for decreasing costs and enhancing generation. Also, they have considered some optimization methods for employing the different types of renewable energies.

Chauhan and Saini [14] have investigated to obtain the part of the growth and improvement of the renewable energy systems needing the government's subsidy. Qiang et al. [25] have suggested that China's policy of the PV industry should change from supply-side policy to demand-side market. Furthermore, it should be considered to meet enough investment for R&D. The demand-side policy includes FIT, subsidies, taxes, green tags, etc., for distributing solar energy to the customer. On the other hand, the supply-side policy contains policies related to the solar PV supply chain specially manufactures. Chen and I. Su [10] have proposed that the government's subsidy induces the overcapacity of solar PV. On the other hand, the government's policies lead to the development and improvement of PV supply chain and price reduction. Xie [29] has investigated the role of policymakers' impact on energy saving level and the prices.

Zhao et al. [26] have demonstrated the problems of the solar PV industry such as overcapacity, inconformity demand and supply, nonuse the new technologies, the presence of the foreign PV market, etc. The government uses the policies for supporting and developing PV industry (such as R&D). They have investigated the cases such as the government's subsidy for decreasing costs, subsidy program for installing PV systems, the law of FIT, and transition from foreign PV market to domestic in their study. Hafezalkotob [16] has investigated the financial intervention of government that affects the competition in price among green and regular chains and the government and members' profit. Due to the point that the installation cost of the solar PV is high, Jia et al. [30] have suggested the government's policies for advancing the solar PV industry. On the other hand, they have considered the global PV industry for five countries and compared them through PV production, environmental aspect, and competition. Tiep et al. [31] have studied perovskite solar cells have features such as high-power conversion efficiencies, easy fabrication, and low cost that is paid attention because of these characteristics, recently.

Chen and I. Su [32] have studied coordination and competition among the members of a photovoltaic supply chain. P. Kumavat et al. [4] have explored the efficiency of solar cells and found it depends on the materials used within cells. Zou et al. [28] have analyzed some cases such as overcapacity, generated power, shortage of R&D, shortage of technological innovation, and quality of domestic and foreign solar PV. The supportive role of the government is considered in this study. Hafezalkotob [20] has evaluated green supply chains (GSCs) as they can attain sustainable objectives by the government's tariff. The government intervention influences GSCs' profits, energy-saving efforts, and prices of the products. Without the government's support, GSCs haven't enough motivation for cooperating, competing, and coordinating. Hafezalkotob [13] has considered the government's policies which affect the competition and cooperation between two manufacturers. The government uses tariffs for developing sustainability. Also, the outsourcing problem can be solved by the government intervention.

Basiri and Heydari [11] have studied green products as they can substitute for the non-green products. Yang and Xiao [15] have explored the effect of channel leadership and the government on the prices, the green levels, and the members' profit. The government intervention leads to the green products development. The profit of members will increase under government's policies. Sampaio and Gonzalez [9] have considered using new technologies of R&D for manufacturing PV modules/panels. Then, they have evaluated the production cost of solar PV and modules, advantages and disadvantages of solar PV. Mora et al. [6] have examined the efficiency of solar cells which affects the improvement of PV system.

Madani and Rasti-Barzoki [21] have evaluated that the government determines pricing policies, the greening levels, and the tariffs. The member's cooperation causes an increase in profit of players and increasing eco-friendly products (EFP). The tariffs improve member's profit, sustainability, and the government's profit. Praveen and VijayaRamaraju [3] have studied the efficiency improvement of solar cells leads to increase electricity output. Furthermore, they have investigated using various materials influences solar cell efficiency. Xu et al. [1] have focused on the efficiency of photovoltaic cells that is enhanced by the efficient material. Applying metals (new materials) with high absorption coefficient helps to receive more solar energy and its convert to electrical energy.

Zhang and Wang [22] have indicated the effect of the government's policy and the protection of environmental on revenue and members' profit. The government considers tariffs due to the member's usage of eco-friendly materials within panels, so the profit of members diminishes. Green et al. [33] have designated tables which determine the efficiency of cells and modules. Chatzisideris et al. [12] have reviewed the households provide and consume their electricity by installing a solar PV system. The households' electricity consumption should coincide with solar radiation and electricity generation. In order to the electricity bill saving, the households can use solar PV system.

Richhariya et al. [5] have shown the importance of dye-sensitized solar cell (DSSC) that leads to the low cost, eco-friendly, favorite efficiency, and the high stability. The materials used within DSSS are influential in the enhancement of the efficiency. Chen et al. [34] have suggested a closed loop supply chain design (CLSC) for the solar energy industry by considering sustainability aspects. Chen and I. Su [24] have studied the government's subsidy which causes overcapacity of (photovoltaic) PV system and the C-pi modules oversupply in the PV global supply chain. The global PV industry resulted in competition and conflict among countries for exporting and importing the PV system.

Dehghani et al. [35] have perused the network design of PV supply chain-based business-as-usual and hazard uncertainty and then they have specified the facilities locations. The number and capacity of the manufacturing centers and solar plants investigated in this model. Dehghani et al. [36] have explored the design of solar PV supply chain in uncertain environment situations. The data envelopment analysis (DEA) is used to determine the location of solar plants. Kabir et al. [7] have examined that the efficiency, stability, and availability of solar cells are enhanced by new technologies. The new technologies cause to decrease balanced system costs and manufacturing cost of modules. Chen and Su [37] stated that the profit of the PV supply chain is increased by social welfare maximization and the least subsidy. Kharaji Manoucheheabadi and Yaghoubi [38] recently showed that the chain's profit is increased by the government's subsidies under competition situation.

For the first time, this research considers the cases such as efficiency, multi-period time horizon, multi-product system, and the degradation of solar panels in an SCSC that induce differences between this work and previous studies to be more realistic. Chen and I. Su [10,24,32,37] have presented coordination and competition of members in a photovoltaic supply chain in the presence of government. But this paper considers some cases such as two kinds of solar cells, domestic and foreign solar cells, the competition among domestic and foreign suppliers, multi periods of time, and the government's subsidy and tax as a parameter for decreasing costs. Also, it is presented subsidy and tax encourage powerhouses to buy domestic solar panels/modules. It is important to substitute solar degraded panels/modules (decreasing efficiency) in powerhouses in each of periods. A comparison of previous papers with present study is demonstrated in Table 1.

This article has considers the efficiency and the impact of government's tariffs on improving efficiency. It is examined

Table 1
Comparison of previous papers with the present study.

Author	Solar cell supply chain	Efficiency	Competition	Government intervention		Multi-period	Multi-product	Coordination contract	Decomposition or degradation	Nash	Stackelberg	Decision variables								
				Subsidy	Tax							Price	Quality	Tax	Subsidy	Order quantity	Greening degree	Energy saving level	Wholesale price	Impact Level of product on the environment
Sheu [17]			*	*	*					*		*		*	*	*				
Sheu & Chen [23]			*	*	*					*				*	*	*			*	
Chen & I. Su [10]	*			*				*				*				*			*	
Hafezalkotob [16]			*	*	*						*	*		*	*	*			*	
Xie [29]								*		*		*						*		
Chen & I. Su [32]	*		*	*				*		*		*				*			*	
Hafezalkotob [20]			*	*	*						*	*		*	*			*	*	
Zhang &Wang [22]	*		*	*	*		*				*	*		*	*				*	*
Hafezalkotob [13]			*	*	*					*				*	*	*			*	
Yang & Xiao [33]				*							*	*					*		*	
Madani & Rasti-Barzoki [21]			*	*	*						*	*					*			
Chen & I. Su [24]	*		*							*	*					*			*	
Chen & I. Su [37]	*			*						*	*	*			*	*			*	
Kharaji Manouchehrabadi & Yaghoubi [38]	*	*	*	*				*		*		*	*		*					
This research	*	*	*	*	*	*	*		*	*		*	*							

technologies R&D applied for manufacturing cells and efficiency improvement. In this paper, the role of the government is seen in the supply-side; for example foreign and domestic suppliers and assembler. Furthermore, the price and efficiency of solar systems are affected by the government's tax and subsidy. This theme is developed competition between foreign and domestic suppliers and the influence of the government on competition and reduction in assembling and manufacturing costs. Mentioned papers have not investigated the quality of domestic and foreign solar cells, but this paper expresses the efficiency as the main factor in electricity output, the performance of solar cells, and lower degradation. It is analyzed that the government as the leader in SCSC has a positive role in price, efficiency, and members' profit. Moreover, the government determines subsidies for manufacturing and assembling costs and also specifies tax for manufacturing cost of foreign cells and exporting foreign products as a leader in SCSC. It is presented the direct effect of subsidy and tax on SCSC whereas the above papers are more considered competition between PV solar chains and only reviewed the papers related to government intervention. Reviewing the above-mentioned articles makes it clear that no mathematical approach has already been developed to study multi-product multi-period SCSC considering the degradation of solar cells. Also, they have not considered the substitution and installation of solar panels and the existence of the powerhouse as the final customer. This article is encouraged powerhouse by the government's subsidy to buy domestic solar systems.

Five contributions are applied to this study. First, it proposes the presence of government in SCSC improvement and competition between members. Second, this paper considers two kinds of solar cells which domestic and foreign suppliers manufacture them in a competitive market. Third, this research investigates the lifetime of solar cells and their efficiency, depending on degradation. Forth, it analyzes the powerhouses that can substitute the solar panels in some periods because of decreasing efficiency. So, the amount of produced energy increases by solar panels/modules. Finally, it presents a competition between domestic and foreign suppliers.

3. Scenarios of the SCSC

In this section, it is investigated three scenarios under non-cooperative Nash game. In scenario 1, the SCSC consists of a domestic supplier and an assembler. The presence of the foreign supplier in the SCSC market leads to a competition between the domestic and foreign suppliers (scenario 2). Considering the government helps to improve competition between suppliers, chain performance, and reduction in manufacturing and assembling cost (scenario 3). Three scenarios under non-cooperative Nash are modeled and solved. Then, the decision variables of each scenario are put in a mixed-integer linear programming for solar cell powerhouse. The model determines which scenario should be chosen and how many domestic and foreign solar panels should be installed in each period and each scenario. It specifies which kind of solar panels (dye-sensitized and perovskite) should be selected and which period chosen. It indicates how much energy is generated in each period and each scenario. Also, it expresses how many solar panels should be collected in each period and each scenario. In fact, it should be explained that it is obtained the optimal decision variables (i.e. efficiency and price) from three scenarios (three markets), separately. These markets are distinct from each other. So, members are added to each market since it can be seen the entrance of the new member's effect can cause the SCSC improvement. Finally, the obtained solutions (price and efficiency) from each scenario are put in the model for the powerhouse and the model decides which scenario is the best with respect to the price and efficiency. Hence, the model based on scenarios determined the number of solar panels installed and substituted. The relation between the game model and the mixed-integer linear programming one for solar panels powerhouse is shown in Fig. 1.

In this paper, three scenarios are taken into account as follow: (1) The presence of domestic supplier in a monopoly market, (2) Arrival of the foreign rival to the competitive market, and (3) The government intervention in a competitive market. At first, these scenarios are investigated separately, and then the mathematical model for solar powerhouse has chosen the optimal scenario. Parameters and decision variables are exposed in Table 2.

3.1. The presence of domestic supplier in a monopoly market

In this section, a domestic supplier and an assembler are members of an SCSC in a monopoly market. The domestic supplier produces two types of solar cells and determines the efficiency of them. The domestic supplier sells solar panels to the assembler and then the assembler determines the price and sells assembled panels to the powerhouses with respect to the efficiency. The assembler decides on the price of solar systems. By passing the time, if each cell does not have the favorite efficiency, the powerhouse can replace panels/modules and install new panels/modules in each of periods. Two substitutable products one dye-sensitive type and the other perovskite type are produced by the supplier. The functions of these two products are the same, and so, they are substitutable. The demand functions are obtained by the related literature (e.g. Basiri and Heydari, 2017). The demand of the first type $(D_{d,1})$ and the second type $(D_{d,2})$ for solar systems and the total demand (D_d) are shown as follows:

$$D_{d,1} = a\alpha - bp_{d,1} + \gamma x_{d,1} + \theta\left(p_{d,2} - p_{d,1}\right) - \theta_s\left(x_{d,2} - x_{d,1}\right) \quad (1)$$

$$D_{d,2} = a(1-\alpha) - bp_{d,2} + \gamma x_{d,2} + \theta\left(p_{d,1} - p_{d,2}\right) - \theta_s\left(x_{d,1} - x_{d,2}\right) \quad (2)$$

$$D_d = D_{d,1} + D_{d,2} = a - b\left(p_{d,1} + p_{d,2}\right) + \gamma\left(x_{d,1} + x_{d,2}\right) \quad (3)$$

The index “d,1” denotes the domestic dye-sensitive solar cell, and index “d,2” refers to the domestic perovskite solar cell. It is rewrote demand for the dye-sensitive product: $D_{d,1} = a\alpha - (b+\theta)p_{d,1} + (\gamma + \theta_s)x_{d,1} + \theta p_{d,2} - \theta_s x_{d,2}$.

Coefficients of $p_{d,1}$ and $x_{d,1}$ in demand function $D_{d,1}$ is bigger than coefficients of $p_{d,2}$ and $x_{d,2}$ which expresses that demand for dye-sensitive product is more sensitive to its own specifications (price and efficiency) rather than the perovskite product specifications. Where a is the primary market potential for each product type, p is the retail price which influences demand coefficient b; γ is the efficiency coefficient, which exhibits the willingness of customers to buy a product (first type) with higher efficiency (x), α is the degree of customers' loyalty to domestic products, and β is the degree of customers' loyalty to foreign products. Parameters θ and θ_s are defined as the sensitivity of switchovers toward price difference and efficiency difference between two products, respectively.

To maximize the profit (i.e. the difference between revenue and cost is multiplied by the demand function) and obtain the optimal decision variables, it is derived from functions with respect to decision variables. The supplier's profit is obtained from Eq. (4) in which demand functions $D_{d,1}$ and $D_{d,2}$ are multiplied by the marginal profit of the supplier (i.e. $(w_{d,1} - cs_{d,1})$ and $(w_{d,2} - cs_{d,2})$, respectively). Then, it is subtracted this amount from technology R&D cost for efficiency. The marginal profit, in this case, is the difference between wholesale price and the manufacturing cost of

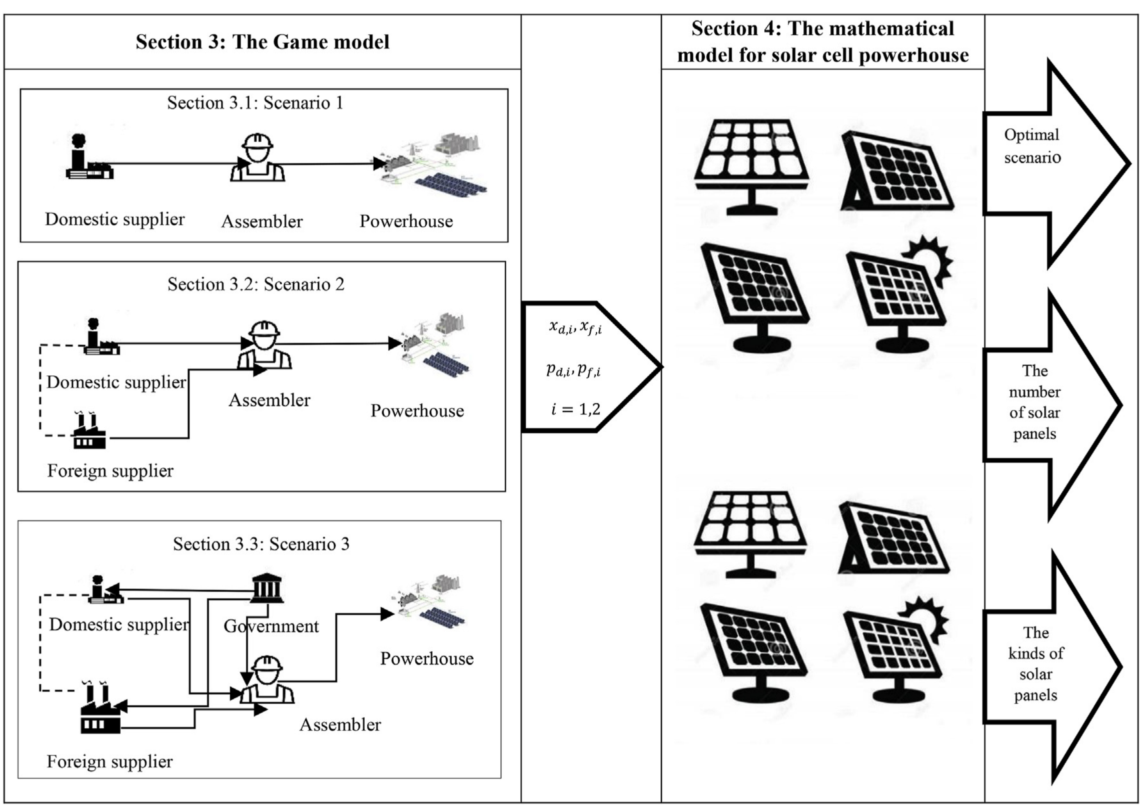

Fig. 1. Framework of solar cell supply chain under the game model and the mathematical model for solar cell powerhouse.

Table 2
Notations for three scenarios under non-cooperative Nash game.

Parameters:	
a	Initial market potential for domestic and foreign solar systems
b	Price elasticity coefficient of demand
γ	Efficiency resilient coefficient of demand
θ	Difference coefficient of domestic/foreign solar system price
θ_s	Difference coefficient of domestic/foreign solar cell efficiency
$cs_{d,i}$	Domestic supplier's manufacturing cost per unit of solar module/panel of $(i=1)$ and $(i=2)$
$cs_{f,i}$	Foreign supplier's manufacturing cost per unit of solar module/panel of $(i=1)$ and $(i=2)$
$c_{d,i}$	Maximum domestic supplier's R&D cost for efficiency of $(i=1)$ and $(i=2)$ for domestic solar cell
$c_{f,i}$	Maximum foreign supplier's R&D cost for efficiency of $(i=1)$ and $(i=2)$ for foreign solar cell
$w_{d,i}$	Unit wholesale price of $(i=1)$ and $(i=2)$ for domestic solar module
$w_{f,i}$	Unit wholesale price of $(i=1)$ and $(i=2)$ for foreign solar module
c_0	Assembler's assembling cost per unit of solar system
$t_{d,i}$	Government's subsidy rate for domestic supplier's manufacturing cost ($(i=1)$ and $(i=2)$ for domestic solar systems)
$t_{f,i}$	Government's tax rate for foreign supplier's manufacturing cost ($(i=1)$ and $(i=2)$ for foreign solar systems)
t_a	Government's subsidy rate for assembler's assembling cost
α	Degree of customer's loyalty to domestic solar system
β	Degree of customer's loyalty to foreign solar system
Decision variables	
$x_{d,i}$	Efficiency of $(i=1)$ and $(i=2)$ for domestic solar cell
$x_{f,i}$	Efficiency of $(i=1)$ and $(i=2)$ for foreign solar cell
$p_{d,i}$	Retailing price per unit of $(i=1)$ and $(i=2)$ for domestic solar system
$p_{f,i}$	Retailing price per unit of $(i=1)$ and $(i=2)$ for foreign solar system

the supplier. The assembler's profit is gained from Eq. (5) in which demand functions $D_{d,1}$ and $D_{d,2}$ are multiplied by the marginal profit of the assembler (i.e. $(p_{d,1}-w_{d,1})$ and $(p_{d,2}-w_{d,2})$, respectively). After that, this amount is subtracted by assembling cost for two products and then, the assembling cost is multiplied by the total demand. The marginal profit is the difference between retailing price and wholesale price of the assembler. The demand functions from Eqs. (1)–(3) are substituted in Eqs. (4) and (5). The profit function of the domestic supplier (π_{DS}) and assembler (π_A) are mentioned as follows:

$$\pi_{DS}=(w_{d,1}-cs_{d,1})D_{d,1}-c_{d,1}x_{d,1}^2+(w_{d,2}-cs_{d,2})D_{d,2}-c_{d,2}x_{d,2}^2 \tag{4}$$

$$\pi_A=\left(p_{d,1}-w_{d,1}\right)D_{d,1}+\left(p_{d,2}-w_{d,2}\right)D_{d,2}-c_0D_d \tag{5}$$

The proof of the concavity of functions (4) and (5) are shown in Appendix A

In the non-cooperative Nash game model (decentralized condition), the profit of each member is obtained, separately. Deriving from π_{DS} with respect to $x_{d,1}$ and $x_{d,2}$, and first-order condition (FOC) of π_{DS} with respect to $x_{d,1}$ and $x_{d,2}$ gives the optimal efficiency. Also, FOC of π_A based on $p_{d,1}$ and $p_{d,2}$ is given $p^*_{d,1}$ and $p^*_{d,2}$. In regard to non-cooperative Nash game model, the optimal efficiency of two kinds of domestic cells $\left(x^*_{d,1},\ x^*_{d,2}\right)$ are indicated as follows:

$$x^*_{d,1}=\frac{\gamma w_{d,1}-(\gamma+\theta_s)cs_{d,1}+\theta_s\left(w_{d,1}-w_{d,2}+cs_{d,2}\right)}{2c_{d,1}} \tag{6}$$

$$x^*_{d,2}=\frac{\gamma\left(w_{d,2}-cs_{d,2}\right)+\theta_s\left(w_{d,2}-w_{d,1}+cs_{d,1}-cs_{d,2}\right)}{2c_{d,2}} \tag{7}$$

$$p_{d,1}=\frac{\alpha a+bc_0+2\theta p_{d,2}+(b+\theta)w_{d,1}-\theta w_{d,2}+(\gamma+\theta_s)x_{d,1}-\theta_s x_{d,2}}{2(b+\theta)} \tag{8}$$

$$p_{d,2}=\frac{a-a\alpha+bc_0+2\theta p_{d,1}-\theta w_{d,1}+(b+\theta)w_{d,2}-\theta_s x_{d,1}+(\gamma+\theta_s)x_{d,2}}{2(b+\theta)} \tag{9}$$

Owing to depending both decision variables on $p_{d,1}$ and $p_{d,2}$, the amount obtained from $p_{d,2}$ in Eq. (9) substitutes at Eq. (8). So, the value of $p_{d,1}$ in Eq. (10) is gained;

$$p_{d,1}=\frac{a(b\alpha+\theta)+b\left(c_0+w_{d,1}\right)(b+2\theta)+(\gamma(b+\theta)+b\theta_s)x_{d,1}+(\gamma\theta-b\theta_s)x_{d,2}}{2b(b+2\theta)} \tag{10}$$

Then the amount attained in Eq. (10) puts in Eq. (9) and $p_{d,2}$ as below form is represented:

$$p_{d,2}=\frac{a(b-b\alpha+\theta)+b\left(c_0+w_{d,2}\right)(b+2\theta)+(\gamma\theta-b\theta_s)x_{d,1}+(\gamma(b+\theta)+b\theta_s)x_{d,2}}{2b(b+2\theta)} \tag{11}$$

The optimal value of $p^*_{d,1}$ and $p^*_{d,2}$ are obtained in Appendix B.

3.2. The arrival of the foreign rival to the competitive market

Now, it will be considered that the market works under competitive conditions. Hence, a foreign supplier can enter the marker. In this scenario, the members of SCSC include a domestic supplier, an assembler and a foreign supplier in the competitive market. The competition among suppliers is due to the efficiency improvement. The suppliers in the solar cells market have to compete for increasing profit and demand. The powerhouses face the two sorts of solar systems. One of them is domestic solar systems and other systems import (foreign). Therefore, for satisfying customers, suppliers should produce substitutable cells with high efficiency and use new technologies for manufacturing cells. These products (two kinds of domestic systems and two types of foreign systems) are substitutable which for example $D_{d,1}$ shows the sensitivity of customer toward dye-sensitive domestic solar cell and customers intend to buy the dye-sensitive domestic solar cell. On the other hand, there is a direct relationship between the demand for a product and its efficiency. However, a reverse relationship between the demand for a product and its price is seen in the demand functions. The domestic supplier decides the efficiency of domestic solar cells. The decision variables of assembler is the price of domestic systems. Also, the assembler makes a decision on the price of foreign systems. The foreign supplier determines the efficiency of foreign solar cells. The demand function of domestic ($D_{d,1}$, $D_{d,2}$) and the foreign $\left(D_{f,1}, D_{f,2}\right)$ solar systems and the total demand (D) are shown as follows:

$$D_{d,1} = a\alpha\beta - bp_{d,1} + \gamma x_{d,1} + \theta\left(p_{f,1} + p_{f,2} + p_{d,2} - p_{d,1}\right) - \theta_s\left(x_{f,1} + x_{f,2} + x_{d,2} - x_{d,1}\right) \quad (12)$$

$$D_{d,2} = a(1-\alpha)\beta - bp_{d,2} + \gamma x_{d,2} + \theta\left(p_{f,1} + p_{f,2} + p_{d,1} - p_{d,2}\right) - \theta_s\left(x_{f,1} + x_{f,2} + x_{d,1} - x_{d,2}\right) \quad (13)$$

$$D_{f,1} = a\alpha(1-\beta) - bp_{f,1} + \gamma x_{f,1} + \theta\left(p_{d,1} + p_{d,2} + p_{f,2} - p_{f,1}\right) - \theta_s\left(x_{d,1} + x_{d,2} + x_{f,2} - x_{f,1}\right) \quad (14)$$

$$D_{f,2} = a(1-\alpha)(1-\beta) - bp_{f,2} + \gamma x_{f,2} + \theta\left(p_{d,1} + p_{d,2} + p_{f,1} - p_{f,2}\right) - \theta_s\left(x_{d,1} + x_{d,2} + x_{f,1} - x_{f,2}\right) \quad (15)$$

$$D = D_{d,1} + D_{d,2} + D_{f,1} + D_{f,2} = \Big(a - b\left(p_{d,1} + p_{d,2} + p_{f,1} + p_{f,2}\right) + \gamma\left(x_{d,1} + x_{d,2} + x_{f,1} + x_{f,2}\right) + 2\theta\left(p_{d,1} + p_{d,2} + p_{f,1} + p_{f,2}\right) - 2\theta_s\left(x_{d,1} + x_{d,2} + x_{f,1} + x_{f,2}\right)\Big) \quad (16)$$

In Eq. (17) and (18), the difference between wholesale price and cost is multiplied demand functions and then is subtracted technology R&D cost from that. In Eq. (19) is represented the difference between retailing price and wholesale price and is subtracted assembling cost from that and then, the assembling cost is multiplied by the total demand. After that, the demand functions Eq. (12)–(16) are put in Eq. (17)–(19). In the competitive market, the profits of both domestic and foreign supplier and also assembler in Eq. (17)–(19) are demonstrated.

$$\pi_{DS} = (w_{d,1} - cs_{d,1})D_{d,1} - c_{d,1}x_{d,1}^2 + (w_{d,2} - cs_{d,2})D_{d,2} - c_{d,2}x_{d,2}^2 \quad (17)$$

$$\pi_{FS} = \left(w_{f,1} - cs_{f,1}\right)D_{f,1} - c_{f,1}x_{f,1}^2 + \left(w_{f,2} - cs_{f,2}\right)D_{f,2} - c_{f,2}x_{f,2}^2 \quad (18)$$

$$\pi_A = \left(p_{d,1} - w_{d,1}\right)D_{d,1} + \left(p_{d,2} - w_{d,2}\right)D_{d,2} + \left(p_{f,1} - w_{f,1}\right)D_{f,1} + \left(p_{f,2} - w_{f,2}\right)D_{f,2} - c_0 D \quad (19)$$

Proving concavity of functions (17–19) are exhibited in Appendix C.

To obtain the optimal efficiency and price, it has derived from π_{DS} with respect to $x_{d,1}, x_{d,2}$, and π_{FS} regard to $x_{f,1}, x_{f,2}$, and π_A based on $p_{d,i}$ and $p_{f,i}$, $i = 1, 2$ that FOC of functions with respect to their decision variables gives the optimal value of efficiency and price. According to the non-cooperative Nash game, the optimal efficiency and price of domestic $\left(x^*_{d,1}, x^*_{d,2}, p^*_{d,1}, p^*_{d,2}\right)$ and foreign $\left(x^*_{f,1}, x^*_{f,2}, p^*_{f,1}, p^*_{f,2}\right)$ solar systems are displayed as follows:

$$x^*_{d,1} = \frac{\gamma w_{d,1} - (\gamma + \theta_s)cs_{d,1} + \theta_s(w_{d,1} - w_{d,2} + cs_{d,2})}{2c_{d,1}} \quad (20)$$

$$x^*_{d,2} = \frac{\gamma(w_{d,2} - cs_{d,2}) + \theta_s(w_{d,2} - cs_{d,2} + cs_{d,1} - w_{d,1})}{2c_{d,2}} \quad (21)$$

$$x^*_{f,1} = \frac{\gamma w_{f,1} - (\gamma + \theta_s)cs_{f,1} + \theta_s\left(w_{f,1} - w_{f,2} + cs_{f,2}\right)}{2c_{f,1}} \quad (22)$$

$$x^*_{f,2} = \frac{\gamma\left(w_{f,2} - cs_{f,2}\right) + \theta_s\left(w_{f,2} - w_{f,1} + cs_{f,1} - cs_{f,2}\right)}{2c_{f,2}} \quad (23)$$

$$p_{d,1}=\frac{a\alpha\beta+(b-2\theta)c_0+bw_{d,1}+\theta\left(2p_{d,2}+2p_{f,1}+2p_{f,2}+w_{d,1}-w_{d,2}-w_{f,1}-w_{f,2}\right)+(\gamma+\theta_s)x_{d,1}-\theta_s\left(x_{d,2}+x_{f,1}+x_{f,2}\right)}{2(b+\theta)} \tag{24}$$

$$p_{d,2}=\frac{a\beta-a\alpha\beta+(b-2\theta)c_0+bw_{d,2}+\theta\left(2p_{d,1}+2p_{f,1}+2p_{f,2}-w_{d,1}+w_{d,2}-w_{f,1}-w_{f,2}\right)+\gamma x_{d,2}-\theta_s\left(x_{d,1}-x_{d,2}+x_{f,1}+x_{f,2}\right)}{2(b+\theta)} \tag{25}$$

$$p_{f,1}=\frac{a\alpha-a\alpha\beta+(b-2\theta)c_0+bw_{f,1}+\theta\left(2p_{d,1}+2p_{d,2}+2p_{f,2}-w_{d,1}-w_{d,2}+w_{f,1}-w_{f,2}\right)+\gamma x_{f,1}-\theta_s\left(x_{d,1}+x_{d,2}-x_{f,1}+x_{f,2}\right)}{2(b+\theta)} \tag{26}$$

$$p_{f,2}=\frac{a(-1+\alpha)(-1+\beta)+(b-2\theta)c_0+\theta\left(2p_{d,1}+2p_{d,2}+2p_{f,1}-w_{d,1}-w_{d,2}-w_{f,1}\right)+(b+\theta)w_{f,2}-\theta_s\left(x_{d,1}+x_{d,2}+x_{f,1}-x_{f,2}\right)+\gamma x_{f,2}}{2(b+\theta)} \tag{27}$$

By reason of depending $p_{d,i}$ and $p_{f,i}$, $i=1,2$, it is substituted price variables to obtain variables with an independence close from.

$$p_{d,1}=\frac{a(\alpha\beta(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)(c_0+w_{d,1})+\gamma x_{d,1}(b-\theta)+\theta_s x_{d,1}(b-4\theta)+\left(x_{d,2}+x_{f,1}+x_{f,2}\right)(\gamma\theta-b\theta_s)}{2\left(b^2-4\theta^2\right)} \tag{28}$$

$$p_{d,2}=\frac{a(-(-1+\alpha)\beta(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)(c_0+w_{d,2})+(\gamma\theta-b\theta_s)\left(x_{d,1}+x_{f,1}+x_{f,2}\right)+x_{d,2}\gamma(b-\theta)+\theta_s x_{d,2}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \tag{29}$$

$$p_{f,1}=\frac{a(-\alpha(-1+\beta)(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)\left(c_0+w_{f,1}\right)+(\gamma\theta-b\theta_s)\left(x_{d,1}+x_{d,2}+x_{f,2}\right)+\gamma x_{f,1}(b-\theta)+\theta_s x_{f,1}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \tag{30}$$

$$p_{f,2}=\frac{ab(-1+\alpha)(-1+\beta)+a(-1+2\alpha+2\beta-2\alpha\beta)\theta+\left(b^2-4\theta^2\right)\left(c_0+w_{f,2}\right)+(\gamma\theta-b\theta_s)\left(x_{d,1}+x_{d,2}+x_{f,1}\right)+(\gamma(b-\theta)+(b-4\theta)\theta_s)x_{f,2}}{2\left(b^2-4\theta^2\right)} \tag{31}$$

The optimal value of domestic and foreign system prices are gained in Appendix D.

3.3. Government intervention in a competitive market

Now, the government can enter in the competitive marker due to the competition between members and SCSC improvement. In this scenario, the government cooperates with chain's members and decreases manufacturing and assembling cost. The government as the leader considers tariffs (subsidy and tax) for supporting of the SCSC. The government's subsidy provides an incentive for the domestic supplier and assembler to improve the SCSC. The financial assistance from the government induces to increase members and government's profit. Also, the government intervention results in growing demand and improving prices and efficiency. The government gives subsidy to domestic supplier and assembler,while foreign supplier pays government tax. The subsidy applies for supporting domestic systems and tax for importing foreign systems. The percentage of the manufacturing cost of the domestic supplier is reduced by the government. Additionally, the assembling cost is fallen by percentage rate of subsidy. Hence, the profit of assembler and domestic supplier go up. The production cost is raised by a positive tariff; thus, a positive tariff acts as a tax. However, the cost of the production in the market is decreased by a negative tariff; therefore, a negative tariff acts as a subsidy. Deciding on the efficiency of domestic and foreign cells is by the domestic and foreign suppliers, respectively. The prices of domestic and foreign systems are determined by the assembler. The demand functions of domestic ($D_{d,1}$,$D_{d,2}$) and foreign $\left(D_{f,1}\ ,D_{f,2}\right)$ systems and total demand (D) already attained in equations (12)-(16):

The domestic and foreign suppliers' profit is gained from equations (32) and (33) in which (the difference between revenue and cost) is multiplied by the demand functions whereas this sentence is subtracted by the technology R&D cost. The assembler's profit is obtained from Eq. (34) in which (the difference between revenue and cost) is multiplied by the demand functions and then, this amount is subtracted by the assembling cost. The demand functions (Eq. (12)–(16)) are substituted in Eq. (32)–(34). The profit of domestic supplier (π_{DS}), foreign supplier (π_{FS}), and assembler (π_A) are presented as follows:

$$\pi_{DS} = (w_{d,1} - cs_{d,1}(1 - t_{d,1}))D_{d,1} + (w_{d,2} - cs_{d,2}(1 - t_{d,2}))D_{d,2} - c_{d,1}x_{d,1}^2 - c_{d,2}x_{d,2}^2 \tag{32}$$

$$\pi_{FS} = \left(w_{f,1} - cs_{f,1}\left(1 + t_{f,1}\right)\right)D_{f,1} + \left(w_{f,2} - cs_{f,2}\left(1 + t_{f,2}\right)\right)D_{f,2} - c_{f,1}x_{f,1}^2 - c_{f,2}x_{f,2}^2 \tag{33}$$

$$\pi_A = \left(p_{d,1} - w_{d,1}\right)D_{d,1} + \left(p_{d,2} - w_{d,2}\right)D_{d,2} + \left(p_{f,1} - w_{f,1}\right)D_{f,1} + \left(p_{f,2} - w_{f,2}\right)D_{f,2} - c_0(1 - t_a)D \tag{34}$$

Concavity confirmation of functions (32–34) are expressed in Appendix E.

It is derived from profit functions regarding their decision variables and FOC of functions with respect to their decision variables is given optimal variables. For a given tariff and non-cooperative Nash game, the amount of $x_{d,i}^*$, $x_{f,i}^*$, $p_{d,i}$ and $p_{f,i}$, $i = 1, 2$ are expressed as follows:

$$x_{d,1}^* = \frac{(\gamma + \theta_s)cs_{d,1}(-1 + t_{d,1}) + \gamma w_{d,1} + \theta_s(w_{d,1} - w_{d,2} - cs_{d,2}(-1 + t_{d,2}))}{2c_{d,1}} \tag{35}$$

$$x_{d,2}^* = \frac{\gamma(w_{d,2} - cs_{d,2}(1 - t_{d,2})) + \theta_s(w_{d,2} - w_{d,1} + cs_{d,1}(1 - t_{d,1}) - cs_{d,2}(1 - t_{d,2}))}{2c_{d,2}} \tag{36}$$

$$x_{f,1}^* = \frac{\gamma w_{f,1} - (\gamma + \theta_s)cs_{f,1}\left(1 + t_{f,1}\right) + \theta_s\left(w_{f,1} - w_{f,2} + cs_{f,2}\left(1 + t_{f,2}\right)\right)}{2c_{f,1}} \tag{37}$$

$$x_{f,2}^* = \frac{\gamma\left(w_{f,2} - cs_{f,2}\left(1 + t_{f,2}\right)\right) + \theta_s\left(w_{f,2} - w_{f,1} + cs_{f,1}\left(1 + t_{f,1}\right) - cs_{f,2}\left(1 + t_{f,2}\right)\right)}{2c_{f,2}} \tag{38}$$

$$p_{d,1} = \frac{a\alpha\beta + (b - 2\theta)c_0(1 - t_a) + bw_{d,1} + \theta\left(2p_{d,2} + 2p_{f,1} + 2p_{f,2} + w_{d,1} - w_{f,1} - w_{f,2} - w_{d,2}\right) + (\gamma + \theta_s)x_{d,1} - \theta_s\left(x_{d,2} + x_{f,1} + x_{f,2}\right)}{2(b + \theta)} \tag{39}$$

$$p_{d,2} = \frac{a\beta - a\alpha\beta + (b - 2\theta)c_0(1 - t_a) + bw_{d,2} + \theta\left(2p_{d,1} + 2p_{f,1} + 2p_{f,2} - w_{d,1} + w_{d,2} - w_{f,1} - w_{f,2}\right) + \gamma x_{d,2} - \theta_s\left(x_{d,1} - x_{d,2} + x_{f,1} + x_{f,2}\right)}{2(b + \theta)} \tag{40}$$

$$p_{f,1} = \frac{a\alpha - a\alpha\beta + (b - 2\theta)c_0(1 - t_a) + bw_{f,1} + \theta\left(2p_{d,1} + 2p_{d,2} + 2p_{f,2} - w_{d,1} - w_{d,2} + w_{f,1} - w_{f,2}\right) + \gamma x_{f,1} - \theta_s\left(x_{d,1} + x_{d,2} - x_{f,1} + x_{f,2}\right)}{2(b + \theta)} \tag{41}$$

$$p_{f,2} = \frac{a(-1 + \alpha)(-1 + \beta) + (b - 2\theta)c_0(1 - t_a) + \theta\left(2p_{d,1} + 2p_{d,2} + 2p_{f,1} - w_{d,1} - w_{d,2} - w_{f,1}\right) + (b + \theta)w_{f,2} - \theta_s\left(x_{d,1} + x_{d,2} + x_{f,1} - x_{f,2}\right) + \gamma x_{f,2}}{2(b + \theta)} \tag{42}$$

Then, it is substituted the amount of prices from equations (40)–(42) in equation (39) to obtain the value of prices, independently.

$$p_{d,1} = \frac{a(\alpha\beta(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)c_0(1-t_a)+\left(b^2-4\theta^2\right)w_{d,1}+(\gamma\theta-b\theta_s)\left(x_{d,2}+x_{f,1}+x_{f,2}\right)+\gamma x_{d,1}(b-\theta)+\theta_s x_{d,1}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \tag{43}$$

$$p_{d,2} = \frac{a(-(-1+\alpha)\beta(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)c_0(1-t_a)+\left(b^2-4\theta^2\right)w_{d,2}+(\gamma\theta-b\theta_s)\left(x_{d,1}+x_{f,1}+x_{f,2}\right)+\gamma x_{d,2}(b-\theta)+\theta_s x_{d,2}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \tag{44}$$

$$p_{f,1} = \frac{a(-\alpha(-1+\beta)(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)c_0(1-t_a)+\left(b^2-4\theta^2\right)w_{f,1}+(\gamma\theta-b\theta_s)(x_{d,1}+x_{d,2}+x_{f,2}\big)+\gamma x_{f,1}(b-\theta)+\theta_s x_{f,1}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \tag{45}$$

$$p_{f,2} = \frac{ab(-1+\alpha)(-1+\beta)+a(-1+2\alpha+2\beta-2\alpha\beta)\theta+\left(b^2-4\theta^2\right)c_0(1-t_a)+\left(b^2-4\theta^2\right)w_{f,2}+(\gamma\theta-b\theta_s)(x_{d,1}+x_{d,2}+x_{f,1}\big)+(\gamma(b-\theta)+\theta_s(b-4\theta))x_{f,2}}{2\left(b^2-4\theta^2\right)} \tag{46}$$

The optimal prices of domestic and foreign solar systems are gained in Appendix F.

4. The mathematical model for solar cell powerhouse

This paper proposes a two-echelon multi-period multi-product SCSC based on non-cooperative Nash game and a mathematical model for solar cell powerhouse. Hence, in the first phase of this paper, three scenarios including (1) The presence of domestic supplier in a monopoly market, (2) The arrival of a foreign rival to the competitive market, and (3) Government intervention in a competitive market are solved to obtain the optimal decision variables (i.e. price and efficiency). In the second phase, the solutions obtained from the first phase are substituted in the mathematical model for the powerhouse to determine the number of installed and substituted panels in each period and each scenario selected as the optimal scenario. Also, this model defines the kinds of solar cells and which solar cell (domestic or foreign) should be used (Fig. 1.). It is investigated how long powerhouses can use solar panels/modules as their profit is maximized. The solar panels gradually decompose during periods of time and their efficiency reduces. The solar cells lifetime and their efficiency depend on degradation or decomposition. Dust, temperature, and solar radiation affect degradation or decomposition. So, for the high utility of solar panels (domestic/foreign), the powerhouses can substitute them and install new panels in each of periods. Installed panels should supply the demand of each period. The powerhouse installs panels/modules at available areas in the period t' and collects each of panels that does not have favorite efficiency since they want to obtain the more amount of energy in the period t. The notations used to formulate the mathematical model for powerhouse is mentioned in Table 3.

Objective Function:

$$Min \sum_{i,j,s,t'} p_{ijs} yp_{ijst'} \tag{47}$$

Constraints:

$$x_{ist't} = xs_{ist'}(1-\theta)^{t-t'} \quad \forall t \geq t', \forall i,s,t,t' \tag{48}$$

$$\sum_{i,s} z_{ist} \geq B_t \quad \forall t \tag{49}$$

$$\sum_{i,j,t',s} y_{ijst't} \leq ss \quad \forall t \tag{50}$$

$$y_{ijst't} \leq y_{ijst't-1} + yp_{ijst} \quad \forall t \geq t', \ \forall i,j,s,t,t' \tag{51}$$

$$z_{ist} = \sum_{t',j} xs_{ijst'}(1-\theta)^{t-t'} y_{ijst't} \quad \forall i,s,t \tag{52}$$

$$y_{ijst't} = 0 \quad \forall t \leq t'-1, \ \forall i,j,s,t',t \tag{53}$$

$$yp_{ijst} \leq mw_s \quad \forall i,j,s,t \tag{54}$$

$$\sum_s w_s = 1 \tag{55}$$

$$x_{ist't}, y_{ist't}, \ yp_{ist'}, \ z_{ist} \geq 0 \tag{56}$$

The total cost is minimized by Eq. (47). Constraint (48)

Table 3
Notations of mathematical model for solar cell powerhouse.

Sets:	
i	Panel types, $i = 1, 2$
s	Scenarios, $s = 1, 2, 3$
t	Periods, $t = 1, \ldots., T$
j	The domestic and foreign panel, j = 1,2
Parameters	
B_t	The demand for the solar modules/panels in period t
p_{ijs}	Price of the solar system (domestic/foreign) of kind i in scenario s
$xs_{ijst'}$	The efficiency of solar cells(domestic/foreign) of kind i in period t' in regard to non-cooperative Nash game
θ	Coefficient of degradation/decomposition
ss	Existent area
m	A large number
Variables	
$x_{ist't}$	The efficiency of solar panels/modules of kind i in period t under scenario s which are installed in the period t'
$y_{ijst't}$	The number of solar panels/modules (domestic/foreign) of kind i that is using in period t under scenario s which is installed in the period t'
yp_{ijst}	The number of solar panels/modules (domestic/foreign) of kind i (m^2) which is installed at the start of period t
z_{ist}	The amount of energ-y is produced from solar panels/modules of kind i in period t under scenario s
w	Takes value 1 if scenario s is selected, 0 otherwise

demonstrates reduction in efficiency driven from degradation. Constraint (49) satisfies powerhouse demands for each period. In other words, the energy obtained from panels that are installed and used is equal to corresponding demands in each period. Constraint (50) is the capacity constraint. In other words, the number of panels that are installed in each period must not exceed its corresponding capacity. Constraint (51) shows the number of solar panels is installed in period t that should be less than the number of panels are using in period t and previous installed solar panels. Constraint (52) demonstrates the total power gained from panels installed in each of period, considering reduction in efficiency. Constraint (53) ensures the panels are installed in period t cannot be used in its previous periods. Constraint (54) expresses that if scenario s is selected, the powerhouse can install the panels. Constraint (55) represents that only one of the scenarios is chosen. The range of the decision variable is specified by constraint (56).

5. Case study

To investigate the effectiveness of the presented model, a real case study is considered for installation and substitution solar panels in a powerhouse of Iran. Iran, where has huge reserves of the fuel fossils, is one of the biggest oil exporters in the world. However, increasing use of fuel fossils, and as a result, enhancing GHG emission causes a lot of environmental problems in Iran. One of the impacts of the high fuel fossils consumption is air pollution in some big cities of Iran. According to the point that solar energy is eco-friendly and one of the important resources of energy, the government of Iran is planned to invest in the production of annual power by 2025. In addition, the government of Iran has assigned solar cell industry policies such as feed-in-tariffs, subsidies, taxes, and grants in order to boost the electricity generated by solar cells and develop solar energy plants. Besides, the Iranian government is allocated 10% of the tariffs to the solar energy industry of Iran. Placed in the world's Sun Belt, Iran has almost 300 days of sunlight annually. So, the generation of electricity can be increased by installing solar panels in many areas of Iran (Dehghani et al., [35,36]).

5.1. Data gathering

In this part, the details of the case study and the main sources for data collection are expressed. The parameters, i.e., the wholesale price of solar modules and taxes are provided by new energy organization of Iran (www.sabainfo.ir) and renewable energy organization (www.satba.gov.ir). The other parameters, i.e., initial market potential, price elasticity coefficient, and subsidies are calculated according to the data employed by Chen and Su [10,24,32,37] and Dehghani et al., [35,36]. The cost parameters for a solar cell supply chain in the year 2017 i.e., the manufacturing cost of solar modules and assembling cost are estimated according to the data used by Chen and Su [37]. Besides, the parameters i.e., efficiency resilient coefficient, difference coefficient of the solar system price, difference coefficient of the solar cell efficiency, and maximum R&D cost are taken from the works existing in the related literature (i.e. Kharaji Manouchehrabadi and Yaghoubi [38]). Also, the parameters i.e., the degree of the customer's loyalty are assumed as: $\alpha = 0.7$, $\beta = 0.3$.

It is considered two kinds of solar cells, whereas the third generation of solar cells is dye-sensitized, and perovskite solar cells are also known as the fourth generation. These solar cells are examined in order to the point that price and efficiency of the perovskite and dye-sensitized solar cells are suitable and both these cells are new and the production cost of them is low. The high conversion efficiency in a very short period of time, easy fabrication, and low cost are the main characteristics of perovskite solar cells [31]. The advantages of dye-sensitized solar cells include some cases such as low cost, easy process ability, and large-scale manufacturing [4]. These solar cells are investigated under five periods of time and three scenarios. Both perovskite and dye-sensitized solar cells contain domestic and foreign ones. Considering values applied for the case study (see Table 4) the results of the non-cooperative Nash game in the scenarios are shown in Table 5. It is worthwhile to mention that in this paper, all of the unit costs and the unit prices are presented based on Toman.

In scenario 1, the price of domestic solar cells is the biggest one. In scenario 2 and 3, the efficiency of domestic solar cells is more than foreign solar cells, while the price of domestic solar systems is lower than foreign solar systems in each scenario since domestic supplier intends to attract more customers and compete with the foreign supplier in the competitive market.

On the other hands, due to the government's support of domestic supplier and assembler in manufacturing cells and assembling panels/modules, the efficiency of domestic solar cells increases and price of domestic systems reduces in scenario 3. The efficiency of domestic solar cells in scenario 3 is more than scenario 1 and 2. In fact, the efficiency of domestic solar cells in scenario 3 is bigger than scenario 2 and the efficiency of domestic solar cells in scenario 2 is as same as scenario 1. The efficiency of domestic solar cells in scenario 2 is similar to scenario 1, but the price in scenario 2

Table 4
Statistical Data of case study.

Case study	Scenarios	a	b	γ	θ	θ_s	$w_{d,1}$	$w_{f,1}$	$cs_{d,1}$	$cs_{f,1}$	$w_{d,2}$	$w_{f,2}$	$cs_{d,2}$	α
	S. 1	393×10^5	0.38	0.5	0.06	0.5	52×10^5	63×10^5	1943×10^3	1953×10^3	57×10^5	73×10^5	2143×10^3	0.7
	S. 2													
	S. 3													
	Scenarios	$cs_{f,2}$	$c_{d,1}$	$c_{d,2}$	$c_{f,1}$	$c_{f,2}$	c_0	$t_{d,1}$	$t_{d,2}$	$t_{f,1}$	$t_{f,2}$	t_a	β	
	S. 1	2543×10^3	9×10^5	12×10^5	15×10^5	15×10^5	29145×10^2	–	–	–	–	–	0.3	
	S. 2							–	–	–	–	–		
	S. 3							0.1	0.1	0.1	0.1	0.25		

Table 5
The results of non-cooperative Nash game in the scenarios.

Case study	Scenarios	$x^*_{d,1}$	$x^*_{d,2}$	$x^*_{f,1}$	$x^*_{f,2}$	$p^*_{d,1}$	$p^*_{d,2}$	$p^*_{f,1}$	$p^*_{f,2}$
	S.1	0.82	0.80	–	–	377725×10^2	223025×10^2	–	–
	S.2	0.82	0.80	0.66	0.86	213795×10^2	169135×10^2	329335×10^2	171693×10^2
	S.3	0.87	0.85	0.63	0.81	210152×10^2	165492×10^2	325692×10^2	16805×10^3
	Scenarios	$D_{d,1}$	$D_{d,2}$	$D_{f,1}$	$D_{f,2}$	D	π_{DS}	π_{FS}	π_A
	S.1	122282×10^2	4243250	–	–	164715×10^2	5.49206×10^{13}	–	4.20747×10^{14}
	S.2	2867010	384006	8094010	4972080	163171×10^2	1.07037×10^{13}	5.88368×10^{13}	2.67779×10^{14}
	S.3	2961730	478727	8188730	5066800	16696×10^3	1.20272×10^{13}	5.67207×10^{13}	2.78236×10^{14}

is lower than scenario 1. It shows that the domestic supplier intends to raise efficiency without increasing price. The price of domestic systems in scenario 3 is the lowest price, owing to the government's subsidy for the assembler that influences the final price. The demand and profit of domestic supplier and assembler in scenario 3 are bigger than scenario 2. For remaining both domestic and foreign supplier in the market, suppliers should try to decrease costs and improve efficiency. High efficiency and low price of domestic solar systems lead to increase demand and profit of the domestic supplier in scenario 3 rather than scenario 2. It is represented the effect of government on the competition among suppliers. Also, the government's tariffs affect improving efficiency, reduction in costs and price, enhancement in demand, and profit of members rather than other scenarios.

The results of non-cooperative Nash game show that a low price increases customers' demand. The profit of members, demand, and efficiency in scenario 3 are better than scenario 2. Considering subsidy for assembling cost has a great effect on the price of domestic solar systems. The government's subsidy for domestic supplier affects the efficiency of domestic solar cells.

5.2. Sensitivity analysis

Regarding the real data in section 5.1., and the data used in section 4 ($b(1) = 10000$, $b(2) = 12000$, $b(3) = 11000$, $b(4) = 9000$, $\theta = 0.01$, $ss = 50000$), the below results are obtained. Due to the importance of subsidy and tax, the effect of them is investigated on the efficiency, price, and installation of solar panels.

According to Table 6, an increase in the $t_{d,1}$ and $t_{d,2}$ values causes the domestic solar cell's efficiency to be improved, and on the contrary, with reducing the amount of subsidies, the domestic cell's efficiency is calculated at a low level. Table 7 shows an increase in taxes gives rise to a reduction in the efficiency of the foreign cell. Besides, the low tariffs lead to increased foreign solar cell's efficiency.

With an increase in tariffs, the price of domestic and foreign solar panels is reduced, as seen in Table 8. As seen in Table 9, with increased tariffs, a lower domestic solar system's price is obtained in comparison with the price of the foreign system. The solar panels' price is raised by decreasing the amount of tariffs.

Table 6
The effect of the subsidy ($\boldsymbol{t_{d,1}}, \boldsymbol{t_{d,2}}$) on the efficiency of the domestic solar cells.

Optimal value	Percentage of reduction				Percentage of increasing			
	−0.20	−0.15	−0.10	−0.05	0.05	0.10	0.15	0.20
$x^*_{d,1}$	0.77	0.80	0.82	0.85	0.89	0.92	0.94	0.97
$x^*_{d,2}$	0.75	0.78	0.80	0.83	0.88	0.90	0.93	0.95

Table 7
The effect of the tax ($\boldsymbol{t_{f,1}}, \boldsymbol{t_{f,2}}$) on the efficiency of foreign solar cells.

Optimal value	Percentage of reduction				Percentage of increasing			
	−0.20	−0.15	−0.10	−0.05	0.05	0.10	0.15	0.20
$x^*_{f,1}$	0.68	0.67	0.66	0.64	0.62	0.61	0.60	0.59
$x^*_{f,2}$	0.91	0.89	0.86	0.84	0.78	0.76	0.73	0.70

Table 8
The effect of increasing tariffs ($\boldsymbol{t_{d,1}}, \boldsymbol{t_{d,2}}, \boldsymbol{t_{f,1}}, \boldsymbol{t_{f,2}}, \boldsymbol{t_a}$) on solar systems price.

Optimal value	Percentage of increasing			
	0.05	0.10	0.15	0.20
$p^*_{d,1}$	20942300	20869400	20796600	20723700
$p^*_{d,2}$	16476300	16403400	16330600	16257700
$p^*_{f,1}$	32496300	32423400	32350600	32277700
$p^*_{f,2}$	16732200	16659300	16586400	16513600

Table 9
The impact of the reduction in tax ($\mathbf{t_{f,1}}, \mathbf{t_{f,2}}$) and subsidy ($\mathbf{t_{d,1}}, \mathbf{t_{d,2}}, \mathbf{t_a}$) on solar systems price.

Optimal value	Percentage of reduction			
	−0.05	−0.10	−0.15	−0.20
$p^*_{d,1}$	21088000	21160900	21238800	21306600
$p^*_{d,2}$	16622000	16694900	16767800	16840600
$p^*_{f,1}$	32642000	32714900	32787800	32860600
$p^*_{f,2}$	16877900	16950700	17023600	17096500

According to Tables 10–14, the tariff considered for costs of manufacturing and assembling decreases the number of installation and substitution solar panels in powerhouses. Indeed, the high tariff leads to a reduction in installing and substituting domestic solar panels. In other words, when the taxes and subsidies increase, the efficiency of domestic solar cells becomes higher, where the efficiency of foreign solar cells decreases. Moreover, the price of solar systems is reduced by an increase in government's tariffs. However, the price of domestic systems is smaller than the price of foreign systems. As a result, the installation and substitution of domestic panels become lower, however, the powerhouses should install and replace higher foreign panels.

Due to the importance of the tariffs, the decreasing trend of the installation and substitution of the domestic panels is shown in Figs. 2 and 3. In contrast, if foreign panels are installed by powerhouses, the upward trend in installing and replacing foreign panels is observed in Figs. 2 and 3.

Tables (10), (15)–(18) show the foreign solar cell's efficiency is extended by decreasing the government's tariffs, whereas the domestic solar cell's efficiency lifts up. Additionally, the solar panels' price is raised by decreasing the amount of tariffs, but the domestic solar system's price is less than the foreign solar system's price. Therefore, the lower foreign panels are installed by powerhouses. On the other hand, the high tariffs cause to be enhanced installation and substitution of domestic solar panels.

The upward trend as to installation and substitution of domestic systems is clearly understandable which is in contrast with the downward trend in installing and substituting foreign panels (see Figs. 4 and 5). In fact, for example in the first period, a large number of domestic solar panels are substituted by powerhouses in comparison with foreign solar panels.

In this paper, it intends to show the impact of the tariffs on the

Table 10
The optimal value of installed, substituted solar panels, and produced energy amount.

$t_{d,1}, t_{d,2} = 0.10 t_{f,1} = 0.10, t_{f,2} = 0.10, t_a = 0.2\ 5$	Decision variables	Optimal value	
	yp_{ijst}	$yp_{2111} = 12500$	$yp_{2112} = 1255.981$
		$yp_{2131} = 11764.706$	$yp_{2132} = 1182.100$
		$yp_{2221} = 11627.907$	$yp_{2222} = 1168.354$
		$y_{21111} = 12500$	$y_{21122} = 1255.981$
		$y_{21112} = 13755.981$	$y_{21123} = 1255.981$
	$y_{ijst' t}$	$y_{21113} = 12633.646$	$y_{21124} = 1255.981$
		$y_{21114} = 10198.830$	$y_{21311} = 11764.706$
		$y_{21312} = 12946.806$	$y_{21313} = 11890.491$
		$y_{21314} = 9598.899$	$y_{21322} = 1182.100$
		$y_{21323} = 1182.100$	$y_{21324} = 1182.100$
		$y_{22211} = 11627.907$	$y_{22222} = 1168.354$
		$y_{22212} = 12796.261$	$y_{22223} = 1168.354$
		$y_{22213} = 11752.229$	$y_{22224} = 1168.354$
		$y_{22214} = 9487.284$	
	z_{ist}	$z_{211} = 10000$	$z_{221} = 10000$
		$z_{212} = 12000$	$z_{222} = 12000$
		$z_{213} = 11000$	$z_{223} = 11000$
		$z_{214} = 9000$	$z_{224} = 9000$
		$z_{231} = 10000$	$z_{233} = 11000$
		$z_{232} = 12000$	$z_{234} = 9000$
	obj	7.40755×10^{11}	$z_{222} = 12000$

Table 11
The impact of increasing in subsidy and tax on installed, substituted solar panels, and produced energy amount.

Percentage of increasing tariffs	Decision variables	Optimal value	
$t_{d,1}, t_{d,2}, t_{f,1}, t_{f,2}, t_a = 0.05$	yp_{ijst}	$yp_{2111} = 12500$	$yp_{2132} = 1141.801$
		$yp_{2112} = 1255.981$	$yp_{2221} = 11627.907$
		$yp_{2131} = 11363.636$	$yp_{2222} = 1168.354$
	$y_{ijst' t}$	$y_{21111} = 12500$	$y_{21314} = 9271.664$
		$y_{21112} = 13755.981$	$y_{21322} = 1141.801$
		$y_{21113} = 12633.646$	$y_{21323} = 1141.801$
		$y_{21114} = 10198.830$	$y_{21324} = 1141.801$
		$y_{21122} = 1255.981$	$y_{22211} = 11627.907$
		$y_{21123} = 1255.981$	$y_{22212} = 12769.261$
		$y_{21124} = 1255.981$	$y_{22213} = 11752.229$
		$y_{21311} = 11363.636$	$y_{22214} = 9487.284$
		$y_{21312} = 12505.437$	$y_{22222} = 1168.354$
		$y_{21313} = 11458.133$	$y_{22223} = 1168.354$
		$y_{22224} = 1168.354$	
	z_{ist}	$z_{211} = 10000$	$z_{223} = 11000$
		$z_{212} = 12000$	$z_{224} = 9000$
		$z_{213} = 11000$	$z_{231} = 10000$
		$z_{214} = 9000$	$z_{232} = 12000$
		$z_{221} = 10000$	$z_{233} = 11000$
		$z_{222} = 12000$	$z_{234} = 9000$
	obj	7.32539×10^{11}	

Table 12
The impact of increasing in subsidy and tax on installed, substituted solar panels, and produced energy amount.

Percentage of increasing tariffs	Decision variables	Optimal value	
$t_{d,1}, t_{d,2}, t_{f,1}, t_{f,2}, t_a = 0.10$	yp_{ijst}	$yp_{2111} = 12500$ $yp_{2112} = 1255.981$ $yp_{2131} = 11111.111$	$yp_{2132} = 1116.427$ $yp_{2221} = 11627.907$ $yp_{2222} = 1168.354$
	$y_{ijst't}$	$y_{21111} = 12500$ $y_{21112} = 13755.981$ $y_{21113} = 12633.646$ $y_{21114} = 10198.830$ $y_{21122} = 1255.981$ $y_{21123} = 1255.981$ $y_{21124} = 1255.981$ $y_{21311} = 11111.111$ $y_{21312} = 12227.539$ $y_{21313} = 11229.908$ $y_{21314} = 9065.627$	$y_{21322} = 1116.427$ $y_{21323} = 1116.427$ $y_{21324} = 1116.427$ $y_{22211} = 11627.907$ $y_{22212} = 12796.261$ $y_{22213} = 11752.229$ $y_{22214} = 9487.284$ $y_{2222} = 1168.354$ $y_{2223} = 1168.354$ $y_{2224} = 1168.354$
	z_{ist}	$z_{211} = 10000$ $z_{212} = 12000$ $z_{213} = 11000$ $z_{214} = 9000$ $z_{221} = 10000$ $z_{222} = 12000$	$z_{223} = 11000$ $z_{224} = 9000$ $z_{231} = 10000$ $z_{232} = 12000$ $z_{233} = 10000$ $z_{234} = 9000$
	obj	7.27069×10^{11}	

Table 13
The impact of increasing in subsidy and tax on installed, substituted solar panels, and produced energy amount.

Percentage of increasing tariffs	Decision variables	Optimal value	
$t_{d,1}, t_{d,2}, t_{f,1}, t_{f,2}, t_a = 0.15$	yp_{ijst}	$yp_{2111} = 12500$ $yp_{2112} = 1255.981$ $yp_{2131} = 10752.688$	$yp_{2132} = 1080.414$ $yp_{2221} = 11627.907$ $yp_{2222} = 1168.354$
	$y_{ijst't}$	$y_{21111} = 12500$ $y_{21112} = 13755.981$ $y_{21113} = 12633.646$ $y_{21114} = 10198.830$ $y_{21122} = 1255.981$ $y_{21123} = 1255.981$ $y_{21124} = 1255.981$ $y_{21311} = 10752.688$ $y_{21312} = 11833.102$ $y_{21313} = 10867.653$ $y_{21314} = 8773.187$	$y_{21322} = 1080.414$ $y_{21323} = 1080.414$ $y_{21324} = 1080.414$ $y_{22211} = 11627.907$ $y_{22212} = 12796.261$ $y_{22213} = 11752.229$ $y_{22214} = 9487.284$ $y_{22222} = 1168.354$ $y_{22223} = 1168.354$ $y_{22224} = 1168.354$
	z_{ist}	$z_{211} = 10000$ $z_{212} = 12000$ $z_{213} = 11000$ $z_{214} = 9000$ $z_{221} = 10000$ $z_{222} = 12000$	$z_{223} = 11000$ $z_{224} = 9000$ $z_{231} = 10000$ $z_{232} = 12000$ $z_{233} = 11000$ $z_{234} = 9000$
	obj	7.19737×10^{11}	

price and efficiency. The graphs express that increasing tariffs have a positive effect on the efficiency and price. Increasing tariffs causes to enhance the efficiency and decrease the price, and reduction in tariffs induces to decrease the efficiency and enhance the price. The model of the non-cooperative Nash game is nonlinear, and so, the graphs drawn are nonlinear. When the solutions of the game model are put in the powerhouses model for solar cells, due to the point that powerhouse model is linear, the relationship between decision variables and tariffs in this model is linear.

The Figs. 6 and 8 illustrate a nonlinear relationship between the efficiency and suppliers' profit which increasing efficiency enhances the profit. As seen in Figs. 7 and 9, at first, increasing price results in going up the assembler's profit to arrive the maximum point (the optimal solution) and then, the profit reduces.

6. Managerial insights

Regarding the case study and sensitivity analysis on tariffs, the managerial insights are proposed as follows:

- The efficiency of the domestic cells is more than the foreign cells in each scenario. The domestic cells' efficiency in scenario 3 is bigger than the foreign cells because the government's subsidy helps to improve efficiency. The efficiency of the domestic solar cells in the competitive market is as same as the monopoly market. The efficiency of the domestic solar cells in scenario 3 is the bigger than the other scenarios.
- The price of the domestic system is lower than the foreign one. The price in the monopoly market is bigger than scenario 2 and

Table 14
The impact of increasing in subsidy and tax on installed, substituted solar panels, and produced energy amount.

Percentage of increasing tariffs	Decision variables	Optimal value	
$t_{d,1}, t_{d,2}, t_{f,1}, t_{f,2}, t_a = 0.2$	yp_{ijst}	$yp_{2111} = 12500$	$yp_{2132} = 1057.668$
		$yp_{2112} = 1255.981$	$yp_{2221} = 11627.907$
		$yp_{2131} = 10526.316$	$yp_{2222} = 1168.354$
	$y_{ijst't}$	$y_{21111} = 12500$	$y_{21322} = 1057.668$
		$y_{21112} = 13755.981$	$y_{21323} = 1057.688$
		$y_{21113} = 12633.646$	$y_{21324} = 1057.688$
		$y_{21114} = 10198.830$	$y_{22211} = 11627.907$
		$y_{21122} = 1255.981$	$y_{22212} = 12796.261$
		$y_{21123} = 1255.981$	$y_{22213} = 11752.229$
		$y_{21124} = 1255.981$	$y_{22214} = 9487.284$
		$y_{21311} = 10526.316$	$y_{22222} = 1168.354$
		$y_{21312} = 11583.984$	$y_{22223} = 1168.354$
		$y_{21313} = 10638.860$	$y_{22224} = 1168.354$
		$y_{21314} = 8588.488$	
	z_{ist}	$z_{211} = 10000$	$z_{223} = 11000$
		$z_{212} = 12000$	$z_{224} = 9000$
		$z_{213} = 11000$	$z_{231} = 10000$
		$z_{214} = 9000$	$z_{232} = 12000$
		$z_{221} = 10000$	$z_{233} = 11000$
		$z_{222} = 12000$	$z_{234} = 9000$
	obj	7.14825×10^{11}	

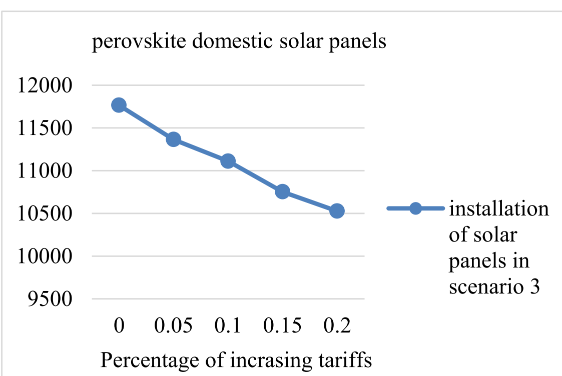

Fig. 2. The effect of increasing tariffs in solar panels installation.

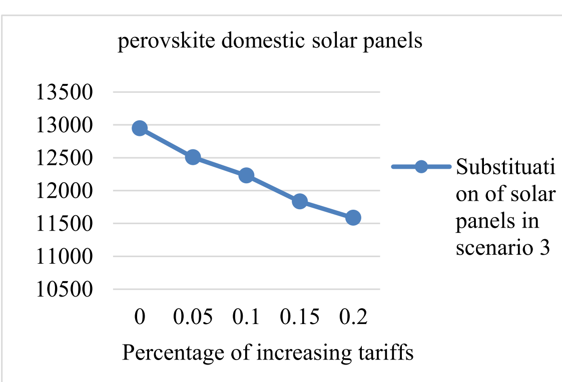

Fig. 3. The effect of increasing tariffs in solar panels substitution.

3. The price of the domestic solar systems in scenario 3 is the lowest one due to the government intervention. The price of domestic systems in scenario 2 is smaller than scenario 1, whereas the efficiency of domestic cells in scenario 2 is similar to scenario 1.

- The competition among the domestic and foreign suppliers causes to progress the efficiency, especially for the domestic supplier and the efficiency of domestic solar cells is better than the foreign one.
- If both tax and subsidy increase, the foreign solar cells' efficiency will be lower than the domestic one. Due to a high tax, the price of foreign systems is more than the domestic systems. So, the powerhouse installs the domestic panels and because of the high efficiency and applying technology R&D, they need to substitute a low number of solar panels. As a matter of fact, solar panels decay later, since the efficiency improves (low degradation).
- If subsidy and tax decline simultaneously, the powerhouses use a low domestic solar cells' efficiency and a high foreign solar cells' efficiency. While both domestic and foreign solar systems' prices increase due to increasing manufacturing cost in the domestic cells, importing the foreign systems, and reduction in the subsidy for assembling cost. Thus, a high production cost affects the price. The powerhouse replaces higher domestic panels, while substitution of foreign panels is reduced by powerhouses. The substitution of domestic panels will be raised since the domestic cells' efficiency reduces.
- With respect to the effect of the subsidy on the price and efficiency improvement, reduction of the installed and substituted solar panels is better than a tax.
- Advance in the efficiency and technology R&D helps low degradation. So, the powerhouses do not need to install a more number of panels.

7. Conclusion

It is proposed a two-echelon supply chain including two suppliers, an assembler, and the government. In this study, three scenarios are studied including (1) The presence of domestic supplier in a monopoly market, (2) Arrival of the foreign rival to the competitive market, and (3) The government intervention in a competitive market. In this paper, it is propounded a competition between the domestic and foreign suppliers for improving the efficiency. Furthermore, the government's tariffs are applied as an

Table 15
The impact of the reduction in subsidy and tax on energy amount, installation, and substitution of solar panels.

Percentage of decreasing tariffs	Decision variables	Optimal value	
$t_{d,1}, t_{d,2}, t_{f,1}, t_{f,2}, t_a = -\ 0.05$	yp_{ijst}	$yp_{2111} = 12500$	$yp_{2132} = 1210.584$
		$yp_{2112} = 1255.981$	$yp_{2221} = 11627.907$
		$yp_{2131} = 12048.193$	$yp_{2222} = 1168.354$
	$y_{ijst't}$	$y_{21111} = 12500$	$y_{21322} = 1210.584$
		$y_{21112} = 13755.981$	$y_{21323} = 1210.584$
		$y_{21113} = 12633.646$	$y_{21324} = 1210.584$
		$y_{21114} = 10198.830$	$y_{22211} = 11627.907$
		$y_{21122} = 1255.981$	$y_{22212} = 12796.261$
		$y_{21123} = 1255.981$	$y_{22213} = 11752.229$
		$y_{21124} = 1255.981$	$y_{22214} = 9487.284$
		$y_{21311} = 12048.193$	$y_{22222} = 1168.354$
		$y_{21312} = 13258.777$	$y_{22223} = 1168.354$
		$y_{21313} = 12177.009$	$y_{22224} = 1168.354$
		$y_{21314} = 9830.198$	
	z_{ist}	$z_{211} = 10000$	$z_{223} = 11000$
		$z_{212} = 12000$	$z_{224} = 9000$
		$z_{213} = 11000$	$z_{231} = 10000$
		$z_{214} = 9000$	$z_{232} = 12000$
		$z_{221} = 10000$	$z_{233} = 11000$
		$z_{222} = 12000$	$z_{234} = 9000$
	obj	7.46883×10^{11}	

Table 16
The impact of the deduction in subsidy and tax on energy amount, installation, and substitution of solar panels.

Percentage of decreasing tariffs	Decision variables	Optimal value	
$t_{d,1}, t_{d,2}, t_{f,1}, t_{f,2}, t_a = -\ 0.10$	yp_{ijst}	$yp_{2111} = 12500$	$yp_{2222} = 1168.354$
		$yp_{2112} = 1255.981$	$yp_{2231} = 11627.907$
		$yp_{2221} = 11627.907$	$yp_{2232} = 1168.354$
	$y_{ijst't}$	$y_{21111} = 12500$	$y_{22222} = 1168.354$
		$y_{21112} = 13755.981$	$y_{22223} = 1168.354$
		$y_{21113} = 12633.646$	$y_{22224} = 1168.354$
		$y_{21114} = 10198.830$	$y_{22311} = 11627.907$
		$y_{21122} = 1255.981$	$y_{22312} = 12796.261$
		$y_{21123} = 1255.981$	$y_{22313} = 11752.229$
		$y_{21124} = 1255.981$	$y_{22314} = 9487.284$
		$y_{22211} = 11627.907$	$y_{22322} = 1168.354$
		$y_{22212} = 12796.261$	$y_{22323} = 1168.354$
		$y_{22213} = 11752.229$	$y_{22324} = 1168.354$
		$y_{22214} = 9487.284$	
	z_{ist}	$z_{211} = 10000$	$z_{223} = 11000$
		$z_{212} = 12000$	$z_{224} = 9000$
		$z_{213} = 11000$	$z_{231} = 10000$
		$z_{214} = 9000$	$z_{232} = 12000$
		$z_{221} = 10000$	$z_{233} = 11000$
		$z_{222} = 12000$	$z_{234} = 9000$
	obj	7.43401×10^{11}	

improving factor in developing the SCSC. The effect of subsidy and tax on the price and efficiency is investigated. The competition and the role of government influence the profit, demand, efficiency, and price. Also, the presence of government has a positive impact on the competition among suppliers. The third scenario exhibits that the manufacturing and assembling cost is decreased by the government's tariffs. The subsidy assists in costs related to the domestic solar cells and supports the domestic products; and the tax is considered for importing the foreign solar cells. It is formulated as a game model for two kinds of the solar cells (dye-sensitized and perovskite) under three scenarios. Then, it is put the decision variables obtained from the solved models under three scenarios, in the mathematical model for the solar cell powerhouses while the degradation is important. The model determines how many solar panels/modules from two kinds of it should be collected in each period and which scenario chose. It decides how many solar modules/panels should be installed in each period and each scenario and how much energy is produced from solar modules in each period and each scenario. In fact, powerhouses can substitute solar modules/panels when the solar cells of each kind (domestic and foreign) do not have enough efficiency in each period. So, the amount of energy produced from both domestic and foreign panels in each period and each scenario delineated.

In the future works, it can be considered the reverse solar cell supply chain coordination under the government intervention. For further studies, it can be presented a coordination in a two-echelon solar cell supply chain under demand uncertainty. It is suggested the allocation and location of the solar powerhouses in many cities of Iran considering degradation.

Table 17
The impact of the reduction in subsidy and tax on energy amount, installation, and substitution of solar panels.

Percentage of decreasing tariffs	Decision variables	Optimal value	
$t_{d,1}, t_{d,2}, t_{f,1}, t_{f,2}, t_a = -0.15$	yp_{ijst}	$yp_{2111} = 12500$	$yp_{2222} = 1168.354$
		$yp_{2112} = 1255.981$	$yp_{2231} = 11235.955$
		$yp_{2221} = 11627.907$	$yp_{2232} = 1128.972$
	$y_{ijst't}$	$y_{21111} = 12500$	$y_{22222} = 1168.354$
		$y_{21112} = 13755.981$	$y_{22223} = 1168.354$
		$y_{21113} = 12633.646$	$y_{22224} = 1168.354$
		$y_{21114} = 10198.830$	$y_{22311} = 11235.955$
		$y_{21122} = 1255.981$	$y_{22312} = 12364.927$
		$y_{21123} = 1255.981$	$y_{22313} = 11356.087$
		$y_{21124} = 1255.981$	$y_{22314} = 9167.488$
		$y_{22211} = 11627.907$	$y_{22322} = 1128.972$
		$y_{22212} = 12796.261$	$y_{22323} = 1128.972$
		$y_{22213} = 11752.229$	$y_{22324} = 1128.972$
		$y_{22214} = 9487.284$	
	z_{ist}	$z_{211} = 10000$	$z_{223} = 11000$
		$z_{212} = 12000$	$z_{224} = 9000$
		$z_{213} = 11000$	$z_{231} = 10000$
		$z_{214} = 9000$	$z_{232} = 12000$
		$z_{221} = 10000$	$z_{233} = 11000$
		$z_{222} = 12000$	$z_{234} = 9000$
	obj	7.36991×10^{11}	

Table 18
The impact of the reduction in subsidy and tax on energy amount, installation, and substitution of solar panels.

Percentage of decreasing tariffs	Decision variables	Optimal value	
$t_{d,1}, t_{d,2}, t_{f,1}, t_{f,2}, t_a = -0.2$	yp_{ijst}	$yp_{2111} = 12500$	$yp_{2222} = 1168.354$
		$yp_{2112} = 1255.981$	$yp_{2231} = 10989.011$
		$yp_{2221} = 11627.907$	$yp_{2232} = 1104.159$
	$y_{ijst't}$	$y_{21111} = 12500$	$y_{22222} = 1168.354$
		$y_{21112} = 13755.981$	$y_{22223} = 1168.354$
		$y_{21113} = 12633.646$	$y_{22224} = 1168.354$
		$y_{21114} = 10198.830$	$y_{22311} = 10989.011$
		$y_{21122} = 1255.981$	$y_{22312} = 12093.170$
		$y_{21123} = 1255.981$	$y_{22313} = 11106.502$
		$y_{21124} = 1255.981$	$y_{22314} = 8966.004$
		$y_{22211} = 11627.907$	$y_{22322} = 1104.159$
		$y_{22212} = 12796.261$	$y_{22323} = 1104.159$
		$y_{22213} = 11752.229$	$y_{22324} = 1104.159$
		$y_{22214} = 9487.284$	
	z_{ist}	$z_{211} = 10000$	$z_{223} = 11000$
		$z_{212} = 12000$	$z_{224} = 9000$
		$z_{213} = 11000$	$z_{231} = 10000$
		$z_{214} = 9000$	$z_{232} = 12000$
		$z_{221} = 10000$	$z_{233} = 11000$
		$z_{222} = 12000$	$z_{234} = 9000$
	obj	7.33246×10^{11}	

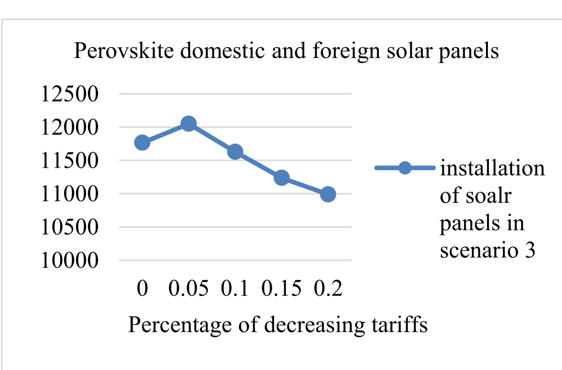

Fig. 4. The effect of decreasing tariffs in solar panels installation.

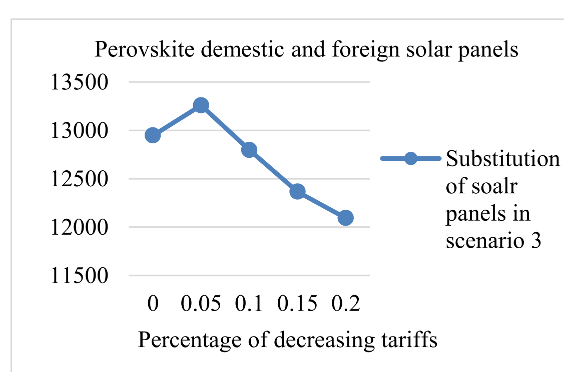

Fig. 5. The effect of decreasing tariffs in solar panels substitution.

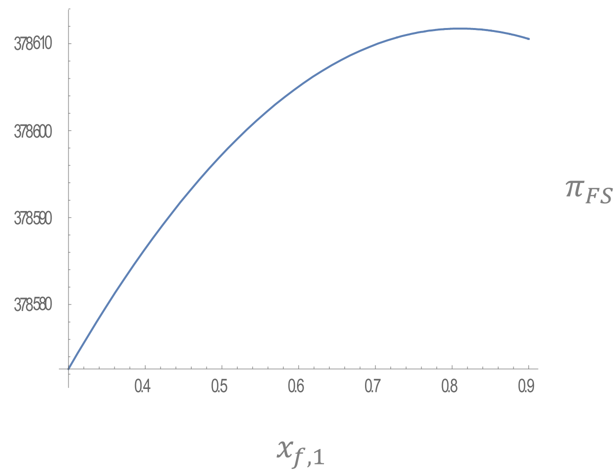

Fig. 6. The effect of the foreign solar cell efficiency on the foreign supplier's profit.

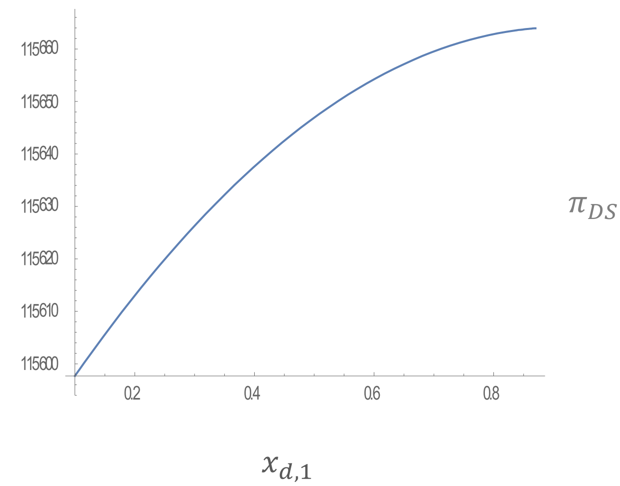

Fig. 8. The effect of the domestic solar cell efficiency on the domestic supplier's profit.

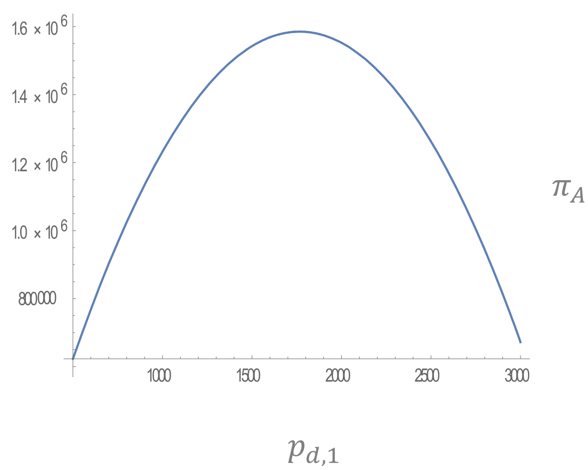

Fig. 7. The effect of the domestic solar system price on the assembler's profit.

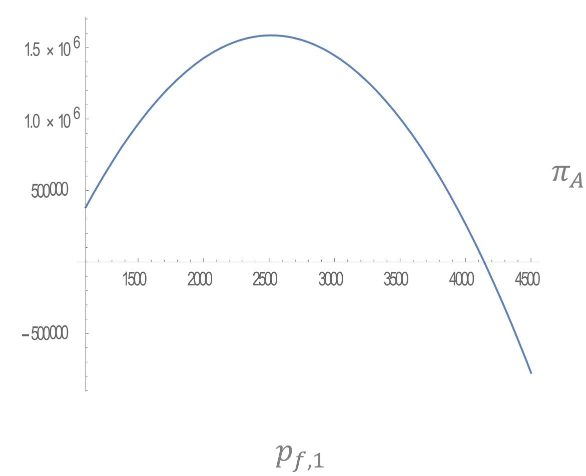

Fig. 9. The effect of the foreign solar system price on the assembler's profit.

Appendix A. Scenario 1

The Eq. (4) is concave with respect to decision variables $x_{d,1}$ and $x_{d,2}$. Hessian matrix of π_{DS} is computed as follows:

$$H(\pi_{DS}(x_{d,1}, x_{d,2})) = \begin{bmatrix} -2c_{d,1} & 0 \\ 0 & -2c_{d,2} \end{bmatrix}$$

$$H_{11}(\pi_{DS}(x_{d,1}, x_{d,2})) = -2c_{d,1} < 0 \text{ and } H_{22}(\pi_{DS}(x_{d,1}, x_{d,2})) = 4c_{d,1}c_{d,2} > 0.$$

To confirm concavity, hessian matrix of π_A is investigated as follows:

$$H\left(\pi_A\left(p_{d,1}, p_{d,2}\right)\right) = \begin{bmatrix} -2b - 2\theta & 2\theta \\ 2\theta & -2b - 2\theta \end{bmatrix}$$

$$H_{11}\left(\pi_A\left(p_{d,1}, p_{d,2}\right)\right) = -2b - 2\theta < 0 \text{ and } H_{22}\left(\pi_A\left(p_{d,1}, p_{d,2}\right)\right) = 4b^2 + 8b\theta > 0.$$

Appendix B. Scenario 1

$$p^*_{d,1} = \frac{a(b\alpha + \theta) + b(c_0 + w_{d,1})(b + 2\theta) + (\gamma(b + \theta) + b\theta_s)x_{d,1} + (\gamma\theta - b\theta_s)x_{d,2}}{2b(b + 2\theta)} \quad \text{(B-1)}$$

$$p^*_{d,2} = \frac{a(b-b\alpha+\theta)+b\left(c_0+w_{d,2}\right)(b+2\theta)+(\gamma\theta-b\theta_s)x_{d,1}+(\gamma(b+\theta)+b\theta_s)x_{d,2}}{2b(b+2\theta)} \tag{B-2}$$

where:

$$x^*_{d,1} = \frac{\gamma w_{d,1}-(\gamma+\theta_s)cs_{d,1}+\theta_s\left(w_{d,1}-w_{d,2}+cs_{d,2}\right)}{2c_{d,1}} \tag{B-3}$$

$$x^*_{d,2} = \frac{\gamma\left(w_{d,2}-cs_{d,2}\right)+\theta_s\left(w_{d,2}-w_{d,1}+cs_{d,1}-cs_{d,2}\right)}{2c_{d,2}} \tag{B-4}$$

Appendix C. Scenario 2

For proving concavity, hessian matrixes of π_{DS}, π_{FS} and π_A are calculated as follows:

$$H\left(\pi_A\left(p_{d,1},p_{d,2},p_{f,1},p_{f,2}\right)\right) = \begin{bmatrix} -2b-2\theta & 2\theta & 2\theta & 2\theta \\ 2\theta & -2b-2\theta & 2\theta & 2\theta \\ 2\theta & 2\theta & -2b-2\theta & 2\theta \\ 2\theta & 2\theta & 2\theta & -2b-2\theta \end{bmatrix} = \begin{bmatrix} -2b-4\theta & 0 & 0 & 0 \\ 0 & -2b-4\theta & 0 & 0 \\ 0 & 0 & -2b-4\theta & 0 \\ 0 & 0 & 0 & -2b-4\theta \end{bmatrix}$$

$$H(\pi_{DS}(x_{d,1},x_{d,2})) = \begin{bmatrix} -2c_{d,1} & 0 \\ 0 & -2c_{d,2} \end{bmatrix}$$

$H_{11}(\pi_{DS}(x_{d,1},x_{d,2})) = -2c_{d,1} < 0$ and $H_{22}(\pi_{DS}(x_{d,1},x_{d,2})) = 4c_{d,1}c_{d,2} > 0.$

$$H\left(\pi_{FS}\left(x_{f,1},x_{f,2}\right)\right) = \begin{bmatrix} -2c_{f,1} & 0 \\ 0 & -2c_{f,2} \end{bmatrix}$$

$H_{11}\left(\pi_{FS}\left(x_{f,1},x_{f,2}\right)\right) = -2c_{f,1} < 0$ and $H_{22}\left(\pi_{FS}\left(x_{f,1},x_{f,2}\right)\right) = 4c_{f,1}c_{f,2} > 0.$and

$H_{11}\left(\pi_A\left(p_{d,1},p_{d,2},p_{f,1},p_{f,2}\right)\right) = -2b - 4\theta < 0,\ H_{22}\left(\pi_A\left(p_{d,1},p_{d,2},p_{f,1},p_{f,2}\right)\right) = 4b^2+16b\theta+16\theta^2 > 0,\ H_{33} = -8b^3-48b^2\theta-96b\theta^2 - 64\theta^3 < 0,\ H_{44}\left(\pi_A\left(p_{d,1},p_{d,2},p_{f,1},p_{f,2}\right)\right) = 16b^4+256\theta^4+128b^3\theta+384b^2\theta^2+512b\theta^3 > 0.$

Appendix D. Scenario 2

$$p^*_{d,1} = \frac{a(\alpha\beta(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)(c_0+w_{d,1})+\gamma x_{d,1}(b-\theta)+\theta_s x_{d,1}(b-4\theta)+\left(x_{d,2}+x_{f,1}+x_{f,2}\right)(\gamma\theta-b\theta_s)}{2\left(b^2-4\theta^2\right)} \tag{D-1}$$

$$p^*_{d,2} = \frac{a(-(-1+\alpha)\beta(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)\left(c_0+w_{d,2}\right)+(\gamma\theta-b\theta_s)\left(x_{d,1}+x_{f,1}+x_{f,2}\right)+x_{d,2}\gamma(b-\theta)+\theta_s x_{d,2}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \quad \text{(D-2)}$$

$$p^*_{f,1} = \frac{a(-\alpha(-1+\beta)(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)\left(c_0+w_{f,1}\right)+(\gamma\theta-b\theta_s)\left(x_{d,1}+x_{d,2}+x_{f,2}\right)+\gamma x_{f,1}(b-\theta)+\theta_s x_{f,1}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \quad \text{(D-3)}$$

$$p^*_{f,2} = \frac{ab(-1+\alpha)(-1+\beta)+a(-1+2\alpha+2\beta-2\alpha\beta)\theta+\left(b^2-4\theta^2\right)\left(c_0+w_{f,2}\right)+(\gamma\theta-b\theta_s)\left(x_{d,1}+x_{d,2}+x_{f,1}\right)+(\gamma(b-\theta)+(b-4\theta)\theta_s)x_{f,2}}{2\left(b^2-4\theta^2\right)} \quad \text{(D-4)}$$

where:

$$x^*_{d,1} = \frac{\gamma w_{d,1}-(\gamma+\theta_s)cs_{d,1}+\theta_s\left(w_{d,1}-w_{d,2}+cs_{d,2}\right)}{2c_{d,1}} \quad \text{(D-5)}$$

$$x^*_{d,2} = \frac{\gamma\left(w_{d,2}-cs_{d,2}\right)+\theta_s\left(w_{d,2}-cs_{d,2}+cs_{d,1}-w_{d,1}\right)}{2c_{d,2}} \quad \text{(D-6)}$$

$$x^*_{f,1} = \frac{\gamma w_{f,1}-(\gamma+\theta_s)cs_{f,1}+\theta_s\left(w_{f,1}-w_{f,2}+cs_{f,2}\right)}{2c_{f,1}} \quad \text{(D-7)}$$

$$x^*_{f,2} = \frac{\gamma\left(w_{f,2}-cs_{f,2}\right)+\theta_s\left(w_{f,2}-w_{f,1}+cs_{f,1}-cs_{f,2}\right)}{2c_{f,2}} \quad \text{(D-8)}$$

Appendix E. Scenario 3

To show concavity, hessian matrixes of π_{DS}, π_{FS}, and π_A are examined as follows:

$$H(\pi_{DS}(x_{d,1},x_{d,2})) = \begin{bmatrix} -2c_{d,1} & 0 \\ 0 & -2c_{d,2} \end{bmatrix}$$

$H_{11}(\pi_{DS}(x_{d,1},x_{d,2})) = -2c_{d,1} < 0$ *and* $H_{22}(\pi_{DS}(x_{d,1},x_{d,2})) = 4c_{d,1}c_{d,2} > 0.$

$$H\left(\pi_{FS}\left(x_{f,1},x_{f,2}\right)\right) = \begin{bmatrix} -2c_{f,1} & 0 \\ 0 & -2c_{f,2} \end{bmatrix}$$

$H_{11}\left(\pi_{FS}\left(x_{f,1},x_{f,2}\right)\right) = -2c_{f,1} < 0$ *and* $H_{22}\left(\pi_{FS}\left(x_{f,1},x_{f,2}\right)\right) = 4c_{f,1}c_{f,2} > 0$ and

$$H\left(\pi_A\left(p_{d,1},p_{d,2},p_{f,1},p_{f,2}\right)\right) = \begin{bmatrix} -2b-2\theta & 2\theta & 2\theta & 2\theta \\ 2\theta & -2b-2\theta & 2\theta & 2\theta \\ 2\theta & 2\theta & -2b-2\theta & 2\theta \\ 2\theta & 2\theta & 2\theta & -2b-2\theta \end{bmatrix} = \begin{bmatrix} -2b-4\theta & 0 & 0 & 0 \\ 0 & -2b-4\theta & 0 & 0 \\ 0 & 0 & -2b-4\theta & 0 \\ 0 & 0 & 0 & -2b-4\theta \end{bmatrix}$$

$$H_{11}\left(\pi_A\left(p_{d,1},p_{d,2},p_{f,1},p_{f,2}\right)\right) = -2b-4\theta<0,$$
$$H_{22}\left(\pi_A\left(p_{d,1},p_{d,2},p_{f,1},p_{f,2}\right)\right)$$
$$=4b^2+16b\theta+16\theta^2>0,\ H_{33}$$
$$=-8b^3-48b^2\theta-96b\theta^2$$
$$-64\theta^3<0,\ H_{44}\left(\pi_A\left(p_{d,1},p_{d,2},p_{f,1},p_{f,2}\right)\right)$$
$$=16b^4+256\theta^4+128b^3\theta+384b^2\theta^2+512b\theta^3>0.$$

Appendix F. Scenario 3

$$p_{d,1}=\frac{a(\alpha\beta(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)c_0(1-t_a)+\left(b^2-4\theta^2\right)w_{d,1}+(\gamma\theta-b\theta_s)\left(x_{d,2}+x_{f,1}+x_{f,2}\right)+\gamma x_{d,1}(b-\theta)+\theta_s x_{d,1}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \tag{F-1}$$

$$p_{d,2}=\frac{a(-(-1+\alpha)\beta(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)c_0(1-t_a)+\left(b^2-4\theta^2\right)w_{d,2}+(\gamma\theta-b\theta_s)\left(x_{d,1}+x_{f,1}+x_{f,2}\right)+\gamma x_{d,2}(b-\theta)+\theta_s x_{d,2}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \tag{F-2}$$

$$p_{f,1}=\frac{a(-\alpha(-1+\beta)(b-2\theta)+\theta)+\left(b^2-4\theta^2\right)c_0(1-t_a)+\left(b^2-4\theta^2\right)w_{f,1}+(\gamma\theta-b\theta_s)(x_{d,1}+x_{d,2}+x_{f,2}\big)+\gamma x_{f,1}(b-\theta)+\theta_s x_{f,1}(b-4\theta)}{2\left(b^2-4\theta^2\right)} \tag{F-3}$$

$$p_{f,2}=\frac{ab(-1+\alpha)(-1+\beta)+a(-1+2\alpha+2-2\alpha\beta)\theta+\left(b^2-4\theta^2\right)c_0(1-t_a)+\left(b^2-4\theta^2\right)w_{f,2}+(\gamma\theta-b\theta_s)(x_{d,1}+x_{d,2}+x_{f,1}\big)+(\gamma(b-\theta)+\theta_s(b-4\theta))x_{f,2}}{2\left(b^2-4\theta^2\right)} \tag{F-4}$$

where:

$$x^*_{d,1}=\frac{(\gamma+\theta_s)cs_{d,1}(-1+t_{d,1})+\gamma w_{d,1}+\theta_s(w_{d,1}-w_{d,2}-cs_{d,2}(-1+t_{d,2}))}{2c_{d,1}} \tag{F-5}$$

$$x^*_{d,2}=\frac{\gamma(w_{d,2}-cs_{d,2}(1-t_{d,2}))+\theta_s(w_{d,2}-w_{d,1}+cs_{d,1}(1-t_{d,1})-cs_{d,2}(1-t_{d,2}))}{2c_{d,2}} \tag{F-6}$$

$$x^*_{f,1}=\frac{\gamma w_{f,1}-(\gamma+\theta_s)cs_{f,1}\left(1+t_{f,1}\right)+\theta_s\left(w_{f,1}-w_{f,2}+cs_{f,2}\left(1+t_{f,2}\right)\right)}{2c_{f,1}} \tag{F-7}$$

$$x^*_{f,2}=\frac{\gamma\left(w_{f,2}-cs_{f,2}\left(1+t_{f,2}\right)\right)+\theta_s\left(w_{f,2}-w_{f,1}+cs_{f,1}\left(1+t_{f,1}\right)-cs_{f,2}\left(1+t_{f,2}\right)\right)}{2c_{f,2}} \tag{F-8}$$

References

[1] L. Xu, et al., Molecular/polymeric metallaynes and related molecules: solar cell materials and devices, Coord. Chem. Rev. 15 (2018) 233–257.
[2] M. Iqbal, et al., Optimization classification, algorithms and tools for renewable energy: a review, Renew. Sustain. Energy Rev. 39 (2014) 640–654.
[3] J. Praveen, V. VijayaRamaraju, Materials for optimizing efficiencies of solar photovoltaic panels, Mater. Today. Proc. 4 (2017) 5233–5238.
[4] P. Kumavat, et al., An overview on basics of organic and dye sensitized solar cells, their mechanism and recent improvements, Renew. Sustain. Energy Rev. 78 (2017) 1262–1287.
[5] G. Richhariya, et al., Natural dyes for dye sensitized solar cell: a review, Renew. Sustain. Energy Rev. 69 (2017) 705–718.
[6] M.B. de la Mora, et al., Materials for downconversion in solar cells: perspectives and challenges, Sol. Energy Mater. Sol. Cells 165 (2017) 59–71.
[7] E. Kabir, et al., Solar energy: potential and future prospects, Renew. Sustain. Energy Rev. 82 (2018) 894–900.
[8] B. Parida, et al., A review of solar photovoltaic technologies, Renew. Sustain. Energy Rev. 15 (2011) 1625–1636.
[9] P.G.V. Sampaio, M.O.A. Gonzalez, Photovoltaic solar energy: conceptual framework, Renew. Sustain. Energy Rev. 74 (2017) 590–601.
[10] Z. Chen, I. Su S-I, Photovoltaic supply chain coordination with strategic consumers in China, Renew. Energy 68 (2014) 236–244.
[11] Z. Basiri, J. Heydari, A mathematical model for green supply chain coordination with substitutable products, J. Clean. Prod. 145 (2017) 232–249.
[12] M.D. Chatzisideris, et al., Cost-competitiveness of organic photovoltaics for electricity self-consumption at residential buildings: a comparative study of Denmark and Greece under real market conditions, Appl. Energy 208 (2017) 471–479.
[13] A. Hafezalkotob, Competition of domestic manufacturer and foreign supplier under sustainable development objectives of government, Appl. Math. Comput. 292 (2017) 294–308.
[14] A. Chauhan, R.P. Saini, A review on Integrated Renewable Energy System based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control, Renew. Sustain. Energy Rev. 38 (2014) 99–120.
[15] D. Yang, T. Xiao, Pricing and green level decisions of a green supply chain with governmental interventions under fuzzy uncertainties, J. Clean. Prod. 149 (2017) 1174–1187.
[16] A. Hafezalkotob, Competition of two green and regular supply chains under environmental protection and revenue seeking policies of government, Comput. Ind. Eng. 82 (2015) 103–114.
[17] J.-B. Sheu, Bargaining framework for competitive green supply chains under governmental financial intervention, Transport. Res. Part E 47 (2011) 573–592.
[18] K.H. Solangi, et al., A review on global solar energy policy, Renew. Sustain. Energy Rev. 15 (2011) 2149–2163.
[19] R. Sawhney, et al., Empirical analysis of the solar incentive policy for Tennessee solar value chain, Appl. Energy 131 (2014) 368–376.
[20] A. Hafezalkotob, Competition, cooperation, and coopetition of green supply chains under regulations on energy saving levels, Transport. Res. Part E 97 (2017) 228–250.
[21] S.R. Madani, M. Rasti-Barzoki, Sustainable Supply chain management with pricing, greening and governmental tariffs determining strategies: a game-theoretic approach, Comput. Ind. Eng. 105 (2017) 287–298.
[22] Y.H. Zhang, Y. Wang, The impact of government incentive on the two competing supply chains under the perspective of Corporation Social Responsibility: a case study of Photovoltaic industry, J. Clean. Prod. 154 (2017) 102–113.
[23] J.-B. Sheu, Y.J. Chen, Impact of government financial intervention on competition among green supply chains, Int. J. Prod. Econ. 138 (2012) 201–213.
[24] Z. Chen, I. Su S-I, Multiple competing photovoltaic supply chains: modeling, analyses and policies, J. Clean. Prod. 174 (2018) 1274–1287.
[25] Z. Qiang, et al., China's solar photovoltaic policy: an analysis based on policy instruments, Appl. Energy 129 (2014) 308–319.
[26] X.-g. Zhao, et al., The turning point of solar photovoltaic industry in China: will it come? Renew. Sustain. Energy Rev. 41 (2015) 178–188.
[27] A. Goetzberger, V.U. Hoffmann, Photovoltaic Solar Energy Generation Handbook, Springer, Germany, 2005.
[28] H. Zou, et al., Market dynamics, innovation, and transition in China's solar photovoltaic (PV) industry: a critical review, Renew. Sustain. Energy Rev. 69 (2017) 197–206.
[29] G. Xie, Modeling decision processes of a green supply chain with regulation on energy saving level, Comput. Oper. Res. 54 (2015) 266–273.
[30] F. Jia, et al., Global photovoltaic industry: an overview and national competitiveness of Taiwan, J. Clean. Prod. 126 (2016) 550–562.
[31] N.H. Tiep, et al., Recent advances in improving the stability of perovskite solar cells, Energy Mater 6 (3) (2016) 1501420.
[32] Z. Chen, I. Su S-I, The joint bargaining coordination in a photovoltaic supply chain, J. Renew. Sustain. Energy 8 (2016), https://doi.org/10.1063/1.4950990, 035904.
[33] M.A. Green, et al., Solar Cell Efficiency Tables (Version 50) vol. 25, Wiley, 2017, pp. 668–676.
[34] Y.-W. Chen, et al., A particle swarm approach for optimizing a multi-stage closed loop supply chain for the solar cell industry, Robot. Comput. Integrated Manuf. 43 (2017) 111–123.
[35] E. Dehghani, et al., Resilient solar photovoltaic supply chain network design under business-as-usual and hazard uncertainties, Comput. Chem. Eng. 111 (2018) 288–310.
[36] E. Dehghani, et al., Robust design and optimization of solar photovoltaic supply chain in an uncertain environment, Energy 142 (2018) 139–156.
[37] Z. Chen, I. Su S-I, Social welfare maximization with the least subsidy: photovoltaic supply chain equilibrium and coordination with fairness concern, Renew. Energy 132 (2019) 1332–1347.
[38] M. Kharaji Manouchehrabadi, S. Yaghoubi, Solar cell supply chain coordination and competition under government intervention, J. Renew. Sustain. Energy 11 (2019), 023701.