Design of Photovoltaics-Based Manufacturing System Using Computer-Aided Design

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Abstract

Carbon dioxide has increased drastically in the last decades due to energy production, exacerbating the global warming problem. To address this issue, researchers have focused on developing energy production technologies from renewable sources. From the renewable energy sources, solar has shown great promise chiefly due to its high availability. The conversion of solar energy into electricity (photovoltaics) requires specialized equipment such as solar cells, and a coordinated supply chain to be able to manufacture this technology in a sustainable way and at low cost. Therefore, this chapter proposes an approach based on mathematical programming for the optimal design of a solar photovoltaics manufacturing system considering diverse criteria linked to economic and environmental variables such as minimum sustainable price, transportation costs, and technical limits. In addition, the dependence of the minimum sustainable price over inflation, electricity price, and weighted average capital cost is analyzed, showing that a variation of minimum sustainable price could significantly change the manufacturing supply chain topology.

3.1 Introduction

Due to an increase in worldwide energy demand and high associated emissions, solar energy has become an attractive low-emission alternative to satisfy electricity demands, due in part to its high availability and null operational emissions. In fact, Michael et al. [1] stated that the total energy consumed in 1 year is lower than 1 h of solar energy. In addition, solar energy has been used mainly by photovoltaic (PV) generation systems [2], with the PV having increased around 40% in recent years as was mentioned by to Razykov et al. [3] and Maycock [4]. Furthermore, Loomis et al. [5] reported an increase of 39% between 2013 and 2014 in the United States; nevertheless, other countries, such as China, have increased their PV installations even at higher rates.

Historically, one of the main barriers for solar PV deployment has been its relative high costs. However, significant cost reductions have been recently achieved; for instance, cost for first generation of solar cells rounded $US 3.50/W, and recently this cost has reached $US 0.50/W [6]. This cost reduction has been caused by a global expansion of the solar energy industry [7]. Such global expansion in deployment and manufacturing consists of optimally producing in a country, while obtaining the different input materials from within, or abroad, and selling the goods also either locally or abroad. In this sense, manufacturing costs and tariffs imposed by countries play a crucial role in the design of the manufacturing supply chain system design. Several studies have proposed different approaches to address the PV manufacturing systems design to satisfy the present and future requirements for the PV industry. For instance, Powell et al. [8] developed a model to obtain the minimum sustainable price (MSP) of a virtually integrated manufacturing company considering the factory capital expenditure, internal rate of return, and weighted average capital cost (WACC), among other variables, in a given PV manufacturing system. Loomis and Aldeman [5] considered different PV systems under several production capacities to examine the number of jobs and the economic impact associated with the manufacturing system. Kim and Jeong [2] developed two models to help PV system establish supply chain planning to choose recycling policies under several circumstances. Nevertheless, most of the previous approaches do not consider the interactions between different countries which ought to include tariffs, typically used to protect small or local industries.

There are some works that have considered the interaction between different countries in PV manufacturing system. For example, Castellanos et al. [9] developed a techno-economic tool and strategy for the PV manufacturing system design considering the diverse value of tariff and transportation cost. Such approach allows for the evaluation of different tariff values between several countries, but important factors such as inflation or electricity price are considered constant. Under some situations, however, the deterministic solutions could be infeasible or suboptimal; hence, uncertainty analysis should be accounted for in supply chain analysis and design. Furthermore, uncertainty in economic parameters could seriously affect the manufacturing system performance since economic parameters are subject to variations due to both global and domestic issues (see [10] and [11]).

Regarding uncertainty in a PV manufacturing system, Dehghani et al. [12] developed an approach for the planning of PV supply chains considering uncertainty in the demand of annual solar energy, where uncertainty was taken into account via the generation of different scenarios. Similarly, Dehghani et al. [13] took into account diverse economic terms as uncertain parameters. Some of these uncertain parameters were the unit manufacturing cost and the unit inventory cost. However, no explicit consideration of the tariff between different countries was implemented [12, 13], which might be a drawback of the paper because the tariff level could affect strongly the final supply chain topology, as seen in Castellanos et al. [9].

As seen, works that have analyzed the PV manufacturing system design through mathematical models have considered diverse aspects such as tariff levels, manufacturing costs, and MSP computing, the interaction between different countries, and uncertainty in economic parameters. Most of them have used tools based on mathematical programming and other tools to evaluate important contributions in the PV manufacturing system design area. Therefore, this chapter presents a part of the model by Castellanos et al. [9] as well as alternatives to consider the uncertainty in that model through diverse computational tools.

3.2 Photovoltaic (PV) Manufacturing System Design

A solar PV module is composed of diverse components, such as the raw material (silicon) which is transformed into wafers, processed afterwards into cells, and assembled into the modules. All these processes are parts of a manufacturing system, which is affected by global and domestic factors.

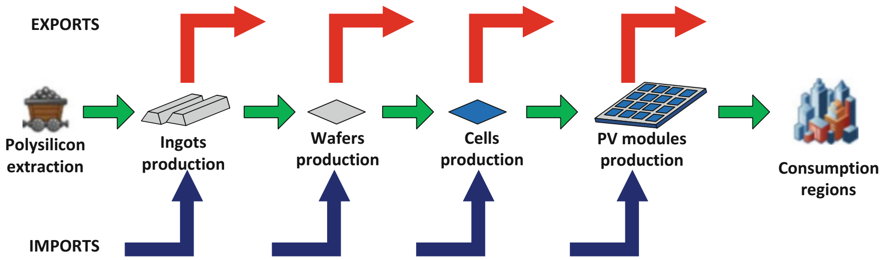

Fig. 3.1 General representation of the proposed PV manufacturing system

This chapter shows a mathematical programming model for analyzing the manufacturing design of PV modules considering external factors such as tariff due to exports and imports, inflation and electricity price, as well as internal factors such as transportation cost, manufacturing cost, and product and raw material prices, akin to that developed in Castellanos et al. [9], and expanded to incorporate uncertainty in a variety of values. Figure 3.1 shows a general representation of the proposed PV manufacturing system. The proposed photovoltaic manufacturing system takes into account silicon extraction and processing, ingots, wafers, solar cells, and PV modules production. The manufacturing system considers the interaction between local and global markets through exports and imports for all products (silicon, ingots, wafers, cells, and PV modules).

Once the PV manufacturing system is defined, the design problem can be stated as follows:

Given:

- Potential locations (global and local) for the manufacturing system's facilities
- Data for lower and upper bounds for electricity cost expected inflation and was a factor
- Distance between the potential manufacturing system nodes
- Transportation cost data for final and intermediate products
- Minimum sustainable price (MSP) dependence over processing capacity for each processing activity
- Data for demand regarding each product

Subject to:

- Constraints based on material balances for each manufacturing system node
- Limits for processing, transportation, exports, and imports in order to promote local production
- Constraints to define if exports are permitted

It is possible to obtain:

- The optimal manufacturing system topology (optimal selection for supply chain locations nodes)
- Production capacity value (W) for the different selected processing nodes
- Capacities (W) of manufactured goods to transport, export and import

It should be noted that the manufacturing system design can be obtained by optimizing one or several objective functions at once. These objective functions can be defined and selected depending on the focus to improve upon: whether economic, environmental, social, or technical performance.

3.3 The Mathematical Formulation for the PV Manufacturing System Design

The mathematical formulation for the PV manufacturing system requires a formulation of the mass balances at each node of the manufacturing system (i.e., polysilicon extraction and processing, ingots, wafers, cells, and PV modules manufacturing).

Equation (3.1) describes the balance in polysilicon extraction nodes with an inventory level at time t equal to previous inventory level, plus the amount of extracted polysilicon, minus the total polysilicon distributed to the international and domestic ingots producer nodes.

$$M_{n0,t}^{\text{inventory}} = M_{n0,t-1}^{\text{inventory}} + \left(\begin{array}{c} M_{n0,t}^{\text{extracted-local}} \\ - \sum\limits_{n1 \in N1} M_{n0,n1,t}^{\text{outlet-local}} - \sum\limits_{e1 \in E1} M_{j,e1,t}^{\text{export-international}} \end{array} \right), \quad \forall n0 \in N0, t \in T \tag{3.1}$$

Besides, Eq. (3.2) can be generalized for the ingot, wafer, cell, and PV modules production nodes. In this case, the nodes receive raw material from previous nodes, which can be sent to processing to obtain the good in which the nodes are specialized (ingots, wafers, cells, and PV modules)

$$G_{j,t}^{\text{inventory}} = G_{j,t-1}^{\text{inventory}} + \left(\begin{array}{c} \sum\limits_{i \in \text{PREVIOUS}} G_{i,j,t}^{\text{intlet-local}} + \sum\limits_{ei \in \text{EXPREVIOUS}} G_{ei,j,t}^{\text{import-international}} \\ -G_{j,t}^{\text{toprocessing-local}} \end{array} \right), \forall_{t \in T}^{j \in \text{NODE}} \tag{3.2}$$

Alike, Eq. (3.3) is used to model the production of ingots, wafer, cell, and PV modules production nodes. In this sense, the nodes can produce a given good, which can be distributed to international nodes or used for domestic production.

$$G_{j,t}^{\text{inventory}} = G_{j,t-1}^{\text{inventory}} + \left(\begin{array}{c} G_{j,t}^{\text{produced-local}} \\ - \sum\limits_{k \in \text{NEXT}} G_{j,k,t}^{\text{outlet-local}} - \sum\limits_{ek \in \text{EXTNEXT}} G_{j,ek,t}^{\text{export-international}} \end{array} \right), \ \forall_{t \in T}^{j \in \text{NODE}} \tag{3.3}$$

As shown in Eq. (3.4), other constraints are focused in including constraints that limit transportation, production, and imports and exports. Constraints in exports limit the amount of exported good and is equal to zero when the good's MSP, plus the imposed tariff and unit transportation cost for the locally produced good, is greater than the good's price plus the imposed tariff and unit transportation cost for the externally produced good. Otherwise, the amount of exported goods could take values between zero and a maximum limit.

$$\begin{array}{ll} \left[\begin{array}{l} \qquad\qquad\qquad Y_{j,ek}^{\text{exported-good}} \\ MSP_{j,ek}^{\text{exported-good}} \cdot \left(1 + \text{Tariff}_{j,ek}^{\text{exported-good}}\right) + TC_{j,ek}^{\text{exported-good}} \cdot d_{j,ek} \\ \qquad\qquad\qquad \leq \\ \dfrac{\sum\limits_{ej} MSP_{ej,ek}^{\text{global-good}} \cdot \left(1 + \text{Tariff}_{ej,ek}^{\text{global-good}}\right) + TC_{ej,ek}^{\text{global-good}} \cdot d_{ej,ek}}{\text{Total global nodes } EJ} \\ G_{j,ek,t}^{\text{exported-good}} \leq^{\text{Max}} G_{j,ek,t}^{\text{exported-good}} \end{array} \right] & \\ \qquad\qquad\qquad \vee & \begin{array}{l} j \in \text{Node} \\ \forall\ ek \in \text{Node} - to - \text{Export} \\ t \in T \end{array} \\ \left[\begin{array}{l} \qquad\qquad\qquad \neg Y_{j,ek}^{\text{exported-good}} \\ MSP_{j,ek}^{\text{exported-good}} \cdot \left(1 + \text{Tariff}_{j,ek}^{\text{exported-good}}\right) + TC_{j,ek}^{\text{exported-good}} \cdot d_{j,ek} \\ \qquad\qquad\qquad \geq \\ \dfrac{\sum\limits_{ej} MSP_{ej,ek}^{\text{global-good}} \cdot \left(1 + \text{Tariff}_{ej,ek}^{\text{global-good}}\right) + TC_{ej,ek}^{\text{global-good}} \cdot d_{ej,ek}}{\text{Total global nodes } EJ} \\ G_{j,ek,t}^{\text{exported-good}} = 0 \end{array} \right] & \end{array} \tag{3.4}$$

In Eqs. (3.1), (3.2), (3.3), and (3.4), index j represents supply chain nodes in which the balance is carried out. Indexes i and ei represent the processing stage previous to stage j. Indexes k and ek represent the following processing stage in the PV manufacturing system.

Further equations ought to be considered in the mathematical model to introduce decision variables or objective functions for the PV manufacturing system.

Equation (3.5) depicts the global MSP, which takes into account the MSP for each node in the manufacturing system. Note that global MSP considers only the terms with a real contribution to the PV manufacturing system, such that if a processing node is not used, then that processing node does not contribute to the global MSP calculated.

$$MSP^{\text{global}} = \begin{array}{c} \sum_{n0} MSP_{n0}^{\text{Step0}} + \sum_{n1} MSP_{n1}^{\text{Step1}} + \sum_{n2} MSP_{n2}^{\text{Step2}} \\ + \sum_{n3} MSP_{n3}^{\text{Step3}} + \sum_{n4} MSP_{n4}^{\text{Step4}} \end{array} \tag{3.5}$$

Equation (3.6) states the transportation cost to markets considering the unit transportation cost from local and international processing plants to their end markets, considering the distance and the amount of transported goods.

$$TC^{\text{Markets}} = \begin{array}{c} \sum_{n4} \sum_{n5} TP_{n4,n5}^{\text{local}-PV} \cdot d_{n4,n5}^{\text{local}} \cdot TC^{\text{local-markets}} \\ + \sum_{e4} \sum_{n5} TP_{e4,n5}^{\text{international}-PV} \cdot d_{e4,n5}^{\text{international}} \cdot TC^{\text{international-markets}} \end{array} \tag{3.6}$$

Total local production, given in Eq. (3.7), is considered because the local manufacturing system can manufacture in each processing stage.

$$P^{\text{Local}} = \begin{array}{c} P^{\text{Local}-Si} + P^{\text{Local}-\text{ingot}} + P^{\text{Local}-\text{wafer}} \\ + P^{\text{Local}-\text{cells}} + P^{\text{Local}-PV} \end{array} \tag{3.7}$$

In addition, export costs account for the transportation costs caused by exporting goods (ingots, silicon, wafers, or cells) and the associated tariff, as described in Eq. (3.8).

$$TC^{\text{Exports}} = \begin{array}{c} \sum_{n0} \sum_{e1} TC_{n0,e1}^{\text{Export}-Si} + \sum_{n1} \sum_{e2} TC_{n1,e2}^{\text{Export}-\text{ingot}} \\ + \sum_{n2} \sum_{e3} TC_{n2,e3}^{\text{Export}-\text{wafer}} + \sum_{n3} \sum_{e4} TC_{n3,e4}^{\text{Export}-\text{cells}} \end{array} \tag{3.8}$$

Furthermore, the PV manufacturing system considers import costs along with the transportation costs for imported materials (ingots, silicon, wafers, or cells), and paid tariffs due to the amount and type of exported materials, as shown in Eq. (3.9).

$$TC^{\text{Imports}} = \begin{array}{c} \sum_{e0} \sum_{n1} TC_{e0,n1}^{\text{Imports}-Si} + \sum_{e1} \sum_{n2} TC_{e1,n2}^{\text{Imports}-\text{ingot}} \\ + \sum_{e2} \sum_{n3} TC_{e2,n3}^{\text{Imports}-\text{wafer}} + \sum_{e3} \sum_{n4} TC_{e3,n4}^{\text{Imports}-\text{cells}} \end{array} \tag{3.9}$$

Equation (3.10) states that total local transportation costs are equal to the sum of transportation costs between internal nodes which consists of a unitary transportation cost multiplied by the distance between involved nodes and the transported amount of material.

$$TC^{\text{Local}} = \begin{aligned}[t] & \sum_{n0}\sum_{n1} TP_{n0,n1}^{\text{Local}-Si} \cdot d1_{n0,n1}^{\text{Local}} \cdot TC_{n0,n1}^{\text{Local}-Si} \\ & + \sum_{n1}\sum_{n2} TP_{n1,n2}^{\text{Local}-\text{ingot}} \cdot d2_{n1,n2}^{\text{Local}} \cdot TC_{n1,n2}^{\text{Local}-\text{ingot}} \\ & + \sum_{n2}\sum_{n3} TP_{n2,n3}^{\text{Local}-\text{wafer}} \cdot d3_{n2,n3}^{\text{Local}} \cdot TC_{n2,n3}^{\text{Local}-\text{wafer}} \\ & + \sum_{n3}\sum_{n4} TP_{n3,n4}^{\text{Local}-\text{cells}} \cdot d4_{n3,n4}^{\text{Local}} \cdot TC_{n3,n4}^{\text{Local}-\text{cells}} \end{aligned} \tag{3.10}$$

The decision variable could be grouped in a single objective function to get the optimal PV manufacturing system topology. Each of the decision variables can be included in a compromise function considering different priorities between them. A compromise function has been formulated for different problems with several objectives in works such as those by Castellanos et al. [9], Sanchez-Bautista et al. [14], and Fuentes-Cortes et al. [15]. Taking into account the decision variables presented in Eqs. (3.5), (3.6), (3.7), (3.8), (3.9), and (3.10), the compromise function is given in Eq. (3.11) as follows:

$$\begin{aligned} OF^{\text{composed}} = & +\omega_{MSP} \cdot \frac{{}^{\text{Upper}}MSP^{\text{global}} - MSP^{\text{global}}}{{}^{\text{Upper}}MSP^{\text{global}} - {}^{\text{Lower}}MSP^{\text{global}}} \\ & + \omega_{TCM} \cdot \frac{{}^{\text{Upper}}TC^{\text{Markets}} - TC^{\text{Markets}}}{{}^{\text{Upper}}TC^{\text{Markets}} - {}^{\text{Lower}}TC^{\text{Markets}}} \\ & + \omega_{LP} \cdot \frac{P^{\text{Local}} - {}^{\text{Lower}}P^{\text{Local}}}{{}^{\text{Upper}}P^{\text{Local}} - {}^{Lower}P^{\text{Local}}} \\ & + \omega_{TCE} \cdot \frac{{}^{\text{Upper}}TC^{\text{Exports}} - TC^{\text{Exports}}}{{}^{\text{Upper}}TC^{\text{Exports}} - {}^{\text{Lower}}TC^{\text{Exports}}} \\ & + \omega_{TCI} \cdot \frac{{}^{\text{Lower}}TC^{\text{Imports}} - TC^{\text{Imports}}}{{}^{\text{Upper}}TC^{\text{Imports}} - {}^{\text{Lower}}TC^{\text{Imports}}} \\ & + \omega_{LTC} \cdot \frac{{}^{\text{Upper}}TC^{\text{Local}} - TC^{\text{Local}}}{{}^{\text{Upper}}TC^{\text{Local}} - {}^{\text{Lower}}TC^{\text{Local}}} \end{aligned} \tag{3.11}$$

Equation (3.11) considers the normalized terms to limit the values of the objective function; in this way, if the target value for all decision variables is obtained, then the compromise solution tends toward 1, otherwise the value of the compromise solution would be near to zero 0.

3.4 Uncertainty in PV Manufacturing Systems Design

Works such as Dehghani et al. [12, 13] have considered uncertainty in diverse parameters when designing PV manufacturing systems. These works included uncertainty through diverse scenarios for economic terms as well as solar energy demand. Nevertheless, the uncertainty element could also be considered in other important parameters such as

Table 3.1 Upper and lower bounds for inflation, WACC, and electricity price

	Upper bound	Lower bound	Units
Inflation	0.07	0.02	%
WACC	0.16	0.08	Dimensionless
Electricity price	0.20	0.02	$US/kWh

inflation, electricity price, and WACC, since these parameters directly (and indirectly) affect manufacturing cost, raw material prices, MSP, and other economic terms.

Therefore, a methodology based on mathematical programming could consider the generation of several scenarios such as weighted-average cost of capital (WACC), inflation, and electricity price. These scenarios could be generated via a probability density function or Latin hypercube sampling, considering a uniform distribution as well as lower and upper limits as shown in Santibañez-Aguilar et al. [16]. This scenario generation can generate a representative uncertain space for all uncertain parameters, and it could be useful whether there is not a specific probability density function for them.

In order to show how the inflation, WACC, and electricity price could be related, we assumed a case study for Mexico to establish limits for inflation, WACC, and electricity price to generate random values, which should be between these two limits. It is worth noting that random values are generated per each location for the case of electricity price and WACC because these parameters could be different depending on each location. In addition, inflation is assumed to equal for all locations since PV manufacturing system is supposed for domestic production. Table 3.1 presents the upper and lower bound for inflation, WACC, and electricity price for the proposed case study.

In addition, Fig. 3.2a shows the relationship between inflation and WACC for each scenario and one of the supply chain nodes (e.g., 1 cells producer), while Fig. 3.2b illustrates the same relationship for all supply chain nodes (i.e., all cells producers). In this case, there are 32 manufacturing nodes where we assume one per state in Mexico. A virtually full uncertain space is met as seen in Fig. 3.2b, which indicates that scenarios are a good representation of the full uncertain space.

Figure 3.3a shows the inflation and WACC behavior regarding each of the modeled scenarios. Figure 3.3b elucidates how a scenario can have either high or low inflation values and yet have both high and low WACC values across different states in the same scenario. This behavior indicates that there is not a direct correlation between these parameters, and also a manufacturing system could be adjusted by taking into account the locations with different WACC values to improve its performance.

3.5 Adjust of Important Functions for the PV Manufacturing System

Another important stage in a model formulation is computing important functions in the PV manufacturing system such as that of MSP as a function of capacity. MSP is the price at which the net present value for a manufacturing process is equal to zero [17].

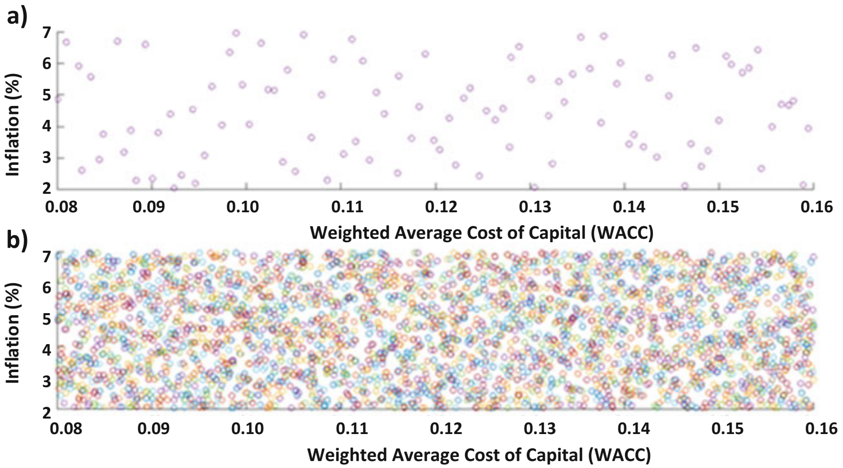

Fig. 3.2 A relationship between inflation and WACC for each scenario. (**a**) The case for one of the manufacturing system nodes, and (**b**) the case for all manufacturing system nodes (32 nodes)

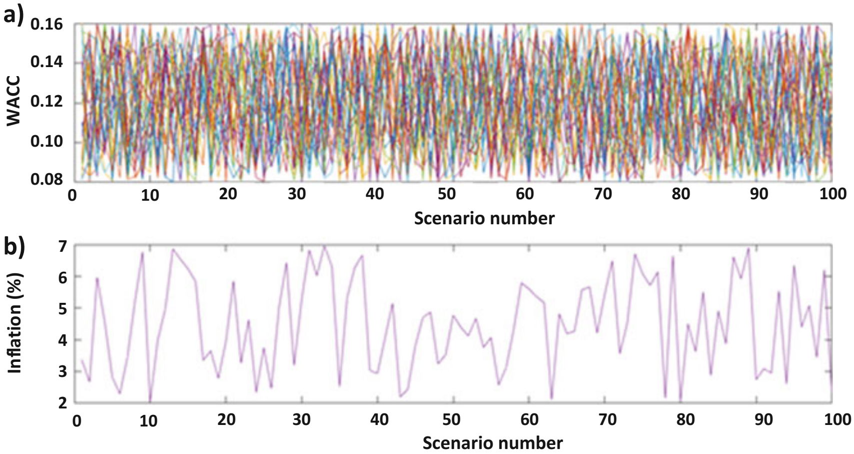

Fig. 3.3 The behavior of inflation and WACC values for each modeled scenario. (**a**) WACC values for different manufacturing system nodes at each scenario, (**b**) inflation values for the entire system at each scenario

This variable could be used to evaluate the performance of a manufacturing system by computing it according to a model presented by Powell et al. [8, 17] for a set of inflation, electricity prices, and WACC. This MSP model could be extended to obtain different MSP values for different inflation, electricity price, and WACC values, which can be useful for PV manufacturing system design under uncertainty. However, the MSP depends on production capacity which is a strongly nonlinear and no convex function, and its values should be first fit to be used in a mathematical programming approach.

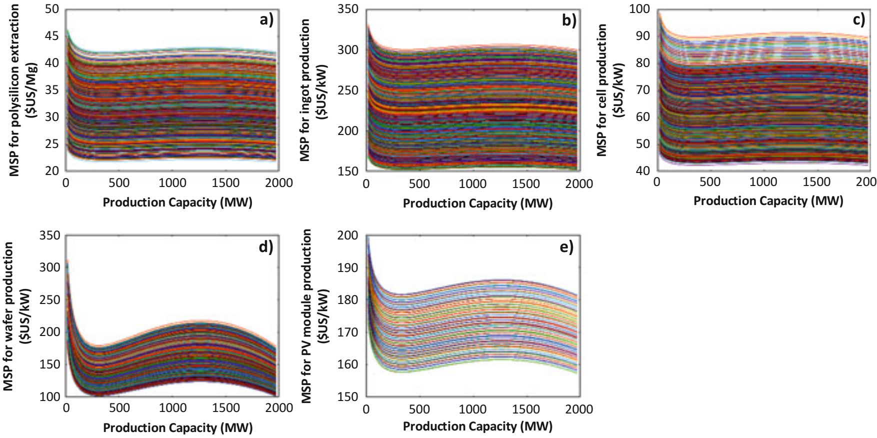

Fig. 3.4 MSP versus production capacity for the manufacturing system nodes under different sets of inflation, WACC, and electricity price values. Each line represents a different modeled scenario. (**a**) Polysilicon extraction and processing, (**b**) ingot production, (**c**) wafers production, (**d**) cells production, and (**e**) PV modules production

The MSP curve is recreated from Powell et al. [8] for several capacity values and processes, and curves are then segmented to find functions to be fit to. Castellanos et al. [9] carried out linear fits for functions of MSP versus capacity. Nevertheless, a linear adjust could be unrealistic in some cases. To address that potential shortcoming, a base function is obtained for MSP versus capacity, the data is then fit using a specialized software to obtain mathematical relationships with an acceptable correlation factor [18].

Figure 3.4 shows MSP versus capacity functions for different process stages in a PV manufacturing system, taking into account multiple values for inflation, WACC, and electricity prices. These variables have important effects in the MSP function. For instance, the MSP for polysilicon production changes from $US 25 to $US 47 per ton of extracted and processed silicon (based on 20 MW), which represents an 88% deviation from the lower bound. MSP value for PV modules could reach values of $US 0.180 and up to $US 0.200 per Watt, being 11% away from the lower limit. It is important to mention that the data fit could be deemed acceptable as the reported fit average errors varied between 2% and 7%.

3.6 Influence of Tariff Level in the PV Manufacturing System Topology

Regarding the tariff level in a PV manufacturing system, most of the previous works have not taken into account the interactions between different countries since that assumption could imply to introduce a tariff value for different combinations of goods and countries. Nevertheless, tariffs are shown to significantly alter PV system topology [9]. Castellanos et al. [9] proposed a TIT-4-TAT model, which considered

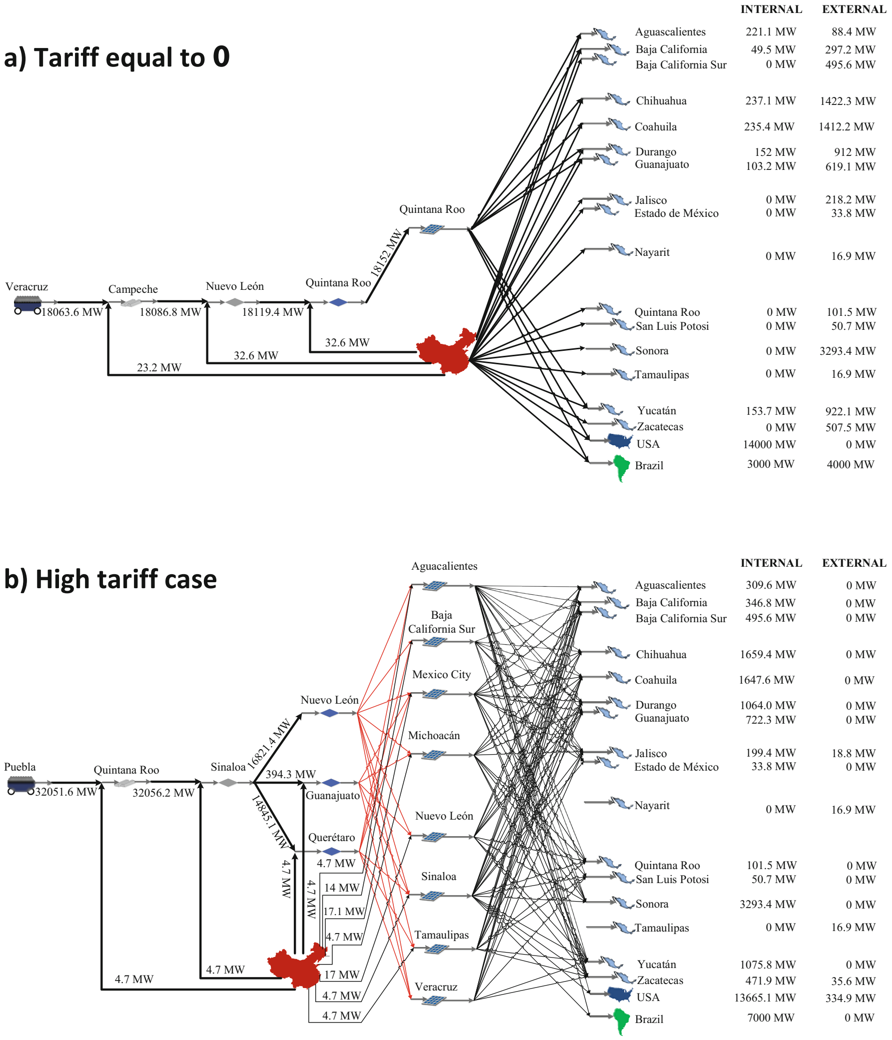

Fig. 3.5 PV manufacturing system topology under different tariff levels. (**a**) A case with no tariffs imposed between the countries China, the USA, Brazil, and Mexico. (**b**) The case where high tariffs are imposed between the same countries, and they retaliate in response with the same tariff level. (Figure based on Castellanos et al. [9])

two case studies with different assumptions in tariff levels for evaluation: a case where all tariffs were supposed to be zero and a case where different tariff levels were introduced for Mexico, Brazil, the USA, and China.

Figure 3.5 illustrates how a PV manufacturing system under the same considerations and different values for tariffs can be drastically affected. Figure 3.5a shows the supply chain configuration when the tariff was assumed equal to zero for all goods and countries, whereas Fig. 3.5b depicts the PV manufacturing system topology when a case with high tariff between countries was considered.

The comparison between no tariff and high tariff cases allows for the impact assessment of protectionist measures in the global PV supply chain. For instance, the high tariff case shows that imported and exported goods are reduced, but the number of PV modules producers increase from one to eight. Moreover, the interconnections between consumption regions are significantly increased, which similarly increases transportation costs. Also, the PV solar modules demand is almost met by domestic production. Lastly, the effect of tariffs is crucial to a system topology because if a tariff war were to occur, the final products would be more expensive for the consumers due to the imposed tariff values, transportation costs, and forced sub-optimal local manufacturing.

3.7 Conclusions

As discussed, there are different stages and aspects to consider in the PV manufacturing system design problem. These aspects could be addressed separately in different approaches such as Castellanos et al. [9] involved different tariff level, Powell et al. [8] proposed a model to compute the MSP, or Dehghani et al. [12] included uncertain parameters and interactions between different countries. However, a methodology able to consider all these aspects simultaneously could help us to introduce the PV energy to the global market more quickly.

In addition, different presented sections show that a combination of diverse aspects such as computing of MSP over inflation and electricity price, adjusting of MSP versus capacity function, or the optimal planning though a mathematical programming model could be accomplished in a sequential manner since some of these are unrelated to each other.

Furthermore, forecast projections need to be altered if market conditions are changed since presented mathematical model in current chapter and Castellanos et al. [9] is deterministic. These modifications could be the new tariff for steel and glass between the USA and China. In this case, a stochastic formulation could be useful to determine the supply chain able to support the variations.

Lastly, local and global PV manufacturing system designs depend on the specific objectives or decision variables being considered; nevertheless, some of the most important ones due to their influence in the supply chain were presented in the this chapter.

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References

1. J.J. Michael, I. Selvarasan, R. Goic, Fabrication, experimental study, and testing of a novel photovoltaic module for photovoltaic thermal applications. Renew. Energy **90**, 95–104 (2016)
2. S. Kim, B. Jeong, Closed-loop supply chain planning model for a photovoltaic system manufacturer with internal and external recycling. Sustainability **8**(7), 596 (2016)
3. T.M. Razykov, C.S. Ferekides, D. Morel, E. Stefanakos, H.S. Ullal, H.M. Upadhyaya, Solar photovoltaic electricity: current status and future prospects. Sol. Energy **85**(8), 1580–1608 (2011)
4. P.D. Maycock, PV news. PV Energy Syst. **29**, 108–119 (2010)
5. D.G. Loomis, J.H. Jo, M.R. Aldeman, Economic impact potential of solar photovoltaics in Illinois. Renew. Energy **87**, 253–258 (2016)
6. P. Díaz, R. Peña, J. Muñoz, C.A. Arias, D. Sandoval, Field analysis of solar PV-based collective systems for rural electrification. Energy **36**(5), 2509–2516 (2011)
7. A.C. Goodrich, D.M. Powell, T.L. James, M. Woodhouse, T. Buonassisi, Assessing the drivers of regional trends in solar photovoltaic manufacturing. Energy Environ. Sci. **6**(10), 2811–2821 (2013)
8. D.M. Powell, R. Fu, K. Horowitz, P.A. Basore, M. Woodhouse, T. Buonassisi, The capital intensity of photovoltaics manufacturing: a barrier to scale and opportunity for innovation. Energy Environ. Sci. **8**(12), 3395–3408 (2015)
9. S. Castellanos, J.E. Santibañez-Aguilar, B.B. Shapiro, D.M. Powell, I.M. Peters, T. Buonassisi, . . ., A. Flores-Tlacuahuac, Sustainable silicon photovoltaics manufacturing in a global market: a techno-economic, tariff, and transportation framework. Appl. Energy **212**, 704–719 (2018)
10. C. Norberto, C.N. Gonzalez-Brambila, Y. Matsumoto, Systematic analysis of factors affecting solar PV deployment. J. Energy Storage **6**, 163–172 (2016)
11. E.R. Shouman, E.T. El Shenawy, N.M. Khattab, Market financial analysis and cost performance for photovoltaic technology through international and national perspective with a case study for Egypt. Renew. Sust. Energ. Rev. **57**, 540–549 (2016)
12. E. Dehghani, M.S. Jabalameli, A. Jabbarzadeh, Robust design and optimization of the solar photovoltaic supply chain in an uncertain environment. Energy **142**, 139–156 (2018a)
13. E. Dehghani, M.S. Jabalameli, A. Jabbarzadeh, M.S. Pishvaee, Resilient solar photovoltaic supply chain network design under business-as-usual and hazard uncertainties. Comput. Chem. Eng. **111**, 288–310 (2018b)
14. A.F. Sánchez-Bautista, J.E. Santibañez-Aguilar, L.F. Fuentes-Cortes, A. Flores-Tlacuahuac, J.M. Ponce-Ortega, A multi-stakeholder approach for the optimal planning of sustainable energy systems. ACS Sustain. Chem. Eng. **6**, 9451–9460 (2018)
15. L.F. Fuentes-Cortés, Y. Ma, J.M. Ponce-Ortega, G. Ruiz-Mercado, V.M. Zavala, Valuation of water and emissions in energy systems. Appl. Energy **210**, 518–528 (2018)
16. J.E. Santibañez-Aguilar, G. Guillen-Gosálbez, R. Morales-Rodriguez, L. Jiménez-Esteller, A.J. Castro-Montoya, J.M. Ponce-Ortega, Financial risk assessment and optimal planning of biofuels supply chains under uncertainty. Bioenergy Res. **9**(4), 1053–1069 (2016)
17. D.M. Powell, M.T. Winkler, A. Goodrich, T. Buonassisi, Modeling the cost and minimum sustainable price of crystalline silicon photovoltaic manufacturing in the United States. IEEE J. Photovoltaics **3**(2), 662–668 (2013)
18. ALAMO, ALAMO software (2018), https://minlp.com/alamo. Accessed Feb 2019