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Determinants of solar photovoltaic deployment in the electricity mix: Do oil prices really matter?*

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Abstract

This paper investigates the determinants of solar photovoltaic (PV) deployment in the electricity mix for a panel of OECD and BRICS countries from 1997 to 2016 by paying particular attention to the impact of oil market conditions. Relying on a nonlinear, regime-switching specification, we show that rising oil prices stimulate PV deployment only if their growth rate is important, above 6.7%. Although we find that various other determinants matter—with the influence of some of them depending on the situation on the oil market—public policies play a crucial role. In particular, our findings show that feed-in-tariffs should be encouraged to ensure a continuous fight against climate change, whatever the dynamics followed by oil prices.

JEL Classification: Q4; Q42; C23; C24.
Keywords: Solar photovoltaic; Renewables deployment; Oil prices; Panel smooth transition regression.

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1 Introduction

While the fight against climate change represents the most important driver of international energy and environmental public policies, the objective of the Paris agreement seeking to limit the increase of global temperature below 2°C in 2100 seems to be hardly achievable with current trends (UNFCCC, 2019). Despite their crucial role in achieving this objective, energy sector industries indeed encounter difficulties in ensuring the energy transition as their greenhouse gases (GhG) emissions have followed a 5.77% upward trend between 1990 and 2016 in OECD countries. Global energy-related CO_2 emissions rose by 1.7% in 2018, with China, India, and the US accounting for 85% of new emissions (IEA, 2019). The electricity and heat production sector produces around half of the CO_2 emissions, highlighting the relevance of focusing on the transformation of the electricity sector. In response to growing energy needs and, in particular, electricity needs—global electricity demand increased by 4% in 2018—natural gas and renewables' consumption respectively rose by 4.6% and 4% in 2018 with renewables representing almost 45% of global energy generation growth (IEA, 2019). However, if the share of electricity generation from coal has registered a downward trend since 2007, this source of energy remains predominant in the world electricity mix.[1] Electricity generation from renewables grew by 7% in 2018, while electricity generation from nuclear increased by 3.3%, with China accounting for half of the new nuclear power plants. Regarding fossil-based energy sources, coal still stands as a major energy with a share representing 27% of total new electricity generation, as well as natural gas amounting at around half of total additional generation—an increase mainly due to the US power sector transformation and, more especially, the switch from coal to gas in many power plants. However, renewables, primarily wind turbines and solar photovoltaic (PV), tend to be more and more attractive.

Although investments in renewable energy (RE) play a central role in the energy transition, they have decreased from \$323 in 2015 to \$274 billion in 2016 (IRENA, 2019).[2] This decline is partly due to the falling costs of technology (-\$30 billion in 2016), as well as investment decisions induced by policy changes. This decreasing trend continued in 2017 for solar PV costs. As an example, utility-scale PV projects were down by 15% in 2017. However, despite the drop in investments, RE capacities have not decreased. On the contrary, solar PV capacities have increased by around 30% (IRENA statistics). According to BP Statistical Review 2019, this cost fall allows RE to reach 4% of the world energy consumption in 2018 against 3.6% in 2017, with an increase of 8.5% in OECD countries between 2017 and 2018.[3] However, in the current energy transition context and given the cost reduction trends in renewable technologies, this dynamic could have been more pronounced. This evolution

[1]In 2018, according to IEA, the global electricity generation mix is as follows: coal (38%), gas (23%), hydro and others (19%), nuclear (10%), solar and wind power (7%), and oil (3%).

[2]See Figure 1 in Appendix A.

[3]Excluding hydroelectric sources.

calls for an in-depth analysis to identify the main determinants of RE deployment to provide policymakers with real insights into designing their emissions target policies. This is the aim of the present paper.

In the economic literature,[4] the deployment of RE is explained by different factors generally split into three classes: (i) economic drivers, (ii) energy and environmental determinants, and (iii) political factors. While these various factors are well documented concerning the deployment of wind turbines technologies, the literature is more scarce regarding the solar PV side. This is an important lack since solar PV constitutes one of the most attractive RE sources since around 2010, and remains the only renewable technology that has registered an investment increase in 2017 (IRENA, 2019). From a macroeconomic perspective and to the best of our knowledge, only Chang et al. (2009) analyze interaction effects between determinants of RE production and economic growth. They show that the impact of energy prices on RE production depends on the GDP growth level. Only countries recording high economic growth levels respond to an increase in energy prices by deploying RE technologies. Macroeconomic variables and the oil price dynamics are yet interconnected,[5] and the conditions observed on the oil market could trigger or not a spillover effect on RE deployment. Specifically, one may expect that the deployment of PV depends on oil price changes. Obviously, such deployment is more likely to be stimulated when oil prices rise—increasing the attractiveness of more affordable alternative energy sources—than when they decrease. Taking these interactions into account is the main contribution of this article since, to the best of our knowledge, no study has been implemented so far on this topical subject.

To this end, we rely on the panel smooth transition regression (PSTR) framework introduced by González et al. (2017), which allows the effects of the determinants of solar PV deployment to switch between—at least—two states depending on oil price changes. The use of a non-linear model enables us to account for the leading role played by oil prices on energy markets,[6] and to assess to which extent their dynamics impact the deployment of solar PV depending on the level reached by the oil price growth rate.[7] In addition to analyze these interactions, our paper fills a gap in the literature as only a few studies exist on the drivers of solar PV deployment. As a further contribution, our variable of interest is the variation in the share of solar PV capacities in the total electricity mix, which is particularly relevant to analyze the role played by the deployment of solar PV in the energy transition. Indeed, growing

[4]See references in Section 2.

[5]For a survey, see, e.g., Brown and Yücel (2002) and Hamilton (2005).

[6]Note that the influence of gas or coal prices as driving the switch from one regime to another has also been tested, but their impact was non-significant.

[7]Regarding the related literature, Reboredo (2015) relies on copulas and shows that high oil prices encourage the development of the RE sector, and Shah et al. (2018) find that the link is particularly acute for the US with oil prices explaining 22% of the variance of investments in RE. See also the references in Section 2.

solar PV capacities do not necessarily reflect a process towards energy transition if fossil fuel capacities grow faster. Reasoning in terms of shares overcomes this issue as a positive share variation inevitably results in a higher growth speed of solar PV capacities compared to the total electricity mix, and thus illustrates substitution towards solar PV-based electricity. Finally, whereas most of the existing studies deal with quite reduced samples of countries, we consider a wide panel of 39 economies from 1997 to 2016, including both OECD and BRICS countries.

Our results show that oil market conditions play a key role in explaining the dynamics of solar PV deployment since they affect their main determinants: environmental commitments, nuclear-based endowments, and the solar PV potential. Specifically, an increase in oil price growth above 6.7% has a positive effect on solar PV by reducing the relative cost between oil and renewables, making this technology relatively more affordable. We find that fossil-based endowments in non-RE are significant drivers for solar PV development by slowing down the incentive to increase RE capacities. Foreign electricity trade, oil production variation, and nuclear capacities negatively impact the deployment of solar PV capacities. A rise in CO_2 emissions plays a negative role during periods of low oil price growth, reflecting a weak level of environmental commitment.

The rest of the paper is organized as follows. Section 2 reviews the literature on the determinants of RE deployment. Section 3 describes the data and methodology. Section 4 presents our findings, and Section 5 concludes the paper.

2 Literature review

Factors promoting the deployment of RE have been analyzed in many different ways.[8] Eyraud et al. (2011, 2013) study the determinants of green energy deployment using a panel fixed-effect estimator and conclude that five variables are statistically significant: (i) GDP in constant dollars, (ii) the long-term real interest rate, (iii) the relative price of international crude oil, (iv) a feed-in-tariff (FIT) dummy, and (v) the carbon pricing mechanism. Focusing on European countries, Marques et al. (2010) use a Fixed Effect Vector Decomposition (FEVD) model and show that both the lobbying efforts and activities from traditional key actors in fossil energy sectors (oil, coal and natural gas) and CO_2 emissions negatively impact RE technologies' development. Considering also the case of Europe, Papiez et al. (2018) conclude that countries with the lowest shares of RE in their energy mix show relatively high energy self-sufficiency, and countries which are not producers of their fossil sources are the ones where RE deployment is the highest. Aguirre and Ibikunle (2014) investigate the drivers of the development of RE from 1990 to 2010 by using a FEVD model. They find that environmental concerns matter in explaining RE deployment,

[8]See Bourcet (2020) for a recent literature review on the determinants of RE deployment.

while energy security appears to be non-significant. They also highlight that ensuring supply security does not encourage RE commitments.

Other studies aim at identifying the determinants of deployment of RE by focusing on specific RE technologies. In particular, Romano and Scandurra (2016a) propose an analysis comparing different types of RE, namely hydroelectric, solar, wind, and biomass. They highlight that the determinants vary according to whether one considers hydroelectric or non-hydroelectric technologies, i.e., solar, wind, and biomass technologies. CO_2 emissions positively explain the development of investments in hydroelectric technologies, but their impact is found to be non-significant for non-hydroelectric technologies. Policies supporting RE investments are significant for both cases, but the effect is stronger for non-hydroelectric sources. They also find that the availability of nuclear or geothermal energy in the electricity mix reduces the incentives to invest in RE. Regarding the nuclear question, Romano and Scandurra (2016b) show that the deployment of RE presents an inverse relationship with the share of nuclear power generation in the electricity mix for countries with nuclear activities. However, in countries with power generation based on fossil fuels, the deployment of RE depends on other different factors.

The role of political factors in RE deployment has been the subject of various studies. Bird et al. (2005), Menz and Vachon (2006), and Yin and Powers (2010) show that the Renewable Portfolio Standard[9] (RPS) mechanism in the US plays a major role in promoting RE deployment, while Delmas and Montes-Sancho (2011) demonstrate its negative effect on the development of RE capacities. However, when splitting utility ownership types between private-owned and publicly-owned electric utilities, the latter authors find a positive impact: investor-owned utilities are more responsive to RPS than publicly-owned electric utilities. Carley (2009) finds no evidence that RPS fulfills its objective of increasing the percentage of RE sources in the electricity mix. Other standalone countries' analyses raise the importance of political motivation: van Rooijen and van Wees (2006) for the Netherlands, Wang (2006) for Sweden, and Wüstenhagen and Bilharz (2006) for Germany.[10] Gan et al. (2007) compare incentive policies and instruments for those different countries. Through a panel data analysis, Polzin et al. (2015) study the effectiveness of public policies for the deployment of RE for institutional investors located in OECD countries. For mature technologies, RPS and tradable permit systems appear to be more effective than feed-in-tariffs (FITs). However, FITs prove to be more effective than subsidies when considering mature technologies. Considering also panel data for 26 European Union countries, Jenner et al. (2013) assess the effectiveness of FIT policies in stimulating solar PV and

[9] RPS is a regulation ensuring that a certain proportion of electricity production comes from RE sources.

[10] See also Shrimali and Jenner (2013) for a study of the impact of 12-state level policies in 16 US states over 1998-2009 on the cost and development of solar PV technologies. The effectiveness of policy incentives to increase solar PV capacity has also been examined by Crago and Chernyakhovskiy (2017) in the Northeast.

onshore wind power development. They show that while such policies significantly encourage solar PV, the interaction of policy design, electricity price, and electricity production cost has more impact on RE deployment than the policy adoption alone. Romano et al. (2017) investigate the role of policy instruments for developed and developing countries. For developing economies, fiscal policies are significant, while it is not the case for regulatory and public investments. For developed countries, fiscal policies and public investments appear to play a key role in promoting RE sources. When it comes to RE policy instruments, FITs emerge as the most effective tool in encouraging the deployment of RE at a lower price and a lower risk compared to other supporting mechanisms such as tradable green certificates.[11] Couture and Gagnon (2010), Fouquet and Johansson (2008), Kilinc-Ata (2016), Menanteau et al. (2003), Nicolini and Tavoni (2017), Rickerson et al. (2007), and Zhao et al. (2013) also conclude that FITs are effective RE instruments. Dijkgraaf et al. (2018) find a positive impact on RE as well, but specify that this effect is generally underestimated in the literature. However, del Río and Bleda (2012) suggest that FITs can be more effective when included in a mix of green policies. Cadoret and Padovano (2016) show for a panel of European countries that the manufacturing industry lobbying hampers the deployment of RE.

Traditionally, positive oil price shocks negatively impact economic growth by increasing inflation and unemployment,[12] oil being viewed as a hard-to-substitute input, especially for the transport sector. However, another perspective is to consider and analyze oil shocks in terms of investment opportunities. Indeed, high oil prices can stimulate investments in RE sources as these technologies become more profitable. Concerning this last point, some studies have examined the interactions between oil, natural gas, coal and electricity prices, and the deployment of RE sources. However, there is no consensus in the literature regarding the impact of the oil price level on GhG emissions. van Ruijven and van Vuuren (2009) conclude that the effect of high hydrocarbon prices on RE sources depends on the implementation (or not) of climate policies. Specifically, (i) with climate policies, high oil prices lead to more commitments towards RE sources, while (ii) without climate policies, they give rise to a shift from natural gas to coal for electricity production.[13] Vielle and Viguier (2007) argue that the impact of high oil prices would be lower than expected due to fuels' substitution effects, and because GhG emissions' reductions obtained *via* high oil prices would be unequally distributed across regions and sectors. Khan et al. (2017) suggest that the 2014 oil plunge from 114 dollars per barrel in June 2014 to 28 dollars per barrel in February 2016 has exerted no significant effect on the deployment of RE. Chang et al. (2009) focus on the link between economic growth, hydrocarbon

[11] Concerning the lower risk, see, e.g., Bürer and Wüstenhagen (2009), Butler and Neuhoff (2008), and Mitchell et al. (2006).

[12] See Blanchard and Gali (2007) and Hamilton (2003).

[13] More precisely, on the one hand, high prices of oil and natural gas increase the use of coal; on the other hand, the cost difference between fossil-based energy and non-carbon energy options decreases.

prices, and RE sources by relying on a Panel Threshold Regression model from 1997 to 2006 for OECD countries. They show that high-growth countries tend to react to a positive shock on oil prices by developing RE, while low-growth countries do not respond to high oil prices by changing their energy mix towards RE (mainly because of fiscal considerations). Another study conducted by Shah et al. (2018) targeting Norway, the UK, and the US and based on the use of Granger causality tests, suggests that movements in oil prices, GDP, and interest rates each contribute to the dynamics of the RE sector. Interestingly, the authors show that oil prices explain 22% of the total variance of RE investments for the US. Awerbuch and Sauter (2006) argue that RE investments can partly offset GDP losses implied by raising prices[14] through the GDP-oil effect. Rout et al. (2008) simulate fossil fuel price hikes scenarios from 2000 to 2030, and find that growing prices reduce CO_2 emissions by 23%.

Aguirre and Ibikunle (2014), Wüstenhagen et al. (2007), and Sadorsky (2009) focus on environmental commitments. Sadorsky (2009) finds that CO_2 emissions drive RE consumption. Dalby et al. (2018) examine green investments under policy uncertainty, and show that investments in RE are high when policy risk is weak and investors prefer a low FIT with a long-expected lifespan. Chassot et al. (2014) also conclude that policy uncertainty negatively impacts RE investment decisions. Furthermore, Lüthi and Wüstenhagen (2012) find that investors choose to invest in the country with the most favorable risk-return profile, and Mitchell et al. (2006) conclude that risks are lower when (i) regulators have a greater autonomy from elected politicians, and (ii) policy-making processes are more "rigid". Among other potential drivers of RE deployment, Masini and Menichetti (2013) investigate non-financial determinants and point out the role of institutional and behavioral factors for green investments. They show that investors seem to have very little faith in dedicated policy measures supporting RE technologies.

3 Data and methodology

3.1 The PSTR model

To analyze interactions between the determinants of the deployment of RE and the oil price dynamics, we rely on the PSTR methodology proposed by González et al. (2017). This specification allows these determinants to vary over time depending on the evolution of the price of oil, the change in the coefficients' value being smooth between—at least—two regimes.

Specifically, let $\Delta SC_{i,t}$ be the variation of the share of solar PV capacities in the total electricity capacities in country i at time t. The PSTR with two regimes can

[14] A 10% increase in RE can offset up to \$53 billion of GDP losses in the US and the European Union (EU), which corresponds to one-fifth of the RE investments' needs according to the European Renewable Energy Council.

be expressed as:

$$\Delta SC_{i,t} = \beta_1' X_{i,t} + \beta_2' X_{i,t} \times F(\Delta OP_t; \gamma, c) + \epsilon_{i,t} \tag{1}$$

with $i = 1, \ldots, N$, N being the number of countries, and $t = 1, \ldots, T$. F is a transition function, bounded between 0 and 1, and is given by:

$$F(\Delta OP_t; \gamma, c) = \left[1 + \exp\left(-\gamma \prod_{l=1}^{m} (\Delta OP_t - c_l) \right) \right]^{-1} \tag{2}$$

where ΔOP_t denotes oil price growth used as the transition variable,[15] γ is the slope parameter describing the transition speed between the various regimes, and $c_l = c_1, \ldots, c_m$ denotes the threshold parameters with $c_1 \leq c_2 \leq \ldots \leq c_m$. As mentioned by González et al. (2017), it is usually sufficient to consider a maximum value of 2 for m as it allows to capture commonly encountered types of nonlinearities.[16]

With this model, the effects of the determinants of RE deployment included in $X_{i,t}$ can vary depending on the change in the price of oil, and are bounded between β_1 in the first regime, i.e., $F(.) = 0$, and $\beta_1 + \beta_2$ in the second one, i.e., $F(.) = 1$.

Following González et al. (2017), we apply the PSTR methodology using a three-step strategy: (i) specification, (ii) estimation, and (iii) evaluation. First, we test the null hypothesis of linearity against the PSTR alternative to check the presence of nonlinearity linked to oil price growth.[17] We employ the bootstrapped version of the Lagrange-multiplier (LM) test with the residual-based wild bootstrap (WB) and the wild cluster bootstrap (WCB) to handle heteroskedasticity and cluster-dependency issues.[18] Second, we estimate the model using the nonlinear least squares (NLS) estimator on demeaned data. Finally, we evaluate the validity of our estimated model by applying the WB and WCB versions of (i) the time-varying specification test aiming at checking the efficiency of our PSTR specification against a time-varying parameter PSTR, and (ii) the no-remaining nonlinearity test aiming at testing a one-transition function PSTR against a two-transition function PSTR (see González et al., 2017).

[15]It should be noticed that we consider the price of oil in first-logarithmic variation and not in level to address unit root issues.

[16]Note that $m = 1$ implies the use of a logistic function, while $m = 2$ refers to a quadratic logistic function.

[17]Note that we also tested for the presence of nonlinearity using the growth rate of GDP per capita as the transition variable, but the tests failed to reject the null hypothesis of linearity (as for the growth rate of gas and coal prices).

[18]See González et al. (2017) for more details about these test statistics.

3.2 Explanatory and dependent variables

The explanatory variables included in $X_{i,t}$ in Equation (1) are chosen according to the literature previously reviewed in Section 2, selected by accounting for the importance of their effects and depending on data availability issues. Specifically, the determinants can be categorized into three groups, as detailed below.

First, we consider two economic determinants, namely economic growth and foreign electricity trade. Regarding economic growth, we use the growth rate of GDP per capita—in constant US dollars—to eliminate the effect of population growth.[19] As recalled by Marques et al. (2010) and Cadoret and Padovano (2016), the contemporaneous impact of GDP growth is hard to anticipate as high economic growth could stimulate RE consumption and production through an income effect, but could also dampen them due to the intermittency problem and "on the spot" availability. On the contrary, past economic growth should have a positive effect on RE production through higher resources that can be mobilized for RE deployment. Furthermore, by focusing our analysis on RE deployment in terms of variation in production capacities, we expect that the effect of GDP growth could be delayed. We also use foreign electricity trade—i.e., exports minus imports—as a measure of energy security. We expect a negative effect of international trade as electricity net importers could have more incentive to develop new electricity capacities—especially RE sources—than exporters.

Second, we consider various energy and environmental factors : (i) environmental commitments measured by CO_2 emissions, (ii) fossil-based energy endowments, (iii) nuclear based-energy capacities, (iv) energy prices, and (v) solar PV potential. Following Marques et al. (2010), Marques and Fuinhas (2011), and Romano and Scandurra (2016a), we use CO_2 emissions—in variation—per capita and kilowatt-hour (kWh) considered as a proxy of environmental commitments in the electricity market. The reduction of CO_2 emissions is at the very heart of energy transition policies and represents a means of measuring country efforts in terms of environmental commitments. We expect that the higher the variation in CO_2 emissions, the lesser the environmental commitment of the country at time t and so, the smaller the deployment of solar PV. We, therefore, anticipate a negative effect of CO_2 emissions' variations on solar PV deployment. We also use non-renewable energy endowments variables, such as the growth of oil production and coal production, as well as nuclear-based electric capacities. A negative effect is expected for these three variables, as an upward trend in these energy sources could create a barrier to RE deployment. Indeed, countries with increasing oil, coal or nuclear-based electricity production could be less interested in investing in RE as (i) economies with oil reserves usually have fossil-based energy assign for electricity generation as coal or gas, and (ii) those with

[19] In other words, we do not consider GDP in level as it is usual in the literature (see, e.g., Eyraud et al., 2011, 2013), as this variable contains a unit root.

nuclear capacities own an electricity sector with low GhG emissions. Furthermore, we follow Marques et al. (2010), Marques and Fuinhas (2011), and van Ruijven and van Vuuren (2009) and include as determinants of solar PV deployment the changes in the prices of oil and gas.[20] These three variables allow us to account for substitution effects between different energy sources in electricity production. We expect that an increase in energy prices could lead to incentives to develop solar PV capacities through an improvement in their relative profitability. The deployment of solar PV should also depend on annual sunshine hours and the geographical area, as in Marques et al. (2011). However, these variables being time-invariant and inappropriate in our retained specification,[21] we integrate solar PV potential of countries through the urbanization rate. Indeed, the higher the urbanization rate, the higher the number of buildings and thus, the higher the number of large roofs usable for solar-based electricity production. We, therefore, expect a positive effect of the urbanization rate on solar PV deployment.

Third, we include a political driver, namely the existence or not of FITs—relating to solar PV—as in Romano et al. (2017) among others. A FIT is a contract allowing to fix the price of electricity produced from RE sources during a specified period (usually between 15-25 years). This policy has been quite famous during the studied period due to its attractiveness for investors as it ensures a certain regularity of cash-flows. The related dummy variable takes the value 1 if the policy is at play in country i at time t, and 0 otherwise.[22] We expect the existence of FITs to stimulate the solar PV capacities deployment.

Turning to our dependent variable, we consider the variation in the share of solar PV capacity in the total electricity capacities. As mentioned by Bourcet (2020), the installed capacities in RE reflect the commitment of policymakers to engage the energy transition. Note that all explanatory variables are stationary and are expressed in growth rate terms, except FITs, the urbanization rate, the nuclear capacities share, and foreign electricity trade (see Table 3 in Appendix B for more

[20] Note that oil price growth is used both as an explanatory variable and as a transition variable. For gas prices, we rely on the available prices for each region. See appendix B for more details.

[21] Indeed, the first step of the PSTR estimation consists of removing the individual-specific means to eliminate the individual effects (González et al., 2017).

[22] It is worth mentioning that due to the inclusion of emerging countries in our sample, we cannot account for FITs through the level of the tariff or the duration of the contract, as in Dijkgraaf et al. (2018). We construct our dummy variable by using the information contained in the country reports of the International Energy Agency (IEA) and consider the FIT policy to be in force if the FIT is given for medium and large-scale projects (above 1 MW). If there is no change, the variable takes the value 1 the year corresponding to the starting date of the FIT until the policy ends for new projects. Concerning federal states (Australia, Canada, India, and the US) we proxy the country by the major state in terms of solar PV capacities (corresponding respectively to Queensland, Ontario, Karnataka, and California). Finally, we do not take into account feed-in-premium contracts as they correspond to the spot price plus a premium, meaning that such contracts are more risky than a fixed price for a given period.

Table 1: Panel of countries

OECD	Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Latvia, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, South Korea, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.
BRICS	Brazil, Russia, India, China, South Africa.

details, including all data sources).

3.3 Time period and sample of countries

We rely on annual data for 39 economies (see Table 1) from 1997 to 2016, focusing on OECD and BRICS countries.[23] Our choice of the starting date is guided by data availability considerations.

4 Empirical results

The results from the estimation of our PSTR specification are presented in Table 2. We start by checking the existence of nonlinearity with oil price growth as the transition variable in Equation (1). As shown, the null hypothesis of linearity is rejected at the 5% significance level when accounting for cross-sectional dependence in the residuals. This justifies the use of a nonlinear, PSTR specification, indicating that the effect of some determinants of RE deployment depends on the behavior of oil prices. It is worth mentioning that our estimated model successfully passed all the misspecification tests. Indeed, in all cases, the null hypothesis of our PSTR specification—against either a time-varying parameter PSTR or a two-transition function PSTR—is never rejected, whatever the bootstrapping methodology used.

Regarding the transition function, the threshold parameter—i.e., the value of the annual growth rate of oil prices for which the transition function takes the value of 0.5—is estimated at 6.7%. Hence, the first regime corresponds to periods in which the price of oil decreases or exhibits a quite low growth rate, i.e., below 6.7%. The second regime refers to a high increase in oil prices, above 6.7%. These two regimes can be interpreted as reflecting two main conditions on the oil market: (i) "calm" or "normal" periods, characterized by a decline or a quite stability in oil prices, and (ii)

[23]Iceland has been removed from our panel due to its particular electricity mix based on hydroelectric (70%) and geothermal (30%) sources. Lithuania is also excluded from our analysis as it has joined OECD only since 2018.

periods of pressures on oil prices, hereafter referenced as "boom" periods. The estimated model reported in Table 2 thus accounts for the fact that some explanatory variables have a different impact on RE deployment depending on the conditions on the oil market, i.e., "normal" or "booming".

Let us now consider the two economic determinants, namely economic growth and foreign electricity trade, both variables being one-period lagged. These variables are significant in both regimes, i.e., whatever the oil market conditions. In more detail, past economic growth exerts a negative effect on RE capacities. Here, we go further than Cadoret and Padovano (2016) who highlight an adverse impact of contemporaneous economic growth on the share of RE in gross final energy consumption. Indeed, while these authors find that economic growth slows down RE deployment in terms of consumption, we show that this variable also negatively impacts the share of RE capacity in the energy mix. The direct negative effect on consumption would be due to the high elasticity of fossil-based energy consumption. However, this one is also transmitted in terms of RE deployment as the share of solar PV capacity in the electricity mix decreases by 2.9 percentage points for each percent of the increase in past economic growth. Based on the assumption that solar PV capacities do not decline, past economic growth could thus lead to additional deployment of fossil-based electricity capacities to address the supplementary energy needs. Turning to the past value of foreign electricity trade, it is associated with a decrease in solar PV capacities. More specifically, an increase of one GWh in the past balance of electricity trade leads to a reduction of 8.9×10^{-6} percentage point in the solar PV share. This result was obviously expected as the net importers of electricity have an additional incentive to deploy RE-based capacities to reduce their trade deficit: this is the well-known double dividend of RE deployment.[24] This result could also be interpreted from a geopolitical point of view as foreign electricity trade could be seen as a proxy for energy insecurity in the electricity sector. The double aim to reduce foreign trade deficit and energy dependency could lead to incentives in RE deployment in addition to GhG emissions' reduction.

Concerning the various energy and environmental explanatory variables included in our specification, their respective effect—except for fossil-based energy endowments—depends on the oil market conditions. First, environmental commitments—measured by the past variation of CO_2 emissions per capita and per kWh in the electricity mix—impact the solar PV deployment positively. Indeed, a 1% increase in CO_2 emissions variation leads to a decrease in the share of solar PV capacities in the electricity mix by 0.43 percentage point during "normal" periods on the oil market. On the contrary, in "boom" times, the environmental commitment of OECD and BRICS countries appears to be non-significant in stimulating solar PV deployment. The higher the price pressures on the oil market, the higher the interest for countries to develop solar PV capacities to minimize the impact of oil prices on electricity

[24]See, among others, Criqui and Mima (2012).

Table 2: PSTR estimation results

	Regime 1	Regime 2
Economic growth$_{i,t-1}$	-2.900^{**}	-2.900^{**}
Foreign elec. trade$_{i,t-1}$	$-8.922 \times 10^{-6**}$	$-8.922 \times 10^{-6**}$
CO_2 growth$_{i,t-1}$	-0.433^{**}	-0.065
Oil prod. growth$_{i,t}$	-0.037^{**}	-0.037^{**}
Coal prod. growth$_{i,t}$	0.117	-0.076^{**}
Nuclear capacity share$_{i,t}$	-9.731^{***}	-9.058^{***}
Gas price growth$_{i,t}$	0.383^{**}	-0.050
Oil price growth$_{i,t}$	-0.096	0.734^{***}
Urbanization rate$_{i,t}$	5.119^{***}	4.663^{***}
FIT$_{i,t}$	0.443^{***}	0.443^{***}
c	0.067^{***}	
γ	119.3^{**}	
WB Linearity test	0.055	
WCB Linearity test	0.047	
TVP parameters WB test	0.999	
TVP parameters WCB test	0.999	
RNL WB test	0.942	
RNL WCB test	0.977	

Note: *** (resp. **, *) denotes significance at the 1% (resp. 5% and 10%) level based on robust standard errors. WB (resp. WCB) Linearity test is the result of the test checking the null hypothesis of linearity against the PSTR model with residual-based wild (resp. wild clustered) bootstrap. The TVP parameters WB and WCB tests check the null hypothesis of our PSTR specification against the alternative hypothesis of time-varying PSTR. The RNL WB and WBC tests mention the results of tests checking the null hypothesis of our PSTR specification against the alternative hypothesis of PSTR with two transition functions.

prices, whatever their willingness to fight against climate change through reduction in CO_2 emissions. Second, fossil-based energy endowments, in terms of oil production growth, slow down the deployment of RE electricity capacities regardless of price conditions on the oil market. An increase of one million barrels per day in oil production is associated with a decrease of 0.037 percentage point in solar PV share growth. This result is in line with Papiez et al. (2018), highlighting higher RE deployment in countries that are not producers of their fossil sources. While we could expect that an increase in oil production could have a positive effect on solar PV deployment in times of booming oil prices by rising energy firms' profits and, in turn, generating a transfer of these financial resources in renewable deployment, our results contradict this expectation. Indeed, the impact of oil endowments does not differ between the two regimes. Third, the growth rate of coal production[25] harms solar PV deployment only during "boom" periods in the oil market. During regimes

[25]Note that we also included the growth rate of gas production in our specification, but this variable was found to be non-significant whatever the considered regime.

of high growth in the price of oil, countries are more prone to produce coal-based electricity, providing coal producers with higher financial resources. However, as a 1% increase in coal production leads to a decrease of 0.07 percentage point in solar PV deployment, the additional financial gain seems not to be invested in deploying solar PV capacities. Fourth, a negative effect is found regarding the nuclear capacity share in the electricity mix during "normal" and "boom" periods. The presence of nuclear plants hampers the deployment of solar PV, albeit to a lesser extent, in times where oil price growth is higher than 6.7%. As expected, countries with low GhG emissions thanks to nuclear power plants tend to have less incentives to deploy solar PV. Fifth, Table 2 shows an interesting result concerning fossil energy prices. Gas price growth has an effect on solar PV deployment during "normal" periods, while oil prices are at play during "boom" periods. More specifically, a 1% increase in gas price growth leads to 0.38 percentage point rise in PV deployment when oil price growth is lesser than 6.7%. On the contrary, in times of high oil price growth, a 1% increase in oil price growth raises by 0.73 percentage point the solar PV share. As expected, all these fossil energy sources could be seen as substitute energies compared to RE, and a rise in their prices thus allows solar PV relative profitability to increase leading to its deployment. Sixth, our results confirm our expectation of a positive effect of the urbanization rate—which accounts for the potential in solar PV installation—on solar PV deployment. An increase in the urbanization rate has a higher effect during "normal" periods, indicating that pressures on oil prices tend to reduce the positive impact on the share of solar PV capacity.

Finally, the political driver proxied by the existence of FITs policy positively affects solar PV deployment regardless of price conditions on the oil market. Adopting this policy is associated with an additional increase in the share of solar PV capacity of 0.44 percentage point per year compared to countries without FITs. By setting the price of electricity during a fixed period for RE sources, policymakers can have an impact on RE deployment. This result is in line with the existing studies presented in Section 2. Furthermore, there is no interaction effect with oil price growth, meaning that the FITs policy is always effective whatever the conditions on the oil market. This result is obviously quite reassuring from a policy-maker point of view.

On the whole, our analysis emphasizes three kinds of determinants regarding the deployment of solar PV. The first category concerns drivers which do not depend on oil market conditions—or to a small extent—: (i) past economic growth, electricity independence, and fossil fuel endowments which influence negatively RE deployment, and (ii) the urbanization rate, as well as FITs which exert a positive effect. Second, two variables play a role in solar PV deployment only when oil price growth is lower than 6.7%: past variation in GhG emissions and gas price growth, which have a negative and positive effect, respectively. Finally, the oil price variation affects positively solar PV capacities only if its annual growth exceeds 6.7%, putting forward the existence of an asymmetric and nonlinear effect of oil prices on RE deployment.

5 Conclusion and policy implications

This paper aims at identifying the determinants of solar PV capacities' deployment, and at investigating their dynamics depending on the conditions on the oil market.

Estimating a PSTR model on a wide sample of countries, we show that the dynamics of oil prices affect various determinants of solar PV deployment. Interestingly, an increase in oil price growth above 6.7% stimulates solar PV capacities: rising oil prices reduce the relative costs between oil and renewables, making renewable investments relatively more affordable. We also find that energy factor endowments are significant drivers for solar PV development. Foreign electricity trade, oil production variation, and nuclear capacities negatively impact the development of solar PV capacities. CO_2 emissions play a negative role during "normal" conditions on the oil market, which may be the result of a lesser or insufficient level of environmental commitments from economies during the studied period. However, policy support (FITs) remains essential in the development of renewables, whatever the dynamics of oil prices.

According to IEA (2017), the share of renewable-based electricity in the world electricity mix has to increase from 23% in 2015 to 59-97% in 2050—depending on the retained scenario—to attain a global warming target of 1.5°C above pre-industrial levels. In its latest report, IEA (2019) estimates in its Sustainable Development Scenario—the only scenario that allows a compatible pathway with global warming below 2°C—that RE investment needs will have to reach $649 billion per year between 2019 and 2030 and $807 billion between 2031 and 2040. Among these investments, IEA estimates that those in the solar PV sector alone should represent $169 billion per year—or 32% of total investments in the electricity sector between 2019 and 2030—and $189 billion between 2031 and 2040—or more than 35% of total investments in the global electricity sector. Achieving this scenario requires many drivers: reducing global energy intensity by 3% per year (compared to 1.2% in 2018), taking advantage of the lower costs of low-carbon technologies to generate a rapid transition from coal to RE in Asia, and bringing all stakeholders—investors, governments, and companies—to focus their efforts on the fight against global warming. Solar PV—as well as biomass and wind—must then play a major role in the RE electricity generation regardless of the pathway followed.

However, despite its significant impact on solar PV deployment, only twelve countries in our panel—i.e., around 30% of our countries—apply a FIT-based policy in 2016. Even if the conditions on the oil market matter for the deployment of solar PV, we show that the role of public policies is crucial. This role is effective whatever the situation on the oil market, indicating that FITs or other instruments sharing similar targets—such as green certificates, Renewable Electricity Standards (RES), and Renewable Portfolio Standards (RPS)—have to be developed to ensure a continuous fight against climate change. In other words, whereas tightened oil market conditions may temporary contribute to a reduction in CO_2 emissions, only structural reforms based on public policies will help in durably achieving this objective.

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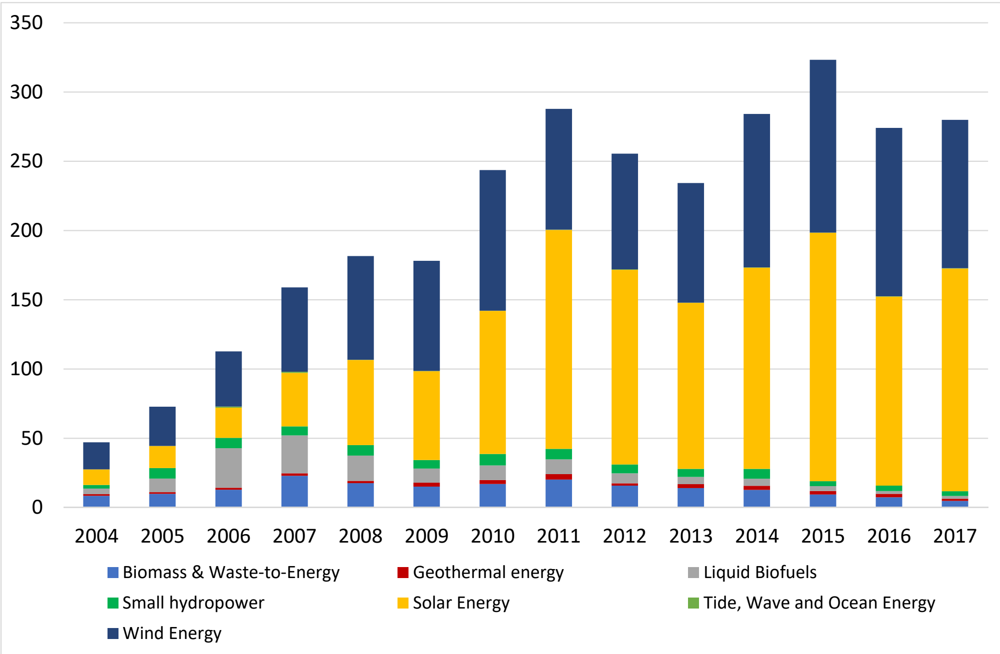
A Appendix. World investments amounts in renewable energy

Figure 1: Investments in renewable energy (in billion US dollars)



Note: Authors' calculations based on data extracted from IRENA.

B Appendix. Data description

Table 3: List of variables

Variable	Unit	Sources
Solar PV capacities	MW	Enerdata
Economic growth	GDP per capita (constant 2010 US dollar)	Enerdata
Foreign elec. trade	GWh	Enerdata
CO_2 emissions	gCO_2 per kWh and per capita	Enerdata
Oil production	million barrels per day	Enerdata
Nuclear capacities	MW	Enerdata
Gas price	US dollars per million Btu	BP statistics
Oil price	US dollars per barrel (Brent)	World Bank
Urban rate	%	Enerdata
FIT_t	dummy (1 or 0)	IEA, EIA, OFGEM, NREL, US Department of Energy, California Public Utilities Commission, , Ministry of New and Renewable Energy (India)
Transformed variable	**Unit**	
Solar PV capacities variation$_{i,t}$	Percentage points	
Economic growth$_{i,t-1}$	Lagged GDP per capita growth %	
Foreign elec. trade	GWh	
CO_2 growth$_{i,t-1}$	Lagged CO_2 emissions per capita and per kWh growth (%)	
Oil prod. growth$_{i,t}$	%	
Nuclear capacities share$_{i,t}$	%	
Gas price growth$_{i,t}$	%	
Oil price growth$_{i,t}$	%	
Urban rate$_{i,t}$	%	
$FIT_{i,t}$	dummy (1 or 0)	