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Systematic analysis of factors affecting solar PV deployment

Carlos Norberto[a,*], Claudia N. Gonzalez-Brambila[b], Yasuhiro Matsumoto[c]

[a] Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (CINVESTAV-IPN), México, Ciudad de México 07360, Mexico
[b] Business School, Instituto Tecnológico Autónomo de México (ITAM), México D.F. 01080, Mexico
[c] Electrical Engineering Department, Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (CINVESTAV-IPN), México, Ciudad de México 07360, Mexico

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ABSTRACT

This article analyzes the determinants of annual installed capacity of photovoltaic power (PV) at a country level. Our results suggest that in the 15 countries studied, the factors promoting the deployment of PV systems are the net consumption of renewable electricity, the existence of a feed-in tariff and sustainable building requirements, as well as the quantity of scientific publications. Meanwhile, the variables that negatively impact the PV deployment are oil reserves and the carbon dioxide emissions from energy consumption. Based on data from 1992 to 2011, the analysis shows that the deployment of PV requires long-term support for scientific research. One successful policy for PV deployment has been the feed-in tariff. Sustainable building requirements also significantly support PV deployment. The deployment of PV is one step towards a low-carbon energy system but the emergence of any renewable energy technology must cope with the energy sector's domination by fossil fuels interests.

1. Introduction

All over the world, changes in energy systems are deeply interlinked with societal development [1,2]. Electricity consumption, which in 2013 represented 18% of total final consumption of fuels in the world [3], is highly correlated with the growth of societies and their productivity. Meanwhile, the world's electricity production grew 97.2%, the population grew 34.8% and the Gross Domestic Product (GDP) increased 82%, over the period 1990–2013 [4]. Currently, the growth of electricity demand increases the use of fossil fuels and hydrocarbons share of global production of electricity was 67.9% in 2013 [3]. Unfortunately, there are some serious problems related to the exploitation of fossil fuel such as scarcity, increasingly difficult extraction, volatility of prices and global warming. Greenhouse gases (GHGs) emissions from the highly fossil-fuel dependent energy sector have driven anthropogenic climate change [5,6]. Globally, in 2013, carbon dioxide (CO_2) emissions from renewable energy (RE) [nuclear, hydro, geothermal, solar, tidal, wind, biofuels and waste] represented only 1% [4] of the anthropogenic emissions of GHGs. However, the share of electricity production from RE of non-hydro sources in the Organization for Economic Co-operation and Development (OECD) countries in 2013 was just 5.7% [3]. Thus, better electricity production options using more affordable and cleaner fuels are needed.

Of all the technologies for renewable electricity production, excluding hydroelectric power, photovoltaic (PV) power had the fastest rate of annual growth from 1990 to 2012 [7] and its cumulative installed capacity in 2014 reached 178,391 MW [8]. However, its share of electricity production from non-hydro sources in OECD countries in 2012 was 8.2% of the total versus wind power that had a share of 48.2%, or solid biofuels that had a 21.9% [7]. As a relatively new technology, PV systems still need support to break into the commercial mainstream. For instance, Chen and Su [9] studied support instruments used in the PV supply chain system in China. They suggested that governments should establish an appropriate subsidy policy to further pursue the development of the PV industry. Nevertheless, many variables may affect the PV market such as the availability of extractable energy resources, energy policies, energy laws, geographic conditions, human resources and regional public awareness.

Academic work focusing on drivers of the PV sector [e.g. 9,10,11,12] includes policy analysis, studies of installed PV capacity, and case studies of PV production. Although there is an increasing number of PV-related case studies, most of the literature of energy drivers has focused its attention on impacts on total RE production, when variability of the impact of the control variables

* Corresponding author.
E-mail addresses: cnorberto@cinvestav.mx, ing.cnorberto@gmail.com (C. Norberto).

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is presented on RE technologies [13]. In addition, an integrative perspective on the production, dissemination and use of technologies has not been applied to analyze PV deployment although this method has been useful to study dynamics of innovation in the energy sector [14–16]. Additionally, previous studies show that there are only few of them related to the driving factors behind the growth of specific renewable energies or the impacts of specific policy instruments [9,12,17,18]. Besides, there is still discussion about the factors that drive RE. Results have not been conclusive; for instance, Carley [19] showed that the price of electricity is significant for the deployment of RE, while Shrimali and Kniefel [13] found that the price was not significant, even though both studies analyze the case of the USA.

Therefore, more studies using different methodologies are still needed for the analysis of the driving factors of the development and deployment of PV. The present paper aims to identify factors that have driven the deployment of PV capacity in its exponential growth by using a holistic approach of socio-technical (ST) theory and longitudinal data of a selected sample of countries. Key differences with previous literature are the integrative approach, the evidence that the academic work on PV requires long-term support and that some policy instruments have had no statistically significant effects for PV deployment. Section 2 shows a review of PV systems in the energy sector and the related literature. The data and the methods are presented in Section 3. In Section 4, the results are shown and a discussion is presented in Section 5. Finally, conclusions are presented in Section 6.

2. PV system in the energy sector and related literature review

2.1. Renewable energy in the electric sector

RE includes nuclear power and renewables [20] (see Table 1). Although RE production is increasing all over the world, there remains a huge global dependence on fossil fuel for primary energy supply. For example, its share was 86.6% in 1973 and 81.4% in 2013 [3]. Also, hydrocarbons dominates the global production of electricity, its share was 67.9% in 2013, of which 41.3% was accounted for by coal, 21.7% by natural gas and 4.4% by oil [3]. Scarcity, increasingly difficult extraction, volatility of prices and global warming are some of the serious problems related to the exploitation of fossil fuel for energy production and use. On the other side, renewability and low GHGs emissions are some benefits of RE production. It has been widely accepted that global warming is a consequence of the significant increase in the atmospheric concentration of CO_2. Globally, CO_2 emissions from fuel combustion in 2013 were 32,189.7 million tonnes and CO_2 emissions share by fuel from combustion during primary energy production were from coal (46%), oil (33%), gas (20%), and RE sources (1%) [4]. Thus, diversifying the energy production with RE could reduce the carbon footprint of the energy sector.

Table 1
Grouping of Renewable Energy Sources.

Renewable Energy Sources	a) Nuclear Power		
	b) Renewables	i) Traditional Biomass	
		ii) Modern renewables	- Hydropower - Geothermal - Solar - Tidal - Wind - Biofuels

Source: Adapted from Ref. [20].

Table 2
Fuel shares of world electricity generation in 2013.

Fuel Source	Share
Fossil Fuels (Coal, oil and natural gas)	67.4%
Nuclear Energy	10.6%
Hydropower	16.3%
Non-hydro sources	5.7%

Source: Adapted from Ref. [3]

Table 3
Electricity Production from non-hydro source in OECD countries in 2012.

Non-hydro source	Share
Wind	48.2%
Solid Biofuels	21.9%
PV	8.2%
Biogas	7.3%
Geothermal	6.0%
Waste	4.0%
Liquid biofuels	0.8%
Solar thermal and Tidal/Wave	0.6%

Source: Adapted from Ref. [7]

However, intermittency in power generation, high costs and considerable upfront investment are some of the issues that holds back RE deployment in the electric sector; it is also important to mention that technology dependence on hydrocarbons is another critical factor. Additionally, RE deployment depends on matching its generation capacity with the constant growth of economies, since demand for electricity increases because it is linked to the growth of economies and their productivity. Global electricity production grew 97.2% (from 11,826.1 to 23,321.6 TWh) over the period 1990–2013 [4]. During the same period, the population grew 34.8% (from 5,278.3 million to 7,117.7 million) and the GDP grew 82% (from 30,998.9 billion to 56,519.0 billion, 2005 USD) [4].

Currently, RE provides some of the electricity demand; in 2013, its share was 32.6% of the total generation [3]. The estimated proportion of world electricity generation in 2013 by fuel is shown in Table 2, as can be seen fossil fuels share was 67.4%. Table 3 shows the share of electricity production from non-hydro sources in OECD countries in 2012 where wind, PV and solid biofuels represented 78.3% of the total; but PV share was only 8.2%. Although the production share of PV was lower than that of wind or solid biofuels, PV had the fastest rate of annual growth of non-hydro electricity production, reaching 46.9%, over the period 1990–2012 (see Table 4).

2.2. PV technology and policy drivers

PV technology might play an important role for power generation in the upcoming years because of its generation

Table 4
Annual growth rates of electricity production from non-hydro renewables (period 1990–2012).

Non-hydro source	Share
Wind	23.1%
Solid biofuels	2.7%
PV	46.9%
Biogas	13.3%
Geothermal	2.2%
Waste	5.7%

Source: Adapted from Ref. [7]

Table 5
General classification of cell types and their submodule efficiencies.

Cell types[a]		Efficiency[b,c]	Material
Wafer-based crystalline	Single crystal sc-Si	25.6%	Silicon
	Multicrystalline mc-Si	20.4%	Silicon
	Compound semi-conductor GaAs	18.4–28.8%	Silicon, Gallium arsenide
Thin film	a-Si	11.8–13.4%	Amorphous, micromorph silicon
	CdTe	19.6%	Cadmium telluride
	CIGS	18.7–20.5%	Copper-indium-gallium-diselenide
Organic		6.8–10.7%	Organic semiconductors

Source: a) Adapted from Ref. [22]. b) Adapted from Ref. [23]. c) Efficiencies measured under global AM1.5 spectrum (1000 W/m^2) at 25 °C, the variation of percentage values are omitted.

potential, its lasting fuel source and the fact that it is a proven technology [21]. A PV system provides electric power either by being connected to the network (grid connected) or not connected (off-grid). Its installation allows several forms i.e. domestic/non-domestic off-grid systems, distributed/centralized grid-connected systems or hybrid systems, in pair with other energy sources. On the other side, the PV module (an arrangement of PV cells) with its mounting structure, the inverter and a storage form (battery or network) are elements of the PV system based on constant innovation. Improvements have been done in PV cells and in inverters to have better efficiencies in energy conversion (see Table 5); meanwhile to solve the intermittency generation problem, better friendly-environment storage devices have been developed.

A PV module can produce between 50-300 W [22] with a lifetime of up to 20 years; its cell-type selection depends on cell efficiency and its associated costs. Although compound semiconductors might offer higher efficiencies than multicrystalline (see Table 5), they have higher associated costs [21]. The market share of wafer-based cells is about 80% in International Energy Agency (IEA) countries [22], this might be because multicrytalline are the least expensive to produce [21]. On the other hand, PV can be competitive in the electricity market with or without subsidies, depending on the country, because in some places reduced manufacturing cost have allowed a 'fuel parity' [8,20]. The world average price for PV modules was about $22 per watt in 1980, and by 2010, it had fallen to less than $1.5 per watt [24] the drop in the price could be the result of a combination of factors including research and development, economies of scale, learning by doing, and increased competition. However, the levelized cost of energy (LCOE, which is used to compare different methods of electricity generation in term of cost) for PV in 2011 was the highest [24] among all renewable technologies.

Nonetheless, the worldwide cumulative installed capacity of PV in 2014 reached 178,391 MW [8], which has experienced an exponential growth since the end of the 1990s [8,18,20]. Peters et al. [18] identified three distinct periods of PV development. In the first stage, from 1970 to 1985, public investment in research and development (R&D) resulted in a few patents being filed, and PV capacity was practically non-existent. Then, from 1985 to 1995, the investment in R&D declined and the number of patents grew slightly. However, in a second boom (1995–2009), patents and installed capacity experienced exponential growth, while investment increased only marginally. Peters et al. [18] noted that Japan and USA filed the highest number of patents, Germany had the most installed capacity, while China was the main producer of cells in 2009. Innovation theory suggests an appropriate combination of supply and demand policies to support the creation and use of knowledge [25,26].

According to the annual report of REN21 [20] policy targets towards RE deployment were reported by 144 countries in 2014, most of them towards the electricity sector, to promote power capacity or generation. These policies could be in the form of regulations, fiscal incentives or financing mechanisms, applied individually or in combination, and they could be enforced at a national or local level. Particularly in PV, even though it is becoming competitive, policies are still needed for supporting its deployment; taking into account that the main objective is to reduce the gap between PV's costs and those of its substitutes. Related to the PV, some sector support schemes have been gathered and analyzed in surveys of IEA countries [22,27] [see Table 6]. According to the results of the survey [22], the share of market drivers in 2012 were 12% for both self-consumption and pure competitive PV; 61% for feed-in tariffs; 21% for both direct subsidies and tax breaks; 4% for Renewable Portfolio Standard (RPS) and similar schemes; and 2% for net-metering. It must be noted that the support schemes shown in Table 6 are not exclusively targeted towards PV deployment instead they are aimed to support RE capacity and/or generation.

2.3. Literature review

2.3.1. Studies related with policies

In the literature review of PV deployment, there have been increasing interests in identifying successful policies that boost PV [9,12,17,18]. However, there are more studies about the impact of

Table 6
Support schemes for PV deployment in IEA countries (1992–2012).

Scheme	Characteristic	Supported by	Observations
Feed-in Tariffs	Payment of the electricity produced and injected into the grid at a predefined price with a guarantee	Taxpayers or a specific electricity bill levy	It can present problems of uncontrolled market development
Direct Capital Subsidies	Subsidy to reduce the high upfront investment	Government expenditure	Limited by government's budget
Renewable Portfolio Standard	Regulation by an authority that defines a RE share that has to be adopted by utilities.	Competitive electricity markets	The share can be produced or fulfilled by buying specific certificates
Tax credits	Subsidy to reduce the high upfront investment	Government expenditure	Limited by government's budget
Sustainable Building Requirements	Regulation by an authority about requirements for new building developments	Competitive PV	It can also be applied to properties for sale
Electricity Compensation Schemes	Compensation of both energy flow or financial flows over what a producer injects into the grid	Competitive electricity markets	Also known as self-consumption or net-metering

Source: Adapted from Ref. [22].

policies on the total RE production than those that intent to measure the impact of policies on specific renewable technologies. Most of the case studies compare a group of selected countries [9,11,17] while others only focus their attention in individual countries or regions [1,28,29].

Chen and Su [9] studied the coordination of the PV supply chain and strategic consumers in China from 2008 to 2012. They found that those policies with the aim of coordinating contracts worked well with strategic buyers. These instruments focus on the discount rate and on reduced modules and production costs that benefit the PV supply chain. Muhammad-Sukki et al. [12] also explored the impact of government policies. The potential of PV in Japan was studied by evaluating the implementation of the feed-in tariff through a financial analysis. The results show that the financial recovery period in Japan was similar to that in the UK but lower than in Germany or Italy. Meanwhile, the total gain in Japan was not as high as in Italy or the UK. The average annual return on investment was quite similar in the countries that were studied, except for Germany, where it was the lowest.

Another example of a study of policy instruments is the work of Carley [19]. This study evaluates the effectiveness of government programs in promoting the development and deployment of RE in the United States and tested the link between the implementation of RPS and the percentage of renewable electricity generation. Carley showed that political institutions, natural resources, deregulation, GDP, and prices for electricity and electricity use per person were significantly related to the RE deployment. However, the implementation of an RPS did not significantly predict the percentage of renewable electricity generation.

Shrimali and Kniefel [13] sought causal links between government policies and emerging sources of renewable electricity in the USA, over the period 1991–2007. It was found that economic variables such as the price of electricity, price of natural gas and GDP did not significantly affect RE deployment, but three types of policies were effective: RPS, green power options and clean energy funds. They emphasized the variability of the impact of the control variables on the different technologies; for instance, the impact of implementing an RPS varies depending on the type of renewable source. In addition, they reveal that government programs such as the state purchase of green power or voluntary renewable portfolios had not been successful.

One example of a regional study is the work of Khan et al. [28]. They studied a region in South Asia from 1975 to 2011. They wanted to find a causal relationship between energy consumption, economic growth, relative prices, financial development and foreign direct investment. Their results suggest that the effects depend upon the co-integration of the variables that were studied. For example, energy consumption and economic growth are affected between each other. They also found a bidirectional relationship between foreign direct investment and the relative price of energy. Also, Zeb et al. [1] studied a group of countries within the South Asian Association for Regional Cooperation over the period of 1975–2010. The results showed that electricity production from RE sources tends to reduce carbon emissions. They analyzed the short- and long-term causal relationships between the production of electricity from renewable sources, CO_2 emissions, GDP and poverty. Positive causal links were found between these tested variables, and long-term relationship between them.

Marques and Fuinhas [30] examined data from 24 European countries from 1990 to 2006. They studied indicators related to the environment and were interested in identifying indicators of the commitment to produce energy from renewable sources. One notable empirical finding from this study was the suggestion that the European market did not encourage RE. Income and the price of fossil fuels did not boost RE deployment. Additionally, their findings support the thesis that awareness of sustainability and climate change mitigation have not been enough to motivate an energy transition. Alagappan et al. [31] analyzed 14 markets in the USA, Canada, and Europe. The policies tested were: market structure, use of the feed-in tariff, transmission planning and transmission interconnection cost. Their results showed that the instruments successfully driving renewable deployment were the feed-in tariff, anticipatory planning and the absorption of the transmission interconnection cost.

2.3.2. Studies related with socio-technical systems and technological transition in the energy sector

There are two general approaches to the study the production and use of PV technology. One approach is to study the production in the PV sector, or the creation of knowledge (for instance, by analyzing the production chain or the PV related patents) [e.g. 9,12,18,28]. Another approach is to study the appropriation of the technology, for instance the stagnation of technology [e.g. 17]. However, there is a holistic approach to study the development of technologies that might be used, the multi-level perspective (MLP) and its concept of ST system [32]. This approach integrates perspectives on the production, dissemination and use of technologies. It allows the analysis of the configurations of technologies, infrastructures, social practices, institutions and markets that determine the development of technologies [14,32]. Although this method has been useful to study technological transition in other sectors, it has been scarcely applied in studies of the energy sector [14–16].

For example, Stephens and Jiusto [15] explored the dynamics of innovation in carbon capture and storage (CCS) and in enhanced geothermal systems (EGS) as ST systems. These emerging technologies require several resources, so the dynamics of

Table 7
The five ST-regimes and their associated variables for the Fixed Effect Model.

ST-Regime	Related to:	Proxy	Variable name
Technological	Product specifications	* patents filed	* *ppatent*
Science	Research programs	* papers produced	* *ppaper*
Policy	Formal regulations of technology	* Net consumption of renewable electricity	* *Prnweleconsu*
		* CO_2 emissions of energy consumption	* *Pco2enrcons*
Socio-cultural	Symbolic meaning of technology.	* Oil reserves	* *Poilreserv*
Users and markets	Construction of markets through laws and rules	* Feed-in tariff	* *feedn*
		* Net metering	* *netmetr*
		* Tax credit	* *taxcrd*
		* Sustainable building requirements	* *buldngreq*
ST-regime	Increased PV system	* Cumulative PV Installation	**PCumInstPV*

Table 8
Dependent and control variables and their type (quantitative or binary) for the Fixed Effect Model.

Dependent Variable	Control Variables	
Quantitative one variable	Quantitative five variables	Binary four variables
Y_{it}	$X_{k,it}$	$d_{k,it}$
PCumInstPV	*Ppatent* *ppaper* *Prnweleconsu* *Pco2enrcons* *Poilreserv*	*feedn* *netmetr* *taxcrd* *buldngreq*

innovation were studied to contribute to policy formulation. They found that CCS is an innovative response to the dominant system of coal power in the USA and that CCS itself became a promoter of new coal plants. In the case of EGS, the concerns are related to profitability, as EGS requires favorable geological conditions. Their results also highlight some impediments; for example, they suggested that the support network of actors is not strong enough, and the awareness of this technology among scientists and environmentalists is limited. Both technologies rely on government funding and/or public-private partnership for their implementation.

Another example is the work of Kern [14] where MLP was used to evaluate a policy initiative promoting the transition to a low-carbon economy in the UK. Kern showed that MLP is useful to study policies and their ex ante impact assessment. The study found that the Carbon Trust policy initiative is well geared to stimulate the development of technological niches and that it has helped to change regimens' practices by influencing specific processes. Verbong and Geels [16] conducted another study on the Dutch electricity system with the aim of analyzing "*technical progress, changes in the rules and visions, and social networks that support and oppose renewable options*". They found that these factors have influenced the dynamics of some technological niches such as wind, biomass and PV. They also supported the thesis that the current energy transition is not based on environmental aspects.

Finally, the literature review shows inconclusive results and there is still discussion about the factors that drive the deployment of RE technologies. For instance, Carly [19] found that the price of electricity was significant for the deployment of RE, while Shrimali and Kniefel [13] found that the price of electricity was not significant; both studies were conducted in the USA. Additionally, the empirical literature focuses mainly on total RE production [13,19,30]. To the best of our knowledge, previous studies have not made an empirical assessment of the factors driving the development of PV, controlling for country and taking into account the parameters of ST theory. This approach seems to be adequate, because different studies in the literature review have considered the variables of the ST theory without integrating them in a systemic way. Moreover, the ST theory has been useful for policy analysis of technological development in energy systems.

3. Data and methods

Data used in this study was collected from four sources of information: the reports "*Trends in photovoltaic applications*" from the IEA, which are compilations of PV data from several countries [27,33]; the OECD statistical database [34]; the Scopus database [35]; and lastly, the Patentscope database of the "World Intellectual Property Organization – Patent Cooperation Treaty" (WIPO PCT) [36,37]. The period of analysis was from 1992 to 2011. For patents and academic papers, the studied period was from 1982 to 2011, the former limit was moved backward by ten years to allow for possible lags in the impact of research.

Some limitations were found when collecting the data. The first one was the availability of the IEA survey reports [27]. The last available report was the 2012 edition. Those reports have compiled PV trends from 1992 to 2011, most of the exponential tendency growth of PV installed capacity [8,18]. The other constraint was the missing data in the IEA reports. In some cases, the information is not available or was not reported by the country.

On the other side, additional information was required which was out of the scope of the IEA survey; i.e. patents or paper data. This information was accessed to adjust to the ST system concept. In the case of patents, the "International Patent Classification (IPC)" scheme was used. It must be noted that for papers and patents a robust research was done. The search query was conducted by seeking information relating to PV (see Appendix A).

The concept of a ST system suggests *meta*-coordination [32] of the different groups that are involved in the development of a technology. This coordination is needed to develop, commercialize and use innovations [32]. A ST regime depends on the interdependencies of five regimes: the technological, the science, the policy, the socio-cultural and the user-and-market [32]. The interdependencies of these regimes drive the technological path of the ST regime. We consider that using this approach can be an advantage because it focuses on the co-evolution of technology and society [32]. In the dominant regime of MLP theory, the different regimes of a system are aligned towards the current technological system (the technology that dominates the market). But the alignment of the five regimes changes to let new technologies enter into the system. In this particular study, we measure the additions of PV capacity within the dominant fossil fuel regime. We hypothesize that the amount of added PV capacity is the result of the changes in the five ST regimes, which were related to the development of PV technology (1).

$$\Delta\text{PV Capacity} = \Delta\text{technological} + \Delta\text{science} + \Delta\text{policy} + \Delta\text{socio-cultural} + \Delta\text{user-market} \quad (1)$$

Each country has its particular configuration that has allowed specific PV capacity additions. Thus, a group of 15 countries was

Table 9
Correlations between variables (only for those variables that are shown in Table 10).

Variable	*PCumInstPV*	*Prnweleconsu*	*Pco2enrcons_1*	*Poilreserv_4*	*ppatent*	*ppaper_8*	*feedn*	*netmetr*	*taxcrd*	*buldngreq*
PCumInstPV	1.00000									
Prnweleconsu	0.4046	1.0000								
Pco2enrcons_1	−0.1516	0.0431	1.0000							
Poilreserv_4	−0.0232	−0.0215	0.0284	1.0000						
ppatent	−0.0101	−0.0949	0.0428	0.1528	1.0000					
ppaper_8	0.0205	0.0067	0.1320	−0.0600	−0.0606	1.0000				
feedn	0.2905	0.1028	−0.1330	0.0850	0.0105	−0.0897	1.000			
netmetr	−0.0006	−0.0569	−0.0547	0.0942	−0.0318	−0.1143	0.4094	1.0000		
taxcrd	0.0599	−0.0619	−0.0875	0.1191	0.0034	−0.1269	0.2124	0.3970	1.0000	
buldngreq	0.0867	−0.0229	−0.0477	0.1465	0.0167	−0.0418	0.5219	0.4021	0.2471	1.0000

Table 10
Regression results (regression coefficients and test results). Dependent variable: Adding PV capacity (PCumInstPV). OLS Fixed Effects (Robust).

Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Specification	Regime
Poilreserv_4	−0.0294*** (0.0067)	−0.0346*** (0.0084)	−0.0225** (0.0077)	−0.0162** (0.0065)	−0.0196** (0.0086)	−0.03431*** (0.0085)	Oil reserves with 4 years lag	Socio-cultural
Prnweleconsu	3.6100*** (0.9810)	3.7042*** (0.9542)	3.7538*** (0.9592)	3.8108*** (0.9504)	3.7398*** (0.9719)	3.6590*** (0.9722)	Net consumption of renewable electricity	Policy
Pco2enrcons_1	−7.0057*** (2.1924)	−7.1371*** (2.2171)	−8.4422** (3.0035)	−8.6472** (2.9496)	−8.5286*** (2.7583)	−7.0769*** (2.2205)	CO_2 emission by energy consumption with 1 year lag	
ppaper_8	0.1558* (0.0773)	0.1582 (0.819)	0.1311 (0.0748)	0.1373 (0.0694)	0.1562 (0.0959)	0.1675 (0.0936)	Papers with 8 years lag	Science
ppatent		0.1185 (0.1450)	0.0655 (0.1527)	0.0702 (0.1512)	0.0561 (0.1513)	0.1129 (0.1419)	Patents	Technological
feedn	1.1259*** (0.3176)	1.1446*** (0.3167)				1.2724** (0.4482)	Feed-in tariff	User and Market
buldngreq			0.6375** (0.2657)			−0.2526 (0.5690)	Sustainable building requirements	
netmetr				0.3512 (0.2404)		−0.2344 (0.3690)	Net metering	
taxcrd					0.6635 (0.5682)	0.3659 (0.5491)	Tax credits	
Constant	0.3311*** (0.1111)	0.2843** (0.1243)	0.6095*** (0.9167)	0.6076*** (0.0865)	0.5544*** (0.1575)	0.2670 (0.1401)	Constant term	
R2 (within)	0.2172	0.2202	0.1829	0.1778	0.1846	0.2248	Coefficients of determination	
R2 (between)	0.6580	0.6624	0.5732	0.5198	0.5182	0.6919		
R2 (overall)	0.2474	0.2502	0.2032	0.1928	0.1984	0.2585		
Prob > F	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	F-statistic	
Wooldridge Autocorrelation Prob > F	0.2667	0.2139	0.2019	0.2006	0.2054	0.2051	Autocorrelation test	

Notes: a) different delays for *ppatent* and *ppaper* (lags of 1–10 years) were tested. b) Robust standard errors in parentheses. Significance:
* 10%.
** 5%.
*** 1%.

studied by means of a panel structure, as it allows for the analysis of longitudinal data at a country level. The selected countries were Austria, Australia, Canada, France, Germany, Israel, Italy, Japan, Korea, Mexico, Spain, Sweden, Switzerland, the United Kingdom and the United States. The selection of countries was limited to the list of countries in the IEA reports [27], since these reports show implemented measures that have driven the global deployment of PV. Seven countries (Canada, France, Germany, Italy, Japan, Spain and the United States) were considered as they were listed in five rankings of Renewables Energy Policy Network for the 21st Century (REN21) in 2012 [38]. The selection of the rankings considers the following criteria: a) annual capacity additions of solar PV; b) investment in new capacity; c) total capacity of renewable energy (not including hydropower); d) total capacity of Solar PV; and e) total PV per capita [38]. These lists show the key actors in PV and RE. Other countries were selected considering that they are also part of the OECD countries (Austria, Australia, Israel, Korea, Mexico, Sweden, Switzerland and the United Kingdom). Unfortunately, other countries that have been critical in PV deployment are not considered in this study because of the lack of information about them. For example, the placement of China in the REN 21 rankings reveals that this country is a key role model in PV deployment but it is not included in the IEA reports [27]. In addition, its information about PV systems is recent, which could shorten the period of study for the panel structure. Hence, it was not included in this study.

The variables were selected considering the ST regime, so that at least one variable could represent one of the regimes. Table 7 summarizes the variables and their related regimes. We assumed that the addition of PV capacity (*PCumInstPV*) is a function of nine explanatory variables (see Table 7 and Table 8). For the technological regime, which refers to product specification, the variable is the number of patents (*ppatent*), which is an accepted measure of innovation activity (data from WIPO database). For the science regime, which refers to research activity, the variable was the number of scientific papers (*ppaper*) [data from Scopus database]. These particular variables (*ppatent* and *ppaper*) were monitored for an additional ten years before the other data, because it was expected that their impact would occur later than when they were issued.

For the policy regime, which refers to the formal rules of technology, two variables were considered; one was the net consumption of renewable electricity (*Prnweleconsu*), and the other was the CO_2 emissions from energy consumption (*Pco2enrcons*). These variables may represent the results of the countries' energy policy towards RE; delays of up to four years were used to observe the influence of policies over time. For the socio-cultural regime, which refers to the symbolic meaning of technology, the variable was oil reserves (*Poilreserv*), assuming that countries are classified based on their oil reserves. The possession of reserves allows for assessment of the energy independence and energy security of a given country (for policy and socio-cultural regimes, data comes from the OECD database)

Finally, for the user-and-market regime four support instruments were considered: feed-in tariffs (*feedn*), net metering (*netmetr*), tax credits (*taxcrd*) and sustainable building requirements (*buldngreq*). These are binary variables (see Table 8) and represent whether or not the given instrument had been implemented in a given year, for a given country (data from IEA). To address the problem of autocorrelation, the annual percentage change of the variables (except for the binary ones) was used. The correlations among the variables can be seen in Table 9 and in Appendix B.

The analysis method used was fixed-effects Ordinary Least-Square (OLS) regression. We used a panel data since it allows controlling for unobserved heterogeneity [39,40]. Examples of similar application are those made by Shrimali and Kniefel [13], Marques and Fuinhas [30] and Carley [19]. Although there are missing data, the constructed panel was balanced.

It is assumed that PV capacity is a function of variables that vary across time t (1992–2011) and countries i (15 countries).

$$Y_{it} = \beta_0 + \beta_k X_{k,it} + \gamma_k d_{k,it} + a_i + u_{it} \quad (2)$$

where:

- Y_{it} is the dependent variable (i = country and t = time.)
- β_0 represents the constant term.
- $X_{k,it}$ represents the control quantitative variables
- β_k represents the regression coefficients of the control variables
- a_i is the unobserved effect or unobserved heterogeneity
- u_{it} is the error term (time-varying error)
- $d_{k,it}$ represents the control binary variables (dummies)
- γ_k represents the regression coefficients of the control binary variables

Some of the quantitative variables have numbers appended to them, which indicate the number of years of lag (For instance, '*ppaper_8*' is the control variable "*paper*" with a lag of 8 years). The software package STATA/SE13.0 was used to obtain the results. To address heteroscedasticity, a fixed-effects robust regression was used.

4. Results

The number of observations was 211, and the number of groups was 15. The correlations between the variables suggest no collinearity among the variables (see Table 9 and Appendix B). Table 10 summarizes our results and shows six regressions. Overall, the regression models were highly significant (Prob > F = 0.0000). A Wooldridge test for autocorrelation failed to detect any autocorrelation in any of the tested models.

The results show that the first three variables, oil reserves with a delay of four years (*Poilreserves_4*), net consumption of renewable electricity (*Prnweleconsu*) and CO_2 emissions from energy consumption with one lag year (*Pco2enrcons_1*), are statistically significant. Their signs and their respective regression coefficients (RCs) are consistent in the six models. *Poilreserves_4* and *Pco2enrcons_1* suppress the addition of PV capacity, while *Prnweleconsu* promotes it.

The variable for the science regime with a delay of eight years (*ppaper_8*) is significant at 10% only in model 1, although its coefficient and sign are consistent in all the models. Suggesting that scientific productivity may promote the addition of PV capacity. The variable representing innovation (*ppatent*) was no significant in any of the six models. It must be noted that these two control variables (*ppaper_8* and *ppatent*) were tested with different lags over a period of 10 years, only results in which one of them were significant are shown.

The control variables for the market-and-user regime, feed-in tariff (*feedn*) and sustainable building requirements (*buldngreq*) were significant for *feedn* in models 1, 2 and 6, while for *buldngreq* only in model 3. The sign and RC of *feedn* was consistent in all the models where it appears, including when all the other market instruments were tested at the same time. In contrast, *buldngreq* was significant only when the other promotion instruments were omitted. Both instruments (*feedn* and *buldngreq*) have a positive impact towards adding PV capacity. On the other hand, the control variables representing net metering (*netmetr*) and tax credits (*taxcrd*) were statistically no significant in the models, both in conjunction with other instruments and when other instruments were omitted.

Hence, the results suggest that the variables that promote the deployment of PV were the net consumption of renewable electricity (*Prnweleconsu*), feed-in tariffs (*feedn*), sustainable building requirements (*buldngreq*) and scientific publications with a delay of eight years (*ppaper_8*). Although public policy to increase the RE portfolio, measured by net consumption of renewable electricity, is the factor with the greatest impact (361%), the use of feed-in tariffs is also very relevant (112%). Additionally, the data shows that feed-in tariffs promote PV deployment more than the sustainable building requirements (63.7%).

Furthermore, the variables with a negative impact with PV deployment are oil reserves with a delay of four years (*Poilreserv_4*) and CO_2 emissions from energy consumption with one lag year (*Pco2enrcons_1*). The variable *Pco2enrcons_1* has the highest negative impact of all the studied factors (700%). Although this result is consistent with the negative impact of oil reserves, by contrast the RC of the latter variable is low (2.9%).

Finally, one of the most interesting results is that the positive impact of scientific publication towards the deployment of installed PV capacity is only evident after a lag time of at least eight years. Surprisingly, patents were no significant in none of the periods shorter than ten years. Another interesting finding was that the only policy instruments that promoted global PV deployment were feed-in tariffs and sustainable building requirements.

5. Discussion

We tested the drivers of exponential growth of PV capacity using the five regimes of ST system. ST theory and MLP support the thesis that technological niches, such as PV, require specific policies with an holistic approach (acting on both supply and demand) in order to compete with established markets (such as the fossil fuel market). Science and technology regimes are related to supply meanwhile policy, socio-cultural and user-and-markets regimes are related to demand. For the technological regime, it was unexpected that the production of PV patents (*ppatent*) did not significantly promote annual cumulative installed PV capacity, at least not in the time period considered (delays of up to ten years). If we consider that technological niches break into a dominant regime by innovating, it might be that the impact of PV patents on PV installed capacity takes more time than the period of analysis. Nevertheless, for the science regime, our results suggested that scientific articles impacted PV deployment with a delay of eight years. One reason of science regime driving PV deployment might be the fact that science-related work prepares high qualified human resources and this kind of personnel supports deployment of PV market by technology transfer [17]. Our results of supply policies suggest robust evidence that PV deployment has required long lasting supply policies in the study group and that production of knowledge has been important, but it is not enough to drive PV deployment as Peters et al. [18] suggested.

On the other side, for policy regime the negative correlation between CO_2 emissions by the energy sector (*Pco2enrcons_1*) and installed PV capacity (*PCumInstPV*), which is considered zero-emissions, is consistent with the results of other studies [1]. However, this does not mean that all reductions of CO_2 emissions result from increases in PV installation. In fact, wind energy and biofuels are also sources for the reduction of emission that compete strongly with PV. Policies such as energy efficiency programs and new technologies for carbon capture and sequestration also need to be considered [15]. Nontheless, the statistical effect of the CO_2 emissions on added PV capacity might be interpreted as robust evidence that low-carbon policies in the group that was studied have been favorable to PV deployment. In fact, policies such as renewable energy targets on primary and final energy production as well as targets on installed renewable energy are seen as critical drivers of RE [20]. However, it must be said that a state policy towards RE might have a different impact on each renewable technology [13]. For instance, the positive correlation between the net consumption of renewable electricity (*Prnweleconsu*) and the growth of photovoltaic capacity (*PCumInstPV*) does not mean that PV is the only renewable option. The empirical evidence suggests that PV installed capacity is greatly increased by a state policy that encourages the consumption of renewable electricity.

Socio-cultural regime was examined with countries' oil reserves (*Poilreserv_4*). Results suggest a negative correlation towards the growth of PV (*PCumInstPV*). Oil reserves is an indicator that had not been previously tested towards RE in other studies, which instead have used oil prices as an indicator. There was a "boom" in the search for renewable energy sources after the oil crisis in the 1970s but global energy production still relies largely on fossil fuels [3,41]. The evidence suggest that levels of oil reserves takes four years to impact in RE policies towards PV deployment. Although countries' search of energy options has not been consistent over time [42], the evidence suggests that exponential additions of PV capacity have been favored. Social sustainability and energy security characteristics that are allowed by PV capacity [21] might be some explanations of the negative correlation towards oil reserves.

Support mechanism of RE or PV market are usually the center of analysis in previous studies. Our results suggest that two instruments to promote RE seem particularly relevant to the growth of installed PV capacity. One instrument is the feed-in tariff (*feedn*) which is a policy instrument that has proved its usefulness towards the PV market. The relevance of the feed-in tariff has been noted in other academic works such as Alagappan et al. [31] and Muhammed-Sukki et al. [12]. While this policy instrument appears to be highly successful, it has not been without its caveats. This instrument gives guaranteed payments to generate electricity; however, problems have appeared in receiving the payment or there have been some delays in reimbursements. Another favorable option is to institute sustainable building requirements, which also favors PV deployment but to a lesser degree compared to the feed-in tariff. On the other side, an interesting result is that in our sample, the presence of market instruments such as net metering (*netmetr*) and tax credits (*taxcrd*) did not significantly promote PV deployment. The result of tax credits was unexpected since one could presume that upfront investment is one driver that holds back PV deployment, however, the evidence suggest that this subsidy has not been particularly effective. For net metering (*netmetr*), which is a mechanism designed for competitive electricity market, its effectiveness might change as PV prices reach complete 'fuel parity'.

6. Conclusion

This paper provides empirical evidence of some factors that drive PV deployment with a holistic approach, using the theory of technology transition, specifically, MLP and the ST system theory. Our results suggest robust evidence that the science, policy, and user-and-market regimes promote the entrance of PV into a ST regime dominated by fossil fuels. PV installed capacity presents a positive response to knowledge creation, in this energy sector, and to policies that support production of PV power; also to a competitive PV market and to the promotion of renewable electricity consumption. Surprisingly, there was no evidence of the impact of innovation in the PV technology sector, considering that innovation is a key factor in technology development.

It is important to mention that the analysis that was done, do not suggest any causality effect, only positive or negative correlation. Nevertheless, by considering this sector as an integrated system, decision-makers may be empowered to develop intervention projects or more effective policy instruments. More research using different approaches is still needed, for example, to study the impact of innovation on PV deployment. The synergistic and competitive effects that different renewable technologies have on development and deployment among them are also interesting to study. This research can be extended testing more variables and analyzing the results by regions. However, one constraint is the lack of complete PV data. Another caveat involves the aggregate data for modeling purposes, because aggregate variables cannot clearly indicate the specific effects on the dependent variable.

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Appendix A.

Searching scripts

- For patent: WIPO PCT, the time period for searching is year by year.

Sections read of the International Patent Classification (IPC).

✓ Section C (chemistry, metallurgy)

✓ Section F (lighting, heating, ranges ventilating)

✓ Section G (physics)

✓ Section H (electricity)

- For Paper: Scopus

AFFILCOUNTRY(__________) AND KEY(*photovoltaic module*) OR KEY(*solar cells*) OR KEY(*solar concentration*) OR KEY(*photovoltaic*) AND PUBYEAR > 1979 AND PUBYEAR < 2013

Appendix B.

Variable Correlations

Figs. B1 and B2.

	PCumIn~V	Prnwel~u	Pco2en~s	Poilre~v	feedn	netmetr	taxcrd	buldng~q
PCumInstPV	1.0000							
Prnweleconsu	0.3908	1.0000						
Pco2enrcons	-0.0991	-0.1170	1.0000					
Poilreserv	-0.0067	-0.0197	0.0629	1.0000				
feedn	0.3132	0.1120	-0.1599	-0.0378	1.0000			
netmetr	0.0228	-0.0298	-0.1624	-0.0357	0.4070	1.0000		
taxcrd	0.0729	-0.0441	-0.0824	-0.0351	0.2245	0.3858	1.0000	
buldngreq	0.1119	-0.0092	-0.1109	-0.0211	0.5385	0.4011	0.2542	1.0000

Fig. B1. Dependent variable PCumInstPV and control variables correlation (except ppatent and ppaper).

	PCumIn~V	ppaper_1	ppaper_2	ppaper_3	ppaper_4	ppaper_5	ppaper_6	ppaper_7	ppaper_8
PCumInstPV	1.0000								
ppaper_1	-0.0267	1.0000							
ppaper_2	-0.0493	-0.2928	1.0000						
ppaper_3	-0.0706	-0.0651	-0.2924	1.0000					
ppaper_4	-0.0172	0.0676	-0.0245	-0.3068	1.0000				
ppaper_5	-0.0715	-0.0272	0.0651	-0.0302	-0.2907	1.0000			
ppaper_6	-0.0197	-0.0537	-0.0645	0.0431	-0.0344	-0.2921	1.0000		
ppaper_7	-0.0087	0.0527	-0.0912	0.0487	0.0264	-0.0454	-0.2399	1.0000	
ppaper_8	-0.0022	0.0521	0.0635	-0.1031	0.0109	-0.0005	-0.0859	-0.2526	1.0000
ppaper_9	-0.0667	-0.0699	0.0889	0.0637	-0.0810	0.0325	-0.0197	-0.0212	-0.2565
ppaper_10	-0.0884	0.0782	-0.0923	0.1248	0.0396	-0.0749	0.0261	-0.0024	-0.0124
ppatent_1	0.0325	-0.0944	-0.0282	0.1460	-0.1172	0.0782	0.0632	-0.0728	0.0168
ppatent_2	0.0504	0.0259	-0.1023	0.0250	0.1133	-0.0562	0.0414	-0.0108	-0.0718
ppatent_3	0.0704	0.1151	0.0459	-0.1363	0.0060	0.0946	-0.1087	0.0033	-0.0082
ppatent_4	0.1373	-0.1211	0.1036	0.0179	-0.1276	0.0566	0.0932	-0.1006	-0.0111
ppatent_5	-0.0593	0.0873	-0.1230	0.1063	0.0770	-0.1648	0.0758	0.1099	-0.0621
ppatent_6	0.0867	-0.0518	0.0816	-0.1349	0.1340	0.0397	-0.1350	-0.0098	0.1586
ppatent_7	0.0368	0.0582	-0.0911	0.0930	-0.1564	0.1409	0.1206	-0.1099	-0.0320
ppatent_8	-0.0309	0.1536	0.0456	-0.1085	0.1114	-0.1947	0.1910	0.1169	-0.0952
ppatent_9	-0.0378	-0.0978	0.1171	0.0849	-0.1075	0.1422	-0.1762	0.3302	0.0766
ppatent_10	-0.0671	0.1459	-0.1165	0.0892	0.0354	-0.0674	0.1717	-0.2121	0.2727

	ppaper_9	ppape~10	ppaten~1	ppaten~2	ppaten~3	ppaten~4	ppaten~5	ppaten~6	ppaten~7
ppaper_9	1.0000								
ppaper_10	-0.2616	1.0000							
ppatent_1	-0.0862	-0.0255	1.0000						
ppatent_2	0.0033	-0.0564	-0.2446	1.0000					
ppatent_3	-0.0796	0.0016	0.0185	-0.2846	1.0000				
ppatent_4	-0.0057	-0.0644	0.1326	0.0347	-0.2727	1.0000			
ppatent_5	-0.0056	-0.0023	-0.0520	0.1338	0.0199	-0.3039	1.0000		
ppatent_6	-0.1063	0.0092	-0.0303	0.0168	0.0938	0.0137	-0.2873	1.0000	
ppatent_7	0.0786	-0.0807	-0.0144	0.0286	-0.0239	0.0230	-0.0783	-0.2202	1.0000
ppatent_8	-0.0477	0.0782	0.0741	-0.0297	0.0085	-0.0041	0.0549	-0.0747	-0.2701
ppatent_9	-0.0661	-0.0483	-0.0272	0.1100	-0.0659	0.0426	-0.0143	-0.0033	-0.0730
ppatent_10	0.0463	-0.0787	0.0558	-0.0510	0.0771	-0.0864	0.0381	-0.0111	0.2004

	ppaten~8	ppaten~9	ppate~10
ppatent_8	1.0000		
ppatent_9	-0.2538	1.0000	
ppatent_10	-0.1175	-0.2363	1.0000

Fig. B2. Dependent variable PCumInstPV and control variables ppatent and ppaper (different lags over a period of 10 years).

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