Applied Energy 212 (2018) 704–719

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Sustainable silicon photovoltaics manufacturing in a global market: A techno-economic, tariff and transportation framework

Sergio Castellanos[a,b,c,d,*], José E. Santibañez-Aguilar[e,*], Benjamin B. Shapiro[f], Douglas M. Powell[g], Ian M. Peters[h], Tonio Buonassisi[h], Daniel M. Kammen[b,c,f], Antonio Flores-Tlacuahuac[e]

[a] Berkeley Energy & Climate Institute, University of California, Berkeley, CA 94720, USA
[b] Renewable and Appropriate Energy Laboratory, University of California, Berkeley, CA 94720, USA
[c] Energy and Resources Group, University of California, Berkeley, CA 94720, USA
[d] Escuela de Gobierno y Transformación Pública, Tecnológico de Monterrey, Campus Ciudad de México, CDMX, Mexico
[e] Escuela de Ingeniería y Ciencias, Tecnológico de Monterrey, Av. Eugenio Garza Sada 2501, Monterrey 64849, Mexico
[f] Goldman School of Public Policy, University of California, Berkeley, CA 94720, USA
[g] Boston Consulting Group, Detroit, MI, USA
[h] Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

HIGHLIGHTS

- A framework to optimize photovoltaics manufacturing supply chains is proposed.
- Techno-economic, transportation, and tariff variables impact supply chain results.
- Multiple objectives can be optimized while achieving low PV manufacturing costs.
- Minimum sustainable price is substantially increased upon tariffs introduction.

ARTICLE INFO

Keywords:
Solar photovoltaics
Photovoltaics manufacturing
Mathematical programming
Minimum sustainable price
Multi-objective approach

ABSTRACT

Solar photovoltaics (PV) manufacturing has experienced dramatic worldwide growth in recent years, enabling a reduction in module costs, and a higher adoption of these technologies. Continued sustainable price reductions, however, require strategies focused in further technological innovation, minimization of capital expenditures, and optimization of supply chain flows. We present a framework: Techno-economic Integrated Tool For Tariff And Transportation (TIT-4-TAT), that enables the study of these different strategies by coupling a techno-economic model with a tariff and transportation algorithm to optimize supply chain layouts for PV manufacturing under equally-weighted objectives.

We demonstrate the use of this framework in a set of interacting countries (Mexico, China, USA, and Brazil) and two extreme tariff scenarios: no tariffs, and high tariff levels imposed. Results indicate that introducing tariffs between countries significantly increase the minimum sustainable price for solar PV manufacturing, alter the optimal manufacturing locations, and render a more expensive final solar PV module price which can hinder the adoption rates required to mitigate climate change. Recommendations for stakeholders on the optimization process, and techno-economic drivers are presented based on our results. This framework may be utilized by policymakers for the spatially-resolved planning of incentives, labor and manufacturing programs, and proper import tariff designs in the solar PV market.

1. Introduction

In an effort to mitigate climate change, an increased number of countries are aligning their investment strategies and incentives towards decarbonizing different sectors of their economies [1–6]. This ongoing transition has led to a global surge in the commissioning of renewable energy projects with solar photovoltaic (PV) technologies representing a significant percentage of the total [7].

* Corresponding authors.
E-mail addresses: sergioc@berkeley.edu (S. Castellanos), santibanez.ezequiel@itesm.mx (J.E. Santibañez-Aguilar).

https://doi.org/10.1016/j.apenergy.2017.12.047
Received 10 October 2017; Received in revised form 27 November 2017; Accepted 8 December 2017

The increase in adoption of solar PV technologies has been driven, to a significant degree, by the enactment of policies that mandate a higher penetration of clean energy sources in the energy mix. The increased rate of adoption has also led to a price drop in excess of 80% in the last 6 years [8], with expectations of further price reductions in the near future [9,10]. Given the expected market growth in global solar PV, firms must compete to serve both existing and new markets at least cost.

Despite current oversupply conditions [11], the cyclic nature of the crystalline silicon photovoltaics (c-Si PV) industry is still a driver for some countries to plan ahead and analyze their options for investing –both directly and indirectly– in developing a local manufacturing base for some or all segments of the PV value chain, as adequate long-term planning policy designs help mitigate volatility risks.

Across many different industries, developing a local, specialized manufacturing base has been shown to bring positive effects, such as knowledge spillovers, where existing firms can benefit from sharing knowledge and human capital, even if not employing the same technology [12]. Geographic proximity between firms and research institutions can enhance the sharing of knowledge in both directions, and can help accelerate R&D cycles and local implementation of technology [13], potentially lowering manufacturing and deployment costs. And through the optics of potential levers to improve environmental conditions, industrial supply chains have been identified as key components for reducing regional carbon footprints and energy use [14].

To continue achieving sustainable price reductions in c-Si PV manufacturing, different strategies can be adopted at different levels. Starting at the module level, technological innovation in material growth conditions can lead to higher conversion efficiencies at least cost [15]. At the facility level, minimizing capital expenditures (capex) has been identified as one of the main drivers in lowering c-Si PV prices [16]. At a market level, optimizing the supply chain flow can lead to reduced factory capex, reduced activity cycle times, and increased demand flexibility [17]. To maximize impact, all these strategies often have to occur simultaneously.

Tariffs are commonly implemented to provide protection to infant industries while they become strong enough to compete in other countries. These measures, however, tend to be over-extended in some instances, turning into long-term corporate welfare, reducing national welfare as a whole by only benefitting interest groups [18,19].

Techno-economic models, whether for installation and operation [20–24], or manufacturing [25–27], can elucidate the variables of merit with highest potential to reduce costs. Recent efforts have been aimed at expanding the impact of these models by broadening the range of the studied supply chains and their carbon emissions [28]. However, these approaches lack the ability to incorporate interactions among various regions in the world, and the impact of tariff levels on supply chain configurations, both relevant and applicable to current real-world situations where financial and environmental impacts need to be contemplated.

In the attempt to develop a quantitative approach for the optimal siting of PV manufacturing supply chains, accounting for financial and environmental objectives, this study introduces a framework to simultaneously analyze all three described levels (module, facility, market) by pairing a cost model with a transportation and import/export tariff model. The techno-economical model for c-Si PV, developed by [29], estimates the minimum sustainable prices (MSP) required to financially sustain a manufacturer at different c-Si PV segments. The transportation and tariff model presented optimizes the geographic steps that render the optimal overall supply chain route considering diverse objectives such as local MSP, transportation costs, and import/export tariffs: from polysilicon, to ingot, to wafer, to cell, and to module assembly, prior to shipping to end destinations.

To demonstrate the applicability of this methodology, we then adapt this coupled model to a case study for Mexico. Mexico was selected based on its ample manufacturing base, number of international treaties, reported economic competitiveness (moderate wage growth, sustained productivity gains, and energy cost advantages), and geographic proximity to North, Central, and South American markets [30]. The authors recognize that many other geographies with PV manufacturing potential also exist, and the proposed methodology can also be implemented in other countries.

We conclude with policy recommendations based on the results for the case of PV manufacturing, given the developed scenarios. We demonstrate that upon a tariff implementation, manufacturing costs in Mexico rise up more than 200%, disrupting supply chains and potentially hindering PV deployment growth, all else equal.

Our proposed framework aims to serve as a tool to support data-driven, strategic decisions in developing local PV manufacturing clusters, as well as to identify the specific drivers that would have the highest impact if modified in a global supply chain context.

2. Material and methods

2.1. Design outlay elements of crystalline silicon photovoltaics supply chain

For the purpose of this analysis, we segment the PV supply chain into five manufacturing and processing steps: (i) polysilicon, (ii) ingot, (iii) wafer, (iv) cell, and (v) module production.

Details on each of these manufacturing and processing steps have been extensively reported in literature [31–35], and herein we merely provide a brief summary of these steps.

Producing polysilicon for PV applications can be done using different methods with varying levels of energy intensity and product purity [36]. The common denominator for this process is the raw material requirement –specifically, quartz– and high temperature processing with coke to produce metallurgical Si (MG-Si), before being transformed into higher purity silicon through one of various processes such as Siemens or fluidized bed reactor, among others [36–39].

For silicon photovoltaic applications, monocrystalline material grown from the Czochralski (Cz) method has consistently been used to develop higher efficiency solar cells, compared to alternative materials, like multi-crystalline silicon [40–43]. In the Cz method, a seed crystal of silicon is dipped into and slowly withdrawn from a crucible containing melted silicon, creating a solidified single crystal as the end product [44,45]. Crystal rods are then cut into wafers, typically through multi-wire sawing [46]. Next, surface texturing and anti-reflection coating deposition is performed to enhance light capturing [47–50]. Metal contacts are then typically printed and fired to convert the wafer into a working solar cell device [51,52]. Finally, solar cells are interconnected, encapsulated, and assembled into a module capable of generating power [53].

2.2. Minimum sustainable price

To estimate the cost for each of the five manufacturing steps previously described, we use the MSP model [54]. The MSP model estimates the minimum price ($/W) at which a manufacturer can financially sustain the production and selling of a good by equating its weighted average cost of capital (WACC) to its internal rate of return (IRR) [14,42].

Using this methodology, we simulate a cash flow for a hypothetical manufacturer located either at a state within the country of interest, or at a city within the country if the latter is considered for import and export interactions. Through this cash flow, we compute the price of the product when the net present value is equal to zero. The MSP calculations, which consider operating costs, investment costs, inflation, and depreciation, are performed by using and modifying the values in the open-access spreadsheet published in [56].