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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 exceeds 6.7% per annum. 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.

JEL Classification: Q4; Q42; C23; C24.
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1 Introduction

While the fight against climate change represents the most important driver of international energy and environmental public policies,[1] 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 3.32% upward trend between 1990 and 2018 in OECD countries (7.24% between 1990 and 2016; source: OECD).

Within this context, OECD countries and the BRICS have implemented policies to limit global warming, in which renewable energies and, especially, solar photovoltaic (PV) are of particular importance. Following the Paris agreement, many countries have made commitments concerning their energy consumption or production by 2030. For instance, regarding the percentage of energy consumption from renewables, the European Union set for 2030 a target of 32% renewable energy (RE) at least. Brazil aims at achieving 45% of renewables in the energy mix, China will increase the share of non-fossil energy sources level in the total primary energy supply to around 20%, and India will augment the share of non-fossil based energy resources to 40% of installed electric power capacity—all these targets having to be reached by 2030. Investments in RE and, in particular, the deployment of solar PV could help countries to achieve their goal.

Although investments in RE play a central role in the energy transition, they have decreased from \$323 billion in 2015 to \$274 billion in 2016 (UNEP, 2017).[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, and solar PV capacities have increased by around 30% from 2016 to 2017 (IRENA statistics).[3] 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.[4] However, in the current energy transition context and given the cost reduction trends in renewable

[1]Other motivations are worth mentioning, such as limiting local air pollution (Coady et al., 2017) or ensuring the energy security strategy of countries by reducing fossil fuels imports (Criqui and Mima, 2012) and energy dependency, etc. Although all these objectives are obviously very important, the fight against climate change stands out as a key goal nowadays.

[2]In 2019, RE capacity investment was \$282.2 billion, i.e., 1% higher than the previous year (source: UNEP). These figures refer to the total flow of new money into RE. See Figure 1 in Appendix A.

[3]See Figure 2 in Appendix B. Note that, as defined by the International Energy Agency, "utility-scale includes electricity generation and capacity of generating units (generators) located at power plants with at least one megawatt (MW) of total electricity generating capacity."

[4]Excluding hydroelectric sources.

technologies, this dynamic could have been more pronounced.

This evolution 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, which focuses on solar PV—one of the most attractive RE sources since around 2010 which remains the only renewable technology that has registered an investment increase in 2017 (IRENA, 2019).

Specifically, we assess the effects of the different factors identified in the literature on RE deployment[5] by paying particular attention to the influence exerted by energy prices—especially oil prices. Traditionally, positive oil price shocks negatively impact economic growth by increasing inflation and unemployment, 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. As shown by Chang et al. (2009), countries recording high economic growth levels indeed respond to an increase in energy prices by deploying RE technologies. Macroeconomic variables and the oil price dynamics are yet interconnected,[6] and the conditions observed on the oil market could trigger or not a spillover effect on RE deployment. As an illustration, 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.[7] Therefore, 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. Indeed, over the period we consider in the present study (1997-2016), the mean annual growth rate of the share of solar PV in the total electricity capacities is always larger during episodes of rapid oil price growth. This is especially true for the BRICS that record an average annual growth rate of the share of solar PV in the total electricity capacities, which is one and a half times higher during periods of booming oil prices—1.2 times higher for our whole sample of countries. This argument is confirmed by Figure 1, which displays the evolution of the annual growth rate of the price of oil together with the annual variation of the share of solar PV capacities in the total electricity capacities for the BRICS. As shown, the main episodes of booming oil prices since 2007 have been accompanied by a huge increase in the share of solar PV in the total electricity capacities. Specifically, the share of solar PV displays an accelerating growth rate during times of rising oil prices, whereas it continues to rise but at a decreasing rate when oil prices diminish. Taking

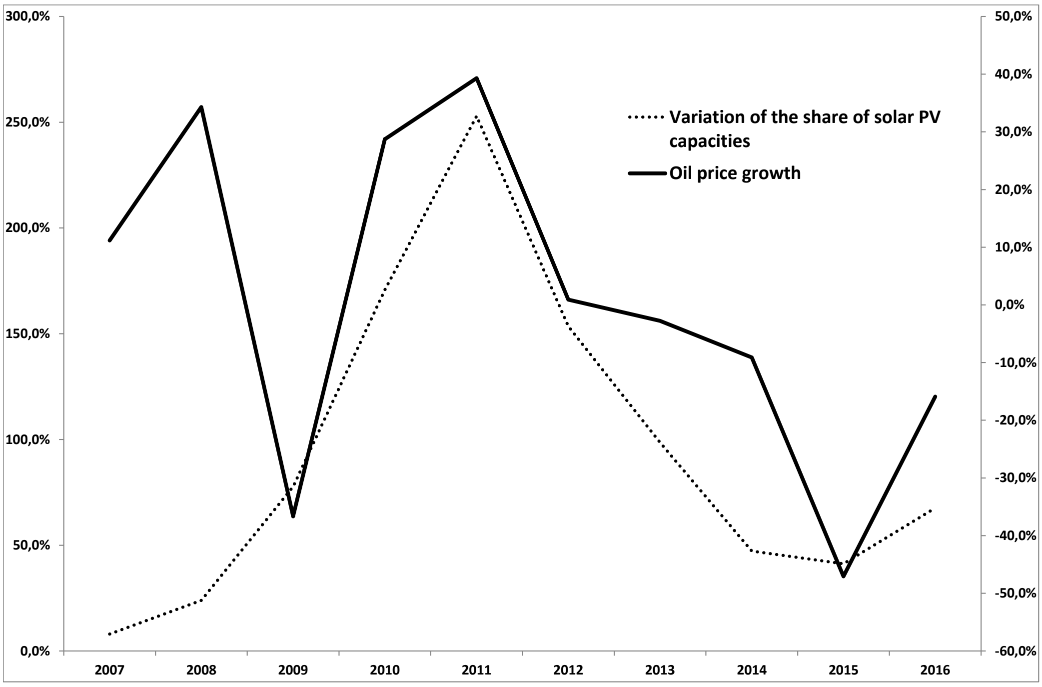
[5]In the economic literature (see Bourcet (2020) for a recent survey), the deployment of RE is explained by different factors generally split into three classes: (i) economic drivers, (ii) energy and environmental determinants, and (iii) policy instruments.

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

[7]See also Awerbuch and Sauter (2006) and Rout et al. (2008).

these interactions between oil prices and RE deployment 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.

Table 1: Oil price growth and annual variation of the share of solar PV capacities in the total electricity capacities for the BRICS



Note: Left axis: annual variation of the share of solar PV capacities in the total electricity capacities; right axis: oil price growth (Brent, nominal price). See Table 3 in Appendix B for data sources.

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. In other words, the use of such a nonlinear model enables us to assess to which extent the dynamics of oil prices impact the deployment of solar PV depending on the level reached by the oil price annual growth rate. It is worth mentioning that we focus on oil prices due to the leading role they play in energy markets.[8] Indeed, oil—due to its physical properties and the importance of its market—is often viewed as an economic "driver" influencing the other energy prices, such as coal and

[8]For an investigation of the relationships between energy prices, the reader may refer to Bachmeier and Griffin (2006), Mjelde and Bessler (2009), Joëts and Mignon (2012) and the references therein.

gas prices. In various countries, especially in Europe, natural gas prices have been historically indexed to oil prices. Although the share of indexation to oil prices is weakened, oil remains a key driver of natural gas and other energy products. As a result, changes in oil prices tend to affect all energy prices, including gas prices through wholesale prices, and coal prices. Turning more precisely to coal, it is the main input to electricity generation. However, it is an extreme pollutant and is, therefore, in competition with gas in power production, likely to create substitution effects. In addition, coal transportation being costly, oil and coal prices are expected to be indirectly related to each other through the fluctuations of the transport fuel derived from oil. Overall, even though oil represents only 3% in the global electricity generation mix in 2018 according to the International Energy Agency (IEA), its key influence on the other energy prices justifies its use as the transition variable in our PSTR specification.[9]

In addition to analyze these interactions between oil prices and RE deployment, we complement the literature on the drivers of solar PV deployment in various ways. Despite the growing number of studies, this literature remains denser regarding the residential solar uptake compared to medium to large utility-scale solar PV on which we focus in the present paper. 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 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, we consider a wide panel of 39 economies from 1997 to 2016, including both OECD and BRICS countries.[10]

Our results show that oil market conditions play a key role in explaining the dynamics of solar PV deployment—especially in OECD countries—since they affect their main determinants: environmental commitments, nuclear-based endowments, and solar PV potential. Specifically, an increase in oil price growth above 6.7% per annum has a positive effect on solar PV, an impact which may operate through a reduction in the relative cost difference 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

[9]For the sake of completeness, 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.

[10]Note that other papers rely on quite large samples of countries. However, they are generally based on unbalanced panels and/or shorter periods than ours. For instance, Baldwin et al. (2017) consider an unbalanced sample of 149 countries that ends in 2010, Best (2017) an unbalanced panel of 137 countries over the 1998-2013 period, and Carley et al. (2017) a panel of 164 economies over the 1990-2010 period.

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 describes the methodology and data. Section 3 presents our findings, and various robustness checks. Section 4 concludes the paper.

2 Methodology and data

2.1 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 be expressed as:

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

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:

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

where ΔOP_t denotes oil price growth used as the transition variable,[11] 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.[12]

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

[11] It should be noticed that we consider the price of oil in first-logarithmic variation and not in level to address unit root issues. In addition, note that the price of oil is expressed in nominal terms.

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

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.[13] 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.[14] 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).

2.2 Explanatory and dependent variables

The explanatory variables included in $X_{i,t}$ in Equation (1) are chosen according to the literature (see Bourcet (2020), and the references that follow), 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 the growth rate of GDP per capita (in constant US dollars) and foreign electricity trade. As recalled by Marques et al. (2010) and Cadoret and Padovano (2016), the contemporaneous impact of GDP per capita 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 per capita 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.

[13] 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).

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

Second, we consider various energy and environmental factors : (i) environmental commitments measured by CO_2 emissions,[15] (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 annual growth rate of 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' growth on solar PV deployment.

We also use non-renewable energy-related 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 (see, e.g., Romano and Scandurra, 2016b). 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,[16] and (ii) those with 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.[17] 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,[18] we integrate solar PV potential of countries through the urbanization rate. The effect of this variable on solar PV deployment is ambiguous.[19] On the one hand, the higher the urbanization rate, the higher the num-

[15] For studies that focus on environmental commitments, see Wüstenhagen et al. (2007), Sadorsky (2009), and Aguirre and Ibikunle (2014).

[16] Let us illustrate this assertion with some figures provided by IEA and related to countries that are among those with the largest oil reserves. Electricity generation from natural gas sources (% of total) in 2015 amounts to 98.5% in the United Arab Emirates, 82% in Nigeria, 79% in Iran, 56% in Saudi Arabia, and 54% in Libya. Regarding electricity generation from coal sources (% of total) for the same year, it amounts to 72% in Kazakhstan and 70% in China, to name a few.

[17] 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.

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

[19] Note that although this variable may fit better for a study of residential solar panels, the

ber of buildings and thus, the higher the number of large roofs usable for solar-based electricity production. On the other hand, for utility-scale solar PV, the opposite could be at play as more available space in non-urban areas may encourage the development of solar farms.

Third, we include a policy instrument, 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.[20] The related dummy variable takes the value 1 if the policy is at play in country i at time t, and 0 otherwise.[21] We expect the existence of FITs to stimulate the solar PV capacities deployment.

Note that many other policies exist to encourage emissions reductions, such as green certificates, renewable electricity standards, renewable portfolio standards, and auctions.[22] Furthermore, it is likely that countries having FITs also have such aforementioned other policies that might influence the effect attributed to FITs.[23] We nevertheless select FITs as this policy has emerged as one of the predominant avenues for transforming RE markets (Sawin, 2004; Baldwin et al., 2017), and because it was the most used policy over our period under study (see, e.g., Baldwin et al., 2017). It has also been proved effective at promoting RE deployment, particularly for solar PV development, in Europe (Lipp, 2007; Alagappan et al., 2011 ; and Jenner et al., 2013). Reverse auctions for renewables have become increasingly popular, but this is especially the case since 2015 according to IRENA. As our period ends in 2016,

urbanization rate was the proxy we had at our disposal for the solar PV potential of countries.

[20]As shown by Romano et al. (2017), 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 (see also Mitchell et al., 2006; Butler and Neuhoff, 2008; and Bürer and Wüstenhagen, 2009). Menanteau et al. (2003), Rickerson et al. (2007), Fouquet and Johansson (2008), Couture and Gagnon (2010), Zhao et al. (2013), Kilinc-Ata (2016), and Nicolini and Tavoni (2017) also conclude that FITs are effective RE instruments.

[21]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 IEA country reports, 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.

[22]See, e.g., Bird et al. (2005), Menz and Vachon (2006), Carley (2009), Yin and Powers (2010), Delmas and Montes-Sancho (2011), and Polzin et al. (2015).

[23]This may be for instance the case for carbon pricing; see, e.g., Eyraud et al. (2013) and Best and Burke (2018).

the use of FITs is more relevant.

Turning to our dependent variable, we consider the variation in the share of solar PV capacity in the total electricity capacities. The dynamics of this share is displayed in Figure 2 in Appendix B. As shown and as previously mentioned, it has grown continuously over the period under study. The average solar PV share in electricity capacity amounts to 1.5% for the whole panel of countries over the 1997-2016 period. 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 details, including all data sources).

2.3 Time period and sample of countries

We rely on annual data for 39 economies (see Table 2) from 1997 to 2016, focusing on OECD and BRICS countries.[24] Our choice of the starting date is guided by data availability considerations.

Table 2: 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.

3 Empirical results

3.1 Whole sample of countries

The results from the estimation of our PSTR specification are presented in Table 3. 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

[24]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.

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.

Table 3: PSTR estimation results

	Regime 1	Regime 2
GDP per capita 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: The dependent variable is the variation in the share of solar PV capacity in the total electricity capacities (percentage point). *** (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. Number of observations: 39 countries over the 1997-2016 period (780 observations).

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% (the associated 95% confidence interval is [5.55%; 7.87%]). 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% per annum. The second regime refers to a high increase in oil prices, above 6.7% per year. Note that over our period under study, there are ten years for which the price of oil grew at 6.7% or faster, which corresponds to half of the observations. 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) periods of pressures on oil prices, hereafter referenced as "boom" periods.[25] The estimated model reported in Table 3 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". Finally, note that the transition from one regime to the other is quite abrupt, as can be shown by the estimated value of the slope parameter γ describing the speed of transition between the two states.

Let us now consider the two economic determinants, namely GDP per capita 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 GDP per capita growth exerts a negative effect on RE capacities. Here, we go further than Cadoret and Padovano (2016) who highlight an adverse impact of contemporaneous GDP per capita growth on the share of RE in gross final energy consumption. Indeed, while these authors find that GDP per capita growth slows down RE deployment in terms of consumption, we show that this variable also negatively impacts the share of RE in the energy-capacity mix. The direct negative effect on consumption would be due to the high elasticity of fossil-based energy sources—which are energy sources that can be more easily stocked and/or imported. 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 percentage point increase in lagged GDP per capita growth. Based on the assumption that solar PV capacities do not decline, past GDP per capita 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.[26] 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

[25]One point is worth mentioning here. Recall that we are working at an annual frequency. Consequently, if a spike in oil prices occurs and disappears within a year, this high volatile intra-year episode cannot be captured. To tackle this issue, we checked whether such episodes have occurred over our sample period using monthly oil price data. Globally, calm periods have been correctly identified, except in 2015 where oil prices have known huge fluctuations. We would like to thank a referee for this very relevant remark, that we will investigate more deeply in future research.

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

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—negatively correlated with the past variation of CO_2 emissions per capita and per kWh in the electricity mix—impact the solar PV deployment positively.[27] 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 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[28] harms solar PV deployment only during "boom" periods in the oil market. During regimes 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 electric-

[27] As previously mentioned, we use CO_2 emissions as a proxy of environmental commitments in the electricity market, and consider its lagged value to minimize the risk of reverse causation—i.e., from solar PV mix to emissions. To assess whether this risk may however be still present, we have calculated the autocorrelation function of emissions' growth. For the majority of the countries in our panel, there is no significant autocorrelation in the emissions' growth rate series.

[28] 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.

ity 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% per annum. As expected, countries with low GhG emissions thanks to nuclear power plants tend to have fewer incentives to deploy solar PV.

Fifth, Table 3 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% per annum. 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 policy instrument 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 cited in Section 2.2. 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 GDP per capita 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 annual growth is lower than 6.7%: past growth rate of 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.

3.2 Robustness checks

3.2.1 Linear versus nonlinear specification

To put forward the interest of our nonlinear specification,[29] we estimate a linear model using the same explanatory variables as in the PSTR specification. As shown in column (1) in Table 5, we obtain quite similar results for the two economic determinants—as expected given the fact that the two variables are significant and are not impacted by the annual oil price growth in the PSTR specification. Indeed, GDP per capita growth and foreign electricity have coefficients which are very close to those obtained with the PSTR model, they are both significant and negatively signed, confirming their influence on solar PV deployment whatever the oil market conditions. As expected as well, the same conclusions apply for the urbanization rate and the policy variable for which we obtain positive significant estimated coefficients.

More interestingly, results in Table 5 indicate that the main differences between linear (column (1) of Table 5) and nonlinear (Table 3) estimates concern energy-related variables. With the exception of the nuclear capacity share in the electricity mix, all the other determinants are found to be non-significant. Clearly, these findings highlight the relevance of our nonlinear specification. Indeed, although one may erroneously conclude that energy-related variables have no impact on RE deployment when a restricting, linear model is estimated, the use of our nonlinear, PSTR specification emphasizes that the role of such variables depends on the size of oil price changes. Overall, to account for a differentiated impact of some explanatory factors on solar PV deployment depending on the oil market conditions, a nonlinear specification is needed.

3.2.2 Model with interaction variables

As a further robustness check regarding our nonlinear specification, we assess the relevance of the PSTR form compared to another nonlinear functional form. Specifically, we augment the previous specification estimated in column (1) of Table 5 with interaction terms: each explanatory variable interacts with the oil price growth.[30] This nonlinear specification allows us to investigate whether oil price growth influences the impact of explanatory variables on solar PV deployment.

As shown in column (2) of Table 5, nonlinear effects are at play, depending on oil market conditions. Specifically, if we focus on energy-related variables, our results

[29]We would like to thank an anonymous referee for suggesting us to estimate two additional (linear and nonlinear) specifications, allowing us to assess the robustness of our PSTR specification results and increasing the believability of our findings.

[30]To facilitate the comparison with the results displayed in Table 3, we report in column (2) of Table 5 the results with the interaction variables that were in the nonlinear part of the PSTR specification. The results for the estimation with all the variables interacting with oil price growth are similar, and are available upon request to the authors.

show that such nonlinearity mainly concerns gas prices and the nuclear capacity share in the electricity mix. Turning to the other variables, the effect of the urbanization rate on RE deployment also depends on the oil price growth, as it is lower when the latter variable is positive.

Overall, this augmented specification with interaction terms indicates that the conditions on the oil market matter in assessing the effect of the factors that influence solar PV deployment. These findings confirm the interest of estimating a nonlinear model, and emphasize the relevance of our PSTR specification. Indeed, whereas the specification with interaction variables indicates the existence of nonlinearities, they can be quantified by the estimation of the PSTR model—the latter allowing us to estimate the threshold value of oil price growth that matters.

3.2.3 Sensitivity analysis: accounting for the countries' type

Given that our sample includes both OECD and BRICS countries that are quite heterogeneous, the drivers of solar PV deployment may differ for these two groups of economies. To investigate this possibility, we estimate our PSTR specification over the two panels separately. The corresponding results are reported in Table 6 in Appendix C.

As shown, the null hypothesis of linearity is rejected at the 5% significance level for the subsample of OECD countries, and the 10% level for BRICS economies when accounting for cross-sectional dependence. Nonlinearity induced by oil market conditions found for the whole sample is thus mainly driven by OECD nations, as corroborated by the estimation results displayed in Table 6. Indeed, the estimates obtained for OECD countries are very close to those reported in Table 3; the same comments as for the whole sample thus apply for this panel of developed economies.

The main differences with the previous results in Table 3 concern the BRICS subsample. Indeed, only four determinants are found to be significant at conventional levels. Foreign electricity trade still exerts a negative effect on solar PV capacities, especially in periods of booming oil prices. Regarding energy and environmental variables, two of them have a significant impact on solar PV deployment in the "normal" regime. An increase in oil production positively impacts the deployment of RE capacities, a finding that we can explain by the fact that some BRICS economies are both important solar PV investors and among the top ten oil producers. This is, for instance, the case of Russia, China, and Brazil, with China ranking first among solar PV investors. Turning to gas prices, an increase in their growth rate is harmful to solar PV deployment, in contrast to OECD countries for which a rise in the prices of fossil energies increases solar PV relative profitability and, in turn, its deployment. Finally and as expected, the sign of the coefficient associated with the urbanization rate is positive, with a more pronounced impact during the first regime.

To sum up, our findings show that, contrary to OECD economies, oil price growth is not a key driver for solar PV deployment in BRICS countries and, more generally, highlight a weak importance of energy factors. Overall, this result confirms the fact that different factors globally drive OECD and BRICS countries in their RE investment decisions. However, this result should be taken with caution as the number of countries is quite small, which may obviously impact the accuracy of the estimates.

4 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.

To this end, we estimate a PSTR model on a wide sample of OECD and BRICS countries. Whereas energy-related factors do not play a key role in driving RE investment decisions in BRICS economies, we show that the dynamics of oil prices affect various determinants of solar PV deployment in OECD countries. Interestingly, an increase in oil price growth above 6.7% per annum 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 size of oil price changes.

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 in OECD economies. 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 high oil prices may temporarily contribute to a reduction in CO_2 emissions, only structural reforms based on public policies will help in durably achieving this objective. This is even more true in the current context characterized by geopolitical tensions and difficulties for oil-exporting countries to reach a coordinated production reduction agreement to stem the fall in crude oil prices.

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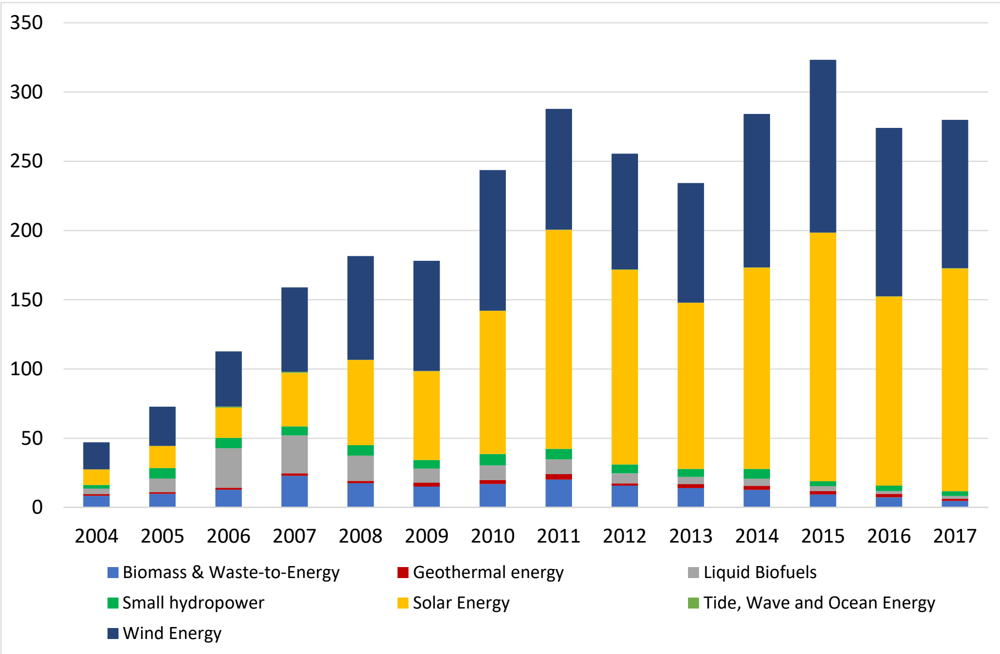
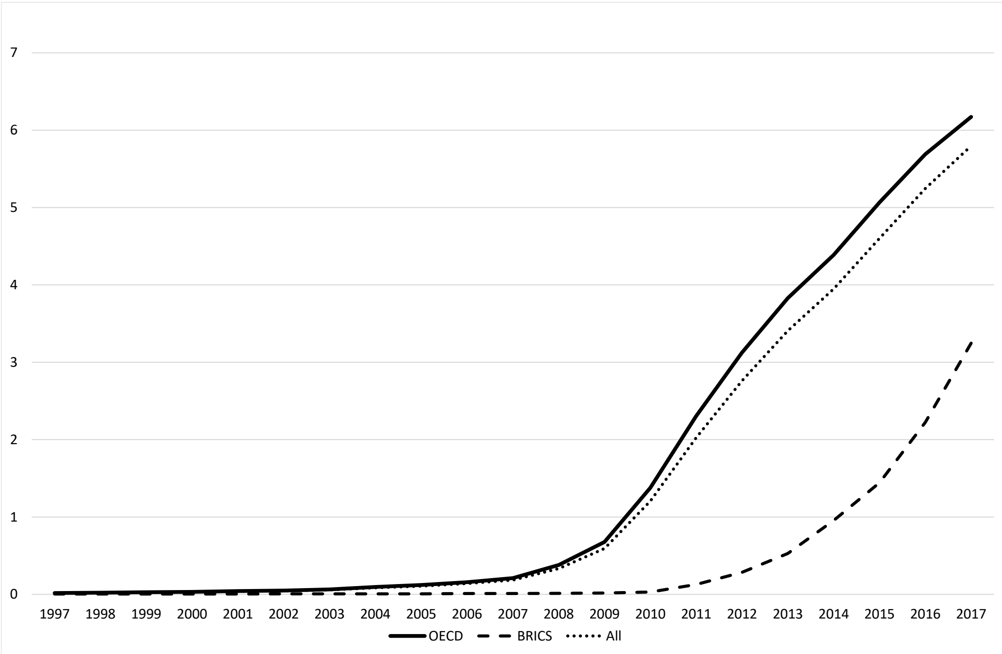
Appendix A. World investments amounts in renewable energy

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



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

Figure 2: Share of utility-scale solar PV in the total electricity capacities (in %)



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

Appendix B. Data description

Table 4: List of variables

Variable	Unit	Sources
Utility-scale solar PV capacities	MW	Enerdata
GDP per capita growth	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	
GDP per capita $growth_{i,t-1}$	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)	

Note: Enerdata is an online interactive data tool, which provides various statistics related to the energy industry (such as production, consumption and trade of oil, gas, coal, power and renewables; CO2 emissions from fuel combustion). Link to Enerdata: `https://yearbook.enerdata.net/`.

Appendix C. Robustness checks

Table 5: Linear model and model with interaction variables estimation results

	Linear (1)	Interacted (2)
	Coefficient	Coefficient
GDP per capita growth$_{i,t-1}$	-2.739^{***}	-2.878^{***}
Foreign elec. trade$_{i,t-1}$	$-8.620 \times 10^{-6**}$	$-8.670 \times 10^{-6**}$
CO_2 growth$_{i,t-1}$	-0.194	-0.310
Oil prod. growth$_{i,t}$	-0.031	-0.027
Coal prod. growth$_{i,t}$	-0.086	-0.107
Nuclear capacity share$_{i,t}$	-9.279^{***}	-9.506^{***}
Gas price growth$_{i,t}$	0.099	0.232^{*}
Oil price growth$_{i,t}$	-0.150	0.433
Urbanization rate$_{i,t}$	4.721^{***}	4.926^{***}
FIT$_{i,t}$	0.431^{***}	0.446^{***}
Constant	-2.421^{***}	-2.565^{***}
CO_2 growth$_{i,t-1} \times \Delta OP$		0.846
Coal prod. growth$_{i,t} \times \Delta OP$		0.207
Nuclear capacity share$_{i,t} \times \Delta OP$		0.868
Gas price growth$_{i,t} \times \Delta OP$		-0.747^{*}
Oil price growth$_{i,t} \times \Delta OP$		0.646
Urbanization rate$_{i,t} \times \Delta OP$		-0.964^{*}

Note: The dependent variable is the variation in the share of solar PV capacity in the total electricity capacities (percentage point). *** (resp. **, *) denotes significance at the 1% (resp. 5% and 10%) level based on robust standard errors. The fixed-effect specification is selected using the Hausman test. ΔOP denotes the interaction oil price growth variable. Number of observations: 39 countries over the 1997-2016 period (780 observations).

Table 6: PSTR estimation results for OECD and BRICS subsamples

	OECD		BRICS	
	Regime 1	Regime 2	Regime 1	Regime 2
GDP per capita growth$_{i,t-1}$	-3.210^{*}	-3.210^{*}	-0.457	-0.457
Foreign elec. trade$_{i,t-1}$	$-8.539 \times 10^{-6**}$	$-8.539 \times 10^{-6**}$	$5.468 \times 10^{-6*}$	$-8.882 \times 10^{-6***}$
CO_2 growth$_{i,t-1}$	-0.347^{*}	-0.077	-0.051	-0.051
Oil prod. growth$_{i,t}$	-0.047^{***}	-0.047^{***}	0.357^{***}	0.000
Coal prod. growth$_{i,t}$	-0.132	-0.082^{**}	-0.038	-0.038
Nuclear capacity share$_{i,t}$	-9.325^{***}	-8.680^{***}	-7.606	0.115
Gas price growth$_{i,t}$	0.501^{**}	-0.089	-0.433^{*}	-0.058
Oil price growth$_{i,t}$	-0.130	0.711^{***}	0.231	0.231
Urbanization rate$_{i,t}$	5.923^{***}	5.400^{***}	5.398^{***}	4.520^{***}
FIT$_{i,t}$	0.503^{***}	0.503^{***}	-0.188	-0.188
c	0.067^{***}		0.067^{***}	
γ	119.3		119.3^{**}	
WB Linearity test	0.020		0.269	
WCB Linearity test	0.018		0.096	
TVP parameters WB test	0.935		0.999	
TVP parameters WCB test	0.966		0.970	
RNL WB test	0.937		0.999	
RNL WCB test	0.966		0.971	

Note: The dependent variable is the variation in the share of solar PV capacity in the total electricity capacities (percentage point). *** (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. Number of observations: 34 OECD and 5 BRICS countries over the 1997-2016 period (680 and 100 observations, respectively).