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The impact of international trade on the price of solar photovoltaic modules: empirical evidence

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Abstract

Purpose – Over the past decades, the global solar photovoltaic (PV) market has experienced an unprecedented development associated with a substantial decline in solar PV module prices. A body of literature has attempted to identify and evaluate the different sources of price variation. However, the impact of international trade on the price of solar PV modules has not yet been empirically examined. This paper contributes to filling this gap in the literature by providing a comprehensive empirical examination on the relationship between international trade and solar PV module prices.

Design/methodology/approach – The author uses a sample of 15 countries over the period 2006–2015 and proposes a linear dynamic panel data model based on a new specification, including a number of relevant factors influencing solar PV module prices.

Findings – The empirical analysis reveals that an increase in imports of solar PV cells and modules is associated with a decline in solar PV module prices. This finding suggests that international trade could lead to further price reductions, thus fostering the deployment of solar PV technology. The study reveals several other important findings. Market and technological development are key factors explaining the decline in solar PV module prices. Moreover, government policies such as public budget for R&D in PV and feed-in tariff for solar PV are effective in reducing the price of solar PV modules.

Originality/value – This paper examines the influence of international trade, government policies, market development and technological development on solar PV module prices. The results may be of interest to both academic research and policy analysis.

Keywords Dynamic panel data models, Solar photovoltaic module prices, Trade and environment

Paper type Research paper

1. Introduction

Climate change, the possibility of fossil fuel scarcity and the necessity to improve the security of energy supply have been recognized as the greatest worldwide threats. The global effort to tackle the climate change challenge has involved more and more countries and reinforced the need for promoting renewable energies. Since 1990, the European Union has pursued its commitment of reducing its greenhouse gas emissions substantially with a target cut of 20% in 2020 compared with 1990 (Böhringer, Löschel, Moslener, & Rutherford, 2009). China has increasingly strengthened its policies and programs in a pledge under the 2009 Copenhagen Accord to lower its carbon dioxide emissions per unit of GDP by 40 to 45% by 2020 compared

JEL Classification — C23, F18, Q42, Q56

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to the 2005 level (Glomsrød, Wei, & Alfsen, 2013). More recently, the adoption of the Paris Agreement in 2015 has brought an increasing number of nations into a common cause to undertake efforts to combat climate change. The ongoing process of global integration enhances the possibility to increase the worldwide deployment of clean energy and find low-cost solutions to the climate change issues (Kirkegaard, Hanemann, Weischer, & Miller, 2010). Despite the stated objectives and the implemented measures, many countries face problems meeting their greenhouse gas emissions targets. At the global level, this has rendered the use of clean energy even more essential to achieve sustainable development goals.

In this context, this paper analyses the global integration in the fastest growing renewable energy sector, the solar photovoltaic (PV) industry. In particular, the study aims to provide a comprehensive empirical examination on the relationship between international trade and the price of solar PV modules. The global solar PV industry is dominated by the key markets such as Germany, China, Japan and the United States (Kirkegaard *et al.*, 2010). China has become the leading producer and player in the global solar PV market since 2010, with a substantial share of global trade (Algieri, Aquino, & Succurro, 2011). Technological innovation, global integration, the shift to lower costs of production and government support for electricity production based on renewable energy are the main drivers of the market development (Kirkegaard *et al.*, 2010). The solar PV industry has experienced an unprecedented globalization over the past years, through new market entrants from developing countries and cross-border investment flows (Kirkegaard *et al.*, 2010). All these factors were conducive to a reduction in the price of solar PV modules, which through the increase in global demand, explains the positive trend in solar panels production (e.g. Kirkegaard *et al.*, 2010; Gillingham *et al.*, 2014; Kavlak, McNerney, & Trancik, 2018).

The solar PV industry is an interesting case study because of its many economic and environmental benefits. First of all, the use of solar energy has positive effects on environment quality since it can reduce the emission of detrimental greenhouse gases by cutting the consumption of conventional fossil fuels, which account for 41% of emissions worldwide (International Energy Agency, 2008). Nevertheless, the wide scale deployment of solar energy can sometimes have potential negative environmental implications, including for instance water and soil pollution (Tsoutsos, Frantzeskaki, & Gekas, 2005). The solar PV sector is also attractive for policymakers because of its high employment potential, which constitutes an interesting solution to reduce unemployment and stimulate economic growth (Kirkegaard *et al.*, 2010). The development of the market also enhances possibilities of access to modern energy services for both developed and developing countries, and thus represents a way to reduce energy poverty (Shahsavari & Akbari, 2018).

Economic and non-economic factors affecting the development of the solar PV market and the evolution of prices are relatively complex. Over the past two decades, the global market has experienced a substantial decline in solar PV module prices. Studying the factors influencing solar PV module prices is important given that price reduction is itself often a stated government policy objective to stimulate demand for renewable energy technologies (Gillingham *et al.*, 2014). The literature on solar PV has identified various factors that have generated the decline in prices, including technological innovation, market structure, global integration, government policies, country's wealth and demographic characteristics, firms' experience and characteristics of the solar PV equipment (e.g. Kirkegaard *et al.*, 2010; Gillingham *et al.*, 2014; Kavlak *et al.*, 2018). Although these studies provide important insights into the drivers of price reductions, to the best of the author's knowledge, there is no theoretical framework that explains the development of the market.

The ongoing process of global integration is having an essential role in the development of the global market [1]. As a result, is seems essential to investigate how international trade can contribute to the development of the solar PV market and influence the evolution of prices. A body of existing literature has attempted to identify and evaluate the different sources of price variation (e.g. Kirkegaard *et al.*, 2010; Gillingham *et al.*, 2014; Kavlak *et al.*, 2018). However, to the best of the author's knowledge, no other previous study has examined the impact of international trade on the price of solar PV modules from a theoretical and empirical perspective. This makes empirical modeling particularly challenging and interesting from the perspective of setting the ground for theoretical and empirical approaches to this issue. This paper contributes to filling this gap in the literature by providing a comprehensive empirical examination on the relationship between international trade and the price of solar PV modules. The author aims to provide evidence on how trade can complement the efforts to achieve environmental sustainability. Besides, this study builds on the existing literature analyzing the determinants of price development in the global solar PV market. In particular, the author examines the influence of government policies, market development and technological development on the price of solar PV modules. Understanding the factors influencing solar PV module prices is of key importance from both an academic and policy perspective.

In this paper, the author adopts a quantitative approach and focuses on crystalline silicon PV modules. Using a sample of 15 countries over the period 2006–2015, the author proposes a linear dynamic panel data model based on a new specification, including a number of relevant factors influencing solar PV module prices. The author evaluates the effect of imports of solar PV panels (cells and modules), which are used as a proxy of trade flows, on solar PV module prices. The model is estimated using the difference generalized method of moment (GMM) estimation one-step procedure. This estimation method allows us to control for unobserved heterogeneity, for possible endogeneity of trade flows of solar PV panels with respect to solar PV module prices and for potential dynamic effects.

The empirical analysis reveals that an increase in imports of solar PV cells and modules is associated with a decline in solar PV module prices. This finding suggests that international trade could lead to further price reductions, thus fostering the deployment of solar PV technology. The empirical part provides several other important findings. Market and technological development are key factors explaining the decline in solar PV module prices. Government policies such as public budget for R&D in PV and feed-in tariffs for solar PV are effective in reducing the price of solar PV modules. Moreover, an increase in renewable energy consumption has a negative influence on solar PV module prices.

The rest of the paper is organized as follows. Section 2 reviews the literature examining the economic and non-economic factors that influence solar PV module prices. Section 3 presents the econometric methodology. Section 4 describes the data and their properties. Section 5 presents the results of the model estimation. Section 6 contains concluding remarks and policy implications.

2. Literature review

A large part of the literature examines the scope to which different economic and non-economic factors influence prices in a variety of settings. Much of the recent work has been done for the online internet markets (e.g. Baye, Morgan, & Scholten, 2004; Ellison & Ellison, 2009), air travel markets (e.g. Borenstein & Rose, 1994), gasoline markets (e.g. Barron, Taylor, & Umbeck, 2004; Chouinard & Perloff, 2007), books (e.g. Clay, Krishnan, & Wolff, 2001), pharmaceuticals (e.g. Sorensen, 2000) and for many other goods and services in the economy (e.g. Crucini & Yilmazkuday, 2014). The common feature of these studies is that they consider factors capturing market structure, firms' characteristics and policy variables. This approach is also commonly used for the examination of price determinants in the electricity market, such as in Andersson and Bergman (1995). The literature on solar PV technology has identified various sources of solar PV module prices variation, including technological innovation, market structure, global integration, government policies, country's wealth and demographic characteristics, firms' experience and characteristics of the solar PV equipment (e.g. Kirkegaard *et al.*, 2010; Gillingham *et al.*, 2014; Kavlak *et al.*, 2018). This section summarizes the main findings of the existing descriptive and empirical literature.

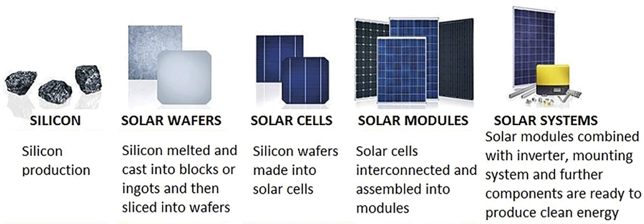
2.1 Description of solar system production chain

This section begins with a short description of the process behind the solar PV system production chain. Before a solar PV module can absorb and convert sunlight into electricity, it has to undergo a multi-stage production process. Figure 1 illustrates the main stages.

The process begins with the extraction of raw silicon materials. Silicon is melted, shaped into blocks and sliced into wafers. These wafers are then cleaned and undergo surface texturing, diffusion, etching, application of anti-reflection film and screen-printing (Zhao, 2015). At the next stage, they are made into solar cells that can convert sunlight into electricity. Multiple solar cells are then interconnected and assembled into modules. Finally, solar PV modules are combined with inverters, mounting systems and further components to form solar PV systems.

2.2 The link between global integration and solar PV module prices

How does global integration drive down the price of solar PV modules? [2] To provide potential answers to this question, let us take as an example the study of the IT hardware sector by Mann and Kirkegaard (2006). This sector has been characterized by the most rapid innovation and global integration, with guaranteed free trade through the World Trade Organization's Information Technology Agreement. Mann and Kirkegaard (2006) identified two main drivers of the decline in computers prices. First of all, innovation itself has been the most important factor in lowering prices. Global competition was the second most important factor, accounting for 10 to 30% of the total decline in computers prices. The lessons learned and concepts emanating from the IT hardware sector case study can be used to understand how the process of global integration affects prices in a sector characterized by rapid technological innovation such as solar PV (Kirkegaard *et al.*, 2010). The equilibrium global price is determined by the basic principle of global supply and demand. When new countries join the global solar PV market, the total production capacity scales up, implying an increase of the global supply of solar PV panels, which exceeds the global demand and subsequently lowers the final price for such products in all global markets (Kirkegaard *et al.*, 2010). In other words, global integration further increases the number of firms, the global supply and product varieties, thus intensifying competition in the global solar PV market and lowering prices (Kirkegaard *et al.*, 2010). International trade is conducive to economic growth as it allows technology transfers between countries, which enable them to build human and physical capacities needed to produce more renewable energy (Omri & Nguyen, 2014).



Source(s): ProSun: Sustainable Solar Energy Initiative for Europe. Available from www.prosun.org

Figure 1.
Solar value chain

Kirkegaard *et al.* (2010) indicate that global competition has particularly intensified in the midstream manufacturing of wafers, cells, modules and components due to the entry of new firms from developing countries and higher levels of cross-border trade. These authors argue that international trade in solar PV markets will bring to future cost reductions and help broaden the global deployment of solar PV technology. On the other hand, Gillingham *et al.* (2014) examine the observed heterogeneity in solar PV system prices across geographic locations and within a given location in the United States by exploring the different sources of price variation. These authors provide empirical evidence for higher market installation density to be associated with lower solar PV system prices, consistent with increased competition.

2.3 Influence of government policies on solar PV module prices

Growing concerns about climate change and rising price of fossil fuels have led governments to promote the development and deployment of renewable energy technologies. One major reason of the rapid growth of solar PV over the past years is the large demand created by strong political pressures in the key markets such as Germany, China, Japan and the United States (Kirkegaard *et al.*, 2010). The solar PV sector is particularly attractive for policymakers because of its high employment prospects (Kirkegaard *et al.*, 2010), its potential benefits on environmental quality (Tsoutsos *et al.*, 2005) and its good potential to reduce energy poverty (Shahsavari & Akbari, 2018). Several studies in the existing literature on the solar PV industry reveal the significant influence of government policies on solar PV module prices. In fact, price reduction in solar PV can be itself a stated government policy objective to stimulate demand for renewable energy technologies (Gillingham *et al.*, 2014). Supportive public programs and specific incentives such as cheap loans, feed-in tariffs and a variety of subsidies accounted for a significant part of the overall solar PV cost decline (Jäger-Waldau, 2007; Algieri *et al.*, 2011; Kavlak *et al.*, 2018). The most common instrument is the feed-in tariff, which is a policy mechanism designed to promote investment in renewable energy technologies (Dijkgraaf, van Dorp, & Maasland, 2018; Kavlak *et al.*, 2018).

Kavlak *et al.* (2018) propose a conceptual framework and quantitative method for quantifying the causes of cost changes in solar PV modules over the period 1980–2012. These authors provide evidence that market-stimulating policies such as feed-in tariffs contribute to reductions in solar PV module prices by catalyzing private R&D, learning-by-doing and economies of scale. On the other hand, a body of literature analyses the influence of feed-in tariffs on the development of solar PV. Dijkgraaf *et al.* (2018) find that feed-in tariffs had a large positive effect on the development of solar PV in a group of 30 OECD member countries over the period 1990–2011. Their findings are in line with Jenner, Groba, and Indvik (2013) and Bolkesjø, Eltvig, and Nygaard (2014).

2.4 Other determinants of solar PV module prices

The literature has identified various other determinants of solar PV module or system prices such as firms' experience acquired with the learning-by-doing mechanism (e.g. International Energy Agency, 2000; Kavlak *et al.*, 2018; Bollinger & Gillingham, 2019), PV system's characteristics (e.g. Gillingham *et al.*, 2014), country's wealth measured as GDP per capita (e.g. Dijkgraaf *et al.*, 2018) and country's demographic characteristics (e.g. Gillingham *et al.*, 2014). Gillingham *et al.* (2014) show how firms' experience and size determine the price of solar PV systems. If firms in a country's industry have more experience in installing solar PV system, the equilibrium market price tends to be lower (Gillingham *et al.*, 2014). This is consistent with the literature on learning-by-doing in new technologies. The International Energy Agency (2000) shows the experience curve for solar PV modules in the world market for the period 1976–1992. The experience curve describes the relationship between price and the cumulative production or use of a technology. The study reveals a progressive decline in prices through cumulative sales, which are used as a measure of the experience accumulated in the industry.

Gillingham *et al.* (2014) establish the important influence of PV system's characteristics on their final equipment price. For instance, batteries and tracking equipment are associated with higher solar PV system prices, while self-installed systems and systems installed in residential new construction are associated with lower solar PV system prices (Gillingham *et al.*, 2014). Using a cost model, Kavlak *et al.* (2018) find that changes in efficiency, non-silicon materials costs, silicon price, silicon usage, wafer area, plant size and yield contributed to the cost reduction in solar PV modules. On the other hand, Dijkgraaf *et al.* (2018) reveal the importance of country's wealth in the development of the domestic solar PV industry. These authors provide evidence that wealthier countries are more likely to invest in solar PV technology, which could subsequently affect its price through the supply and demand factors of the solar PV market. Finally, Gillingham *et al.* (2014) reveal the importance of country's demographic characteristics in the determination of solar PV system prices since they may be an accurate indicator of the aggregate demand for solar PV systems.

3. Econometric methodology

This section presents the linear dynamic panel data model used for the examination of the impact of international trade on the price of solar PV modules. This analysis enables to study the dynamics of behavior of certain variables of interest and control for unobserved effects that vary among countries but are constant over time. Introducing dynamics in the underlying process is crucial for recovering consistent estimates of parameters of interest for three main reasons. First, the price of solar PV modules is likely to depend on its past values. Second, this procedure is well designed for panels with many cross-sections and few periods. Third, it has the advantage of preventing endogeneity issues by addressing the risk of omitted variables bias and the potential endogeneity of trade flows of solar PV panels. In fact, it is very likely that there is a simultaneous relationship between solar PV module prices and trade flows of solar PV panels, since demand for imports may have increased due to the decline in prices. Thus, the author would not estimate the causal effect with simple estimation methods. However, in dynamic panel estimations, it is possible to instrument the potential endogenous variables using the appropriate lags as instruments of the variables. The linear dynamic panel data model is based on a new specification, including a number of relevant factors influencing solar PV module prices. The model is estimated using the one-step GMM estimator derived by Arellano and Bond (1991). Subsection 3.1 presents the specification of the model and subsection 3.2 describes the GMM methodology used for the estimation.

3.1 Dynamic panel data model specification

The model specification regresses the solar PV module price on a number of covariates influencing the solar PV module price. The estimated baseline model has the following form:

$$\log PPV_{it} = \gamma \log PPV_{it-1} + \beta_1 \log IPV_{it} + \beta_2 BRD_{it} + \beta_3 FIT_{it} + \beta_4 CIC_{it} + \beta_5 \log TD_{it} + \beta_6 REC_{it} + \beta_7 \log OP_{it} + \alpha_i + \varepsilon_{it} \quad (1)$$

Where PPV_{it} is the solar PV module price in country i in year t, PPV_{it-1} is the value of solar PV module price in year $t-1$, IPV_{it} is the country's imports of solar PV panels including cells and modules, BRD_{it} is the country's public budget for research and development (R&D) in PV. FIT_{it} is the country's feed-in tariff policy for solar PV, CIC_{it} is the country's cumulative installed PV capacity, TD_{it} is the country's technological development in PV, REC_{it} is the country's renewable energy consumption, OP_{it} is the country's crude oil import price, α_i captures country's fixed effects, ε_{it} is the error term and β_k are the coefficients.

The dependent variable is the log of solar PV module price. The log of imports of solar PV panels is used as a proxy of trade flows. Several exogenous variables are added to control for aggregate supply and demand effects. Public budget for R&D in PV per capita is added to account for technological advancements acquired through R&D. Feed-in tariff for solar PV is treated as a dummy and takes the value one if the corresponding policy measure is present in a particular country-year and zero otherwise. Policy characteristics are included to account for the significant influence of government policies on the evolution of solar PV module prices. Country's cumulative installed PV capacity per capita is used as a measure of solar PV market development. Public budget for R&D in PV and cumulative installed PV capacity are normalized by population to prevent heteroskedasticity. Technological development in PV is measured as the log of the number of inventions related solar PV energy generation developed by country's inventors. The latter is included to control for the autonomous developments in the solar PV industry. Renewable energy consumption is defined as the share of renewable energy consumption in total final energy consumption. It may be plausible to expect that countries with a larger share of renewable energy consumption would tend to have more important deployment of solar PV. Finally, crude oil import price is added to account for potential substitution effects, emanating from changes in non-renewable energy prices.

In the sensitivity analysis, the author augments the benchmark specification by adding a control variable that rotates between country's real GDP per capita (Y), the political stability index (PS), per capita carbon dioxide emissions (CDE) and population density (D) to test whether the results are sensitive to the inclusion of other variables. The augmented model has the following form:

$$\log PPV_{it} = \gamma \log PPV_{it-1} + \beta_1 \log IPV_{it} + \beta_2 BRD_{it} + \beta_3 FIT_{it} + \beta_4 CIC_{it} + \beta_5 \log TD_{it} + \beta_6 REC_{it} + \beta_7 \log OP_{it} + \beta_8 Q_{it} + \alpha_i + \varepsilon_{it} \quad (2)$$

Where, Q_{it} is the control variable. The log of real GDP per capita is used as a measure of country's wealth and is included to account for the possibility that wealthier countries might invest more in solar PV. The political stability index is added to account for the possibility that stable political conditions may be conducive to the development of the solar PV market. Per capita carbon dioxide emissions are included to account for the possibility that countries with higher levels of emissions may have an incentive to invest more in renewable energy. Population density is used as a measure of country's demographic characteristics and is added as solar PV is a land intensive technology.

3.2 Generalized method of moments estimation

This subsection presents the difference GMM estimation one-step procedure for linear dynamic panel data models developed by Arellano and Bond (1991) [3]. The GMM requires a set of moment conditions that are implied by the assumption of the underlying econometric model.

Let us first rewrite Equation (1) in a more compact way:

$$PPV^*_{it} = \gamma PPV^*_{it-1} + X_{it}\beta + \alpha_i + \varepsilon_{it} \quad (3)$$

Where $PPV^*_{i(t-s)} = logPPV_{i(t-s)}, X_{it} = (logIPV_{it}, BRD_{it}, FIT_{it}, CIC_{it}, logTD_{it}, REC_{it}, logOP_{it})$ and $\beta = (\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7)'$. By construction PPV^*_{it-1} is correlated with the unobserved country's fixed effect α_i. This makes standard estimators no longer consistent.

Arellano and Bond (1991) derived a consistent GMM estimator for the parameters of this model. In this procedure, the first step consists in first differencing the regression (3) to eliminate the fixed effect:

$$PPV^*_{it} - PPV^*_{it-1} = \gamma\left(PPV^*_{it-1} - PPV^*_{it-2}\right) + (X_{it} - X_{it-1})\beta + \varepsilon_{it} - \varepsilon_{it-1} \tag{4}$$

Equation (4) can be rewritten as:

$$\begin{aligned} &\Delta PPV^*_{it} = \gamma\Delta PPV^*_{it-1} + \Delta X_{it}\beta + \Delta\varepsilon_{it} \quad |\gamma| < 1 \\ &i = 1, 2, \ldots, N \\ &t = 3, 4, \ldots, T \end{aligned} \tag{5}$$

GMM requires that the dependent variable does not exhibit a substantial persistence, which means that the absolute value of γ must be lower than unity. Since PPV^*_{it-1} in ΔPPV^*_{it-1} is a function of ε_{it-1}, which is also in $\Delta\varepsilon_{it}$, this implies that ΔPPV^*_{it-1} is correlated with $\Delta\varepsilon_{it}$ and is thus endogenous.

The second step of the Arellano–Bond procedure is to use deeper lags of the dependent variable as instruments for differenced lags of the dependent endogenous variables. The instrumental variable matrix used for ΔPPV^*_{it-1} has the following form:

$$Z_i = \begin{pmatrix} 0 & 0 & \ldots & 0 \\ PPV^*_{i1} & 0 & \ldots & 0 \\ 0 & PPV^*_{i2} & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & PPV^*_{iT-2} \end{pmatrix} \tag{6}$$

Where the rows correspond to the first-differenced equations for period $t = 3, 4\ldots, T$. Equation (6) shows that only one lag is used to create the GMM instruments. For the strictly exogenous variables, their first differences are used as standard instruments. Z_i is a valid instrument only if the following moment conditions are satisfied:

$$E\left(Z_i'\Delta\epsilon_i\right) = 0 \quad \text{for i} = 1, 2, \ldots, \text{N} \tag{7}$$

Where, $\Delta\varepsilon_i = (\Delta\varepsilon_{i3}, \Delta\varepsilon_{i4}, \ldots, \Delta\varepsilon_{iT})'$. The GMM estimator is consistent if the second-order autocorrelation of the first-differenced errors is zero for all periods in the sample:

$$\text{E}(\Delta\varepsilon_{it}\Delta\varepsilon_{it-2}) = 0 \tag{8}$$

Although the moment conditions use first-differenced errors from Equation (5), the GMM estimation provide estimates of the coefficients of Equation (1). The asymptotically efficient GMM estimator based on this set of moment conditions minimizes the following criterion:

$$J_N = \left(\frac{1}{N}\sum_{i=1}^{N}\Delta\varepsilon_i' Z_i\right) W_{1N} \left(\frac{1}{N}\sum_{i=1}^{N} Z_i'\Delta\varepsilon_i\right) \tag{9}$$

Where, W_{1N} is the optimal weight matrix. It does not depend on any estimated parameters, which makes the asymptotic distribution approximation more reliable than for the two-step estimator.

4. Data description

The author uses annual panel data for a sample of 15 countries over the period 2006–2015. The group of countries included in this study is composed of: Australia, Austria, Canada, China, Denmark, France, Germany, Israel, Italy, Japan, Republic of Korea, Spain, Sweden, Switzerland and the United States. The series used are available for a small number of developed countries and for a relatively short time period. Appendix provides details on definitions and data sources. Solar PV module prices, imports of solar PV panels and public budget for R&D in PV are in real terms and were obtained by dividing them by the United States GDP deflator. The series are obtained from five main sources. Imports value of solar PV panels series are taken from Commodity Trade Statistics database (COMTRADE). PV panels (cells and modules) are a part of the category HS 854140 [4], "Photosensitive Semiconductor Devices, PV Cells and Light-Emitting Diodes". Solar PV module prices, cumulative installed PV capacity and public budget for R&D in PV series are constructed from the PVPS report Trends in PV Applications of the International Energy Agency (IEA). Solar PV module prices refer to the cost of the PV modules. Population density, the political stability index, renewable energy consumption and per capita carbon dioxide emissions series are all obtained from the World Bank (WB). Real GDP per capita series is taken from Federal Reserve Bank of St. Louis (FRED). Technological development in PV and crude oil import price series are drawn from the Organization for Economic Co-operation and Development (OECD) database. Since crude oil import price series are not available for China and Israel, the author uses the West Texas Intermediate spot crude oil price as a proxy. The dummy for presence of feed-in tariff for solar PV is constructed from the OECD database.

This section provides a preliminary examination of the data properties. Figure 2 shows the evolution of solar PV modules prices over the period 2006–2015. The figure indicates a significant negative trend of solar PV module prices.

Figure 3 shows the log-log linear regression of solar PV module prices on imports of solar PV panels (cells and modules) for the period 2006–2015. The data indicates a slight and progressive decline in prices through the imports of solar PV cells and modules, which are used as a proxy of trade flows. Table 1 provides descriptive statistics of the data.

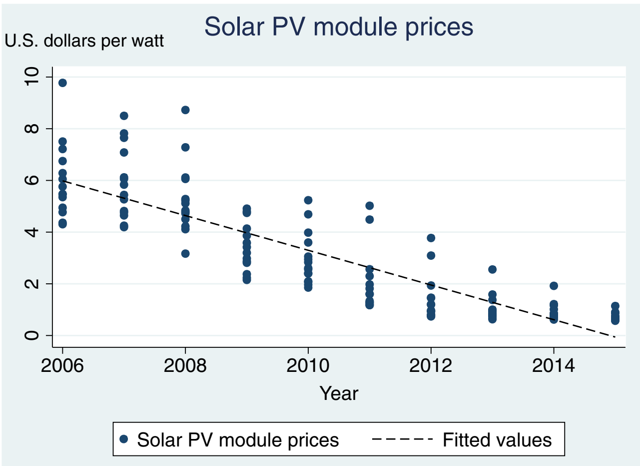


Figure 2.
Evolution of solar PV module prices (2006–2015)

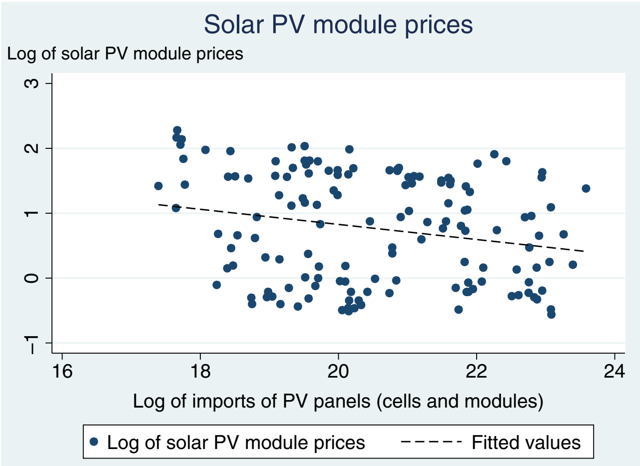


Figure 3. Log-log linear regression of solar PV module prices on imports of solar PV panels (2006–2015)

Variables	Unit	Mean	Std. dev	Min	Max
Solar PV module price	US dollars per watt	2.96	2.22	0.57	9.77
Imports of solar PV panels	Million US dollars	2378.45	3310.65	35.80	17473.85
GDP per capita	Thousand US dollars	42.62	16.07	3.07	76.55
Population density	Capita per square kilometers	166.93	142.21	2.69	523.53
Public budget for R&D in PV	US dollars per capita	0.82	0.98	0.02	7.58
Feed-in tariff for solar PV	Binary 0/1	0.75	0.44	0	1
Cumulative installed PV capacity	Watt per capita	61.62	96.80	0	480.18
Technological development in PV	Number of inventions	285.59	469.31	2.11	2136.67
Crude oil import price	US dollars per barrel	88.76	19.07	58.83	117.78
Political stability index	[−2.5; 2.5]	0.57	0.71	−1.63	1.42
Renewable energy consumption	Percent	16.70	11.20	2.69	53.25
Per capita carbon dioxide emissions	Metric tons per capita	9.32	4.22	4.31	19.22

Table 1. Descriptive statistics

5. Empirical analysis

This section presents the results from the empirical analysis. The dynamic panel data analysis is carried out to evaluate the effects of international trade and a number of covariates on the price of solar PV modules. The obtained results reveal that international trade causes a significant decline in the price of solar PV modules. In addition, the empirical analysis confirms that other well-known factors such as government policies, market development and technological development are also driving down prices. Subsection 5.1 describes and interprets the results of the GMM estimation. The results of the sensitivity analysis are discussed in Subsection 5.2. Finally, Subsection 5.3 presents the main results of the postestimation tests implemented.

5.1 Empirical results

The use of a GMM approach poses several challenges for the choice of the variables and number of lags. The difference GMM estimator requires the number of instruments used for the estimation to be lower than the number of groups to avoid the risk of overfitting (Roodman, 2009). Ignoring this prerequisite can potentially make the results of the postestimation tests no longer reliable and produce biased coefficient estimates (Roodman, 2009). In addition, since each exogenous variable uses its first difference as standard instrument, the choice of the variables included in the model specification is constrained when using a small panel data set. To limit the number of instruments generated by difference GMM, the dynamic panel data models are estimated using only one lag as instruments for differenced lags of the dependent endogenous variables. Table 2 shows the estimation results with robust standard errors at the 1, 5 and 10% level of significance for the benchmark model and the augmented specifications.

The coefficient of the lagged value of solar PV module price is positive (0.563), which indicates some persistence of the dependent variable. However, the coefficient in absolute value is lower than unity, meaning that the model satisfies the stability condition. The empirical analysis reveals that a 1% increase in imports of solar PV cells and modules is associated with a 0.1% decline in solar PV module prices on average, all other things being equal. This finding could be explained by the basic principle of global supply and demand. International trade intensifies competition in the global solar PV market and allows technology transfers between countries. This enables them to build human and physical capacities needed to produce more renewable energy. Consequently, the increase in the global supply of solar PV panels, which exceeds the global demand, lowers the final price for such products in all global markets. This finding suggests that international trade could lead to further price reductions, thus fostering the development and deployment of solar PV technology. The increased use of renewable energy can in turn have positive effects on environmental quality by reducing the emission of detrimental greenhouse gases generated by the consumption of conventional fossil fuels. Therefore, the empirical results suggest that international trade can support the transition to clean and modern energy by facilitating the diffusion of renewable energy related goods, services and technologies.

In addition, the findings of the author reveal that government policies are effective in decreasing solar PV module prices. An increase in public budget for R&D in PV has a significant negative impact on solar PV module prices. Technological advancements acquired through R&D could enhance modules efficiency and thus reduce costs. The author also finds that the presence of feed-in tariffs for solar PV in a specific country-year leads to a significant decline in solar PV module prices. Kavlak *et al.* (2018) suggest that market-stimulating policies such as feed-in tariffs can reduce the price solar PV modules by catalyzing private R&D, learning-by-doing and economies of scale.

The empirical results indicate that market and technological development are key factors explaining the decline in solar PV module prices. Technological development in PV is associated with a significant decline in the price of solar PV modules. An increasing number of inventions related solar PV generation can improve the yield in production and the conversion efficiency, thus reducing associated production costs. The author also finds that an increase in cumulative installed PV capacity, used as a measure of market development, leads to a decline in solar PV module prices.

An increase in renewable energy consumption has a negative impact on solar PV module prices. At first glance, this finding may seem a little counterintuitive as the author would expect countries with a larger share of renewable energy consumption in total final energy consumption to have a higher demand for solar PV technology, which would increase prices. However, it could also reflect the fact that countries with high consumption of renewable energy may deploy more solar PV technology and have achieved greater technological advancements, which would reduce associated production costs. Finally, crude oil import price increases have a positive influence on solar PV module prices. This finding could be explained on the grounds that higher imported oil prices can lead to an increase in demand for solar PV panels through the substitution effect. However, it can be noted that the estimated coefficient is only significant at the 10% level under specification (3).

Table 2. Estimation results: dynamic panel data model

	(1)	(2)	(3)	(4)	(5)
Log_PPV (L1)	0.563*** (0.167)	0.567*** (0.202)	0.559*** (0.171)	0.505*** (0.171)	0.575*** (0.152)
Log_IPV	−0.094** (0.041)	−0.091** (0.042)	−0.104** (0.044)	−0.094** (0.045)	−0.099** (0.041)
BRD	−0.081*** (0.021)	−0.082*** (0.021)	−0.080*** (0.022)	−0.080*** (0.019)	−0.083*** (0.020)
FIT	−0.354* (0.180)	−0.340* (0.179)	−0.329* (0.174)	−0.341** (0.170)	−0.370** (0.184)
CIC	−0.0018*** (0.0006)	−0.0017** (0.0007)	−0.0018*** (0.0006)	−0.0016** (0.0006)	−0.0018*** (0.0007)
Log_TD	−0.169** (0.084)	−0.178* (0.101)	−0.200** (0.089)	−0.160* (0.085)	−0.171** (0.082)
REC	−0.072** (0.031)	−0.073* (0.038)	−0.076** (0.034)	−0.059** (0.027)	−0.077* (0.042)
Log_OP	0.206 (0.138)	0.227 (0.158)	0.261* (0.158)	0.104 (0.165)	0.200 (0.145)
Log_Y	—	−0.303 (2.117)	—	—	—
PS	—	—	−0.465 (0.400)	—	—
CDE	—	—	—	0.155* (0.092)	—
D	—	—	—	—	0.014 (0.046)
Observations	71	71	71	71	71
Number of groups	15	15	15	15	15
Number of instruments	14	15	15	15	15
A-B test for second-order serial correlation in first differences[a]	0.6897	0.6803	0.8482	0.5075	0.7155
Wald test[b]	0.0000	0.0000	0.0000	0.0000	0.0000
Sargan test for over-identifying restrictions	—	—	—	—	—

Note(s): *** Significant at the 1% level ** Significant at the 5% level * Significant at the 10% level
Robust standard errors are in parentheses
[a]First-differenced errors autocorrelation test (p-value). No serial correlation under the null hypothesis
[b]Wald test of overall significance (p-value). All coefficients are equal to zero under the null hypothesis

5.2 Sensitivity analysis

In the sensitivity analysis, the author augments the benchmark specification by adding a control variable that rotates between country's real GDP per capita, the political stability index, per capita carbon dioxide emissions and population density to test whether the results are sensitive to the inclusion of other critical variables. The augmented specifications yield similar results to those of the benchmark specification with only small differences in the magnitude of the estimated coefficients. From Table 2, it can be noted that only per capita carbon dioxide emissions have a positive and statistically significant impact on solar PV module prices at the 10% level. This finding suggests that countries with relatively high levels of emissions could invest more in renewable energy. The coefficients of real GDP per capita and political stability index are negative and insignificant. Moreover, the author finds that population density has no significant influence on solar PV module prices.

To check whether the impact of imports of solar PV panels on solar PV module prices depends on where the countries are importing from, the author estimates the benchmark specification by isolating specific countries' imports of solar PV panels from China. The estimation results are presented in Table A1 and generally reveal similar conclusions. Nevertheless, the coefficient of imports of solar PV panels (−0.085) is a little smaller in absolute value and is no longer significant. This finding suggests that imports from China contribute significantly to reductions in solar PV module prices.

5.3 Postestimation tests

After proceeding with the GMM estimation, the author needs to check whether the benchmark model and the augmented specifications are correctly specified. The results of the postestimation tests are presented in Table 2. The first step is to ensure that there is no autocorrelation in the second-order first-differenced errors. The Arellano–Bond residual autocorrelation test does not reject the null hypothesis of no second-order serial correlation in the first-differenced errors. In other words, this means that the moment conditions are valid and the GMM estimation can be properly carried out. The Sargan test of over identifying restrictions checks whether the instruments are uncorrelated with the first-differenced errors. However, the test cannot be implemented with robust standard errors since its distribution is not known when the errors are heteroskedastic. Finally, the author performs the Wald test of overall significance and finds that the coefficients are jointly significant at the 1% level of significance. The results of postestimation tests help ensure that the models are correctly specified.

6. Conclusions and policy implications

This paper provides an empirical examination on the relationship between international trade and the price of solar PV modules. Over the past decades, the global solar PV market has experienced an unprecedented development associated with a substantial decline in solar PV module prices. A body of literature has attempted to identify and evaluate the different sources of price variation. However, to the best of the author's knowledge, the impact of international trade on the price of solar PV modules has not yet been empirically examined. Using a sample of 15 countries over the period 2006–2015, the author proposes a linear dynamic panel data model based on a new specification, including a number of relevant factors influencing solar PV module prices.

The results obtained in this paper may be of interest to both academic research and policy analysis. The empirical analysis reveals that an increase in imports of solar PV cells and modules is associated with a decline in solar PV module prices. This finding suggests that international trade could lead to further price reductions, thus fostering the deployment of solar PV technology. The use of renewable energy can in turn have positive effects on environmental quality by reducing the emission of detrimental greenhouse gases generated by the consumption of conventional fossil fuels. This new finding can help achieve a better understanding of the relationship between international trade and the price of solar PV modules. In this study, the author also provides important insights on the factors influencing solar PV module prices. Market and technological development are key factors explaining the decline in solar PV module prices. Government policies such as public budget for R&D in PV and feed-in tariffs for solar PV are effective in reducing the price of solar PV modules. Moreover, an increase in renewable energy consumption has a negative influence on solar PV module prices. This analysis is useful given that price reduction is itself often a stated government policy objective to stimulate demand for renewable energy technologies. Finally, the sensitivity analysis reveals that the results are robust to the inclusion of other critical control variables.

The results occurring from this paper have several policy implications. First of all, specific trade policies of developed countries aimed at reducing existing barriers to imports and exports can lead to reductions in solar PV module prices, which in turn can promote the development and deployment of solar PV technology. Thus, they can support the transition to clean and modern energy by facilitating the diffusion of renewable energy related goods, services and technologies. However, as expected, international trade is not by itself capable of substantially reducing solar PV module prices and other types of government policies need to be implemented jointly. In addition, the findings of the author reveal that public sector support for technological development and specific market-stimulating policies such as feed-in tariffs in the solar PV industry can contribute to reductions in solar PV module prices by catalyzing private R&D, learning-by-doing and economies of scale.

Above all, this study reveals the importance of considering international trade in the analysis of renewable energy development. However, the study is subject to some limitations due to the availability of the data. First, the results are obtained from a panel data based on developed countries. This means that the conclusions are not necessarily applicable to developing countries. Second, the author was not able to test the influence of PV system's characteristics and market structure that have been recognized as important factors in the literature. Further research should be done to see whether the conclusions remain valid with the inclusion of these factors and in the context of developing countries. The author believes this study can provide a useful starting point for future research on the relationship between trade and environment.

Notes

1. From this same perspective, the implication of domestic renewable energy industry development on trade conflicts has been little addressed in the literature. Most renewable energy technologies including solar PV require some form of government support in order to be deployed. In addition, country policies used to support renewable energy industry development require direct government intervention in international trade flows, which may lead to direct conflict with multiple WTO provisions and domestic trade laws (Lewis, 2014). Many legal questions still remain with regard to the types of industrial policies that are in direct conflict with existing trade rules (Lewis, 2014). Although this analysis cannot be performed in this paper, the author believes that future studies should investigate the policies that many countries have used to build up their solar PV industry and their implications for trade disputes. This would provide a more comprehensive framework to study the link between international trade and solar PV industry development.

2. Since the theoretical and empirical literature on the relationship between international trade and the price of solar PV modules is not yet developed, the author was unable to provide a detailed review of the literature on this subject. This subsection describes the main findings of studies analyzing the role of global integration and market structure in the development of prices in the solar PV industry.

While the author recognizes that these studies are less directly related to the main topic of the paper, the author believes that the insights they reveal can provide a solid foundation for addressing this new research question.

3. The notation is based on the representations used by Arellano and Bond (1991) and Bond (2002).
4. The main caveat of using this broader measure is that it also includes other goods than PV such as light-emitting diodes. The more disaggregated 8-digit Combined Nomenclature (CN) classification allows for separation of solar PV goods from light-emitting diodes. However, the CN classification provides data only for European countries. The author decided to use the 6-digit category HS 854140 since it has the advantage of making the data internationally uniform. In addition, it can be considered as a reasonable indicator of trade in PV panels because the 8-digit CN classification represents more than 90 percent of the EU import-export under the HS 854140 code (Jha, 2009).

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Appendix

A.1 Data description

Solar PV module price (PPV): Cost of the PV modules. Source: PVPS report Trends in Photovoltaic Applications of the International Energy Agency (IEA).

Imports of solar PV panels (IPV): Imports of PV cells and modules. PV panels (cells and modules) are a part of the category HS 854140, "Photosensitive Semiconductor Devices, Photovoltaic Cells and Light-Emitting Diodes". Source: Commodity Trade Statistics database (COMTRADE).

GDP per capita (Y): Source: Federal Reserve Bank of St. Louis (FRED).

Population density (D): Source: World Bank (WB).

Public budget for R&D in PV (BRD): Source: PVPS report Trends in Photovoltaic Applications of the International Energy Agency (IEA).

Feed-in tariff for solar PV (FIT): Dummy for presence of feed-in tariff for solar PV. Source: Organization for Economic Co-operation and Development (OECD).

Cumulative installed PV capacity (CIC): Source: PVPS report Trends in Photovoltaic Applications of the International Energy Agency (IEA).

Technological development in PV (TD): Number of inventions related solar PV energy generation developed by country's inventors. Source: Organization for Economic Co-operation and Development (OECD).

Crude oil import price (OP): Sources: Organization for Economic Co-operation and Development (OECD) and Federal Reserve Bank of St. Louis (FRED).

Political stability index (PS): Source: World Bank (WB).

Renewable energy consumption (REC): Share of renewable energy consumption in total final energy consumption. Source: World Bank (WB).

Per capita carbon dioxide emissions (CDE): Source: World Bank (WB).

Population: Total population. Source: World Bank (WB).

United States GDP deflator: GDP implicit price deflator. Source: Federal Reserve Bank of St. Louis (FRED).

A.2 Empirical results of the sensitivity analysis

	(1)
Log_PPV (L1)	0.571*** (0.184)
Log_IPV	−0.085 (0.062)
BRD	−0.087*** (0.022)
FIT	−0.370** (0.181)
CIC	−0.0018*** (0.0006)
Log_TD	−0.179** (0.091)
REC	−0.074** (0.032)
Log_OP	0.188 (0.139)
Observations	69
Number of groups	14
Number of instruments	14
A-B test for second-order serial correlation in first differences[a]	0.6922
Wald test[b]	0.0000
Sargan test for over-identifying restrictions	—

Note(s): *** Significant at the 1% level ** Significant at the 5% level * Significant at the 10% level
Robust standard errors are in parentheses
[a]First-differenced errors autocorrelation test (p-value). No serial correlation under the null hypothesis
[b]Wald test of overall significance (p-value). All coefficients are equal to zero under the null hypothesis

Table A1. Estimation results: dynamic panel data model (China excluded from analysis)

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