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Title: Energy transition and technological innovation: do enabling technologies facilitate the energy transition in emerging and developing countries (EMDCs) ?

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Abstract:

As well as issues relating to climate change, the last decade has also seen a number of other issues relating to energy security and economic competitiveness, which have given rise to considerable international concern. For this reason, and due to rising fossil fuel prices and depletion, the gradual transition to renewable energy sources is now accepted as one of the possible solutions for limiting environmental risks without compromising economic progress.

Nevertheless, because of their dependence on weather conditions, it should be stressed that renewable sources are intermittent, which reveals certain limitations. To overcome this problem of intermittence, technological innovation is likely to help the transition process, based on more efficient use of renewable resources. The aim of this study is to examine the contribution of technological innovation to the energy transition process in ten emerging and developing countries (EMDCs) over the period 2000-2020. Using Lewbel's (2012) instrumental variable (IV) estimator, the results of this study reveal that technological innovation is expected to facilitate the energy transition process in the selected countries.

Key words : Energy transition, Technological Innovation, Enabling technologies, Renewables Energies, Instrumentals variables, Panel Data

Introduction:

In recent decades, the global energy system has been shaped by a succession of unprecedented changes. In fact, concerns about energy security, energy poverty, climate change, and economic competitiveness are leading these major changes in the energy sector (IEA, 2017). In addition, energy demand is continually growing, as a result of the rapid development of industry, the economy and demographics. However, this has been accompanied by a significant increase in emissions of greenhouse gases (GHGs), which are recognized as the leading cause of global warming and environmental degradation.

Beyond climate change issues, which are causing great concern on the international scene, ensuring a continuous supply of energy is now crucial to ensure economic viability and deal with environmental threats. In this respect, switching from conventional energy to renewable sources is now recognized as one of the viable solutions for limiting environmental risks while preserving economic progress.

Furthermore, the idea that energy transition can promote more sustainable development has been the subject of much research (Hmida and REY, 2023). One example is the Brundtland Report (1987) on sustainable development, which recommends the use of renewable energies to meet the energy needs of the coming century. For their part, advocates of renewable energies see them as a clean, safe solution for producing energy while reducing dependence on ever-dwindling fossil resources (Heal, 2009).

Nevertheless, with regard to renewable energies, it should be pointed out that, even if they are considered renewable sources, they remain intermittent and weather-dependent, which reveals certain limitations. To overcome this problem of intermittence, technological innovation is likely to make the transition process more efficient (Churchill, et al., 2019). With this in mind, political decision-makers are developing new measures to save energy efficiently, while guaranteeing economic growth and environmental protection. In this sense, technological innovations can constitute a favorable technological support for the development of new renewable energy solutions (Khan, et al., 2022).

It's also worth noting that a number of enabling, cross-cutting technological innovations in the energy sector, which can ensure the optimal use of renewable energies, are now booming. These innovations can play a key role in managing fluctuations and interruptions in renewable energy production. As a result, their integration into the energy system, in conjunction with renewable energies, can promote optimal deployment of renewable energies.

The aim of this paper is therefore to examine the contribution of new enabling technologies (NEETs) to the energy transition in emerging and developing countries. With this in mind, we will attempt to examine the effect of NTECH development on different measures of energy transition in ten emerging and developing countries over the period 2000-2020.

Enabling technologies and energy transition:

In recent decades, innovation in the energy sector has become essential for mitigating climate change (IEA, 2021). The trend towards innovation in low-carbon energy has never been so central to the concerns of policymakers. According to the IEA report (2021), the transition to clean energy requires the implementation of new innovations that represent a turning point with regard to the technologies deployed in recent decades in the energy sector. Moreover, these new technologies

not only promote greater dependence on electric power, but also solutions that are more suitable for use by the general public, with a greater distribution of resources.

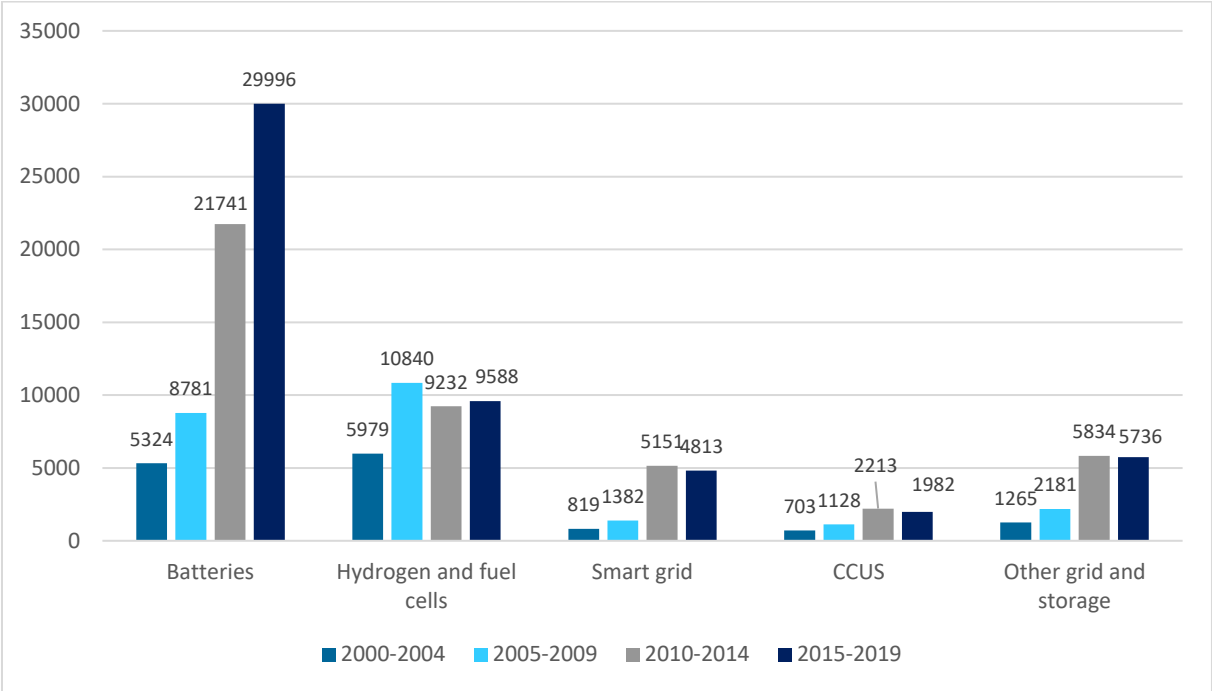
In addition, these changes are leading to the emergence of new players in the energy sector, increasing the pressure to innovate in product design and manufacture. As described in the IEA report (2021), the changing dynamics of innovation in the energy sector are clearly visible in patent data.

Against this backdrop, cross-cutting technologies¹ can play a central role in today's energy transitions. Indeed, they promote the deployment and integration of green sources of energy into end-use consumption, in particular electricity generated from renewable sources. As a result, technical progress in NTECH is driving innovation in energy supply and end-use, which are becoming intrinsically linked. In fact, almost a third of the number of international “IPF” patents relating to NTECH, filed since 2010 (IEA, 2021).

The positive overall trend in enabling energy technology patenting activity was mainly driven by innovation in battery technologies, which accounted for 57% of IPFs between 2010 and 2019, growing by 13% a year on average (Figure 1).

This trend reflects the increasing adoption of batteries in an increasing range of household appliances and tools, and particularly the fast growth and development of lithium-ion battery solutions in electric mobility (IEA, 2021).

Figure.1 Number of IPFs for enabling technologies worldwide, 2000-2019



The growing trend in battery use since 2010 can be explained in particular by the almost 90% drop in the price of lithium-ion batteries, typically used in electric vehicles. NTECHs such as batteries have many links with LCE supply and end-use technologies, facilitating their integration or emissions reduction (IEA, 2021).

¹ including battery storage, hydrogen, smart grids and carbon capture and storage (CCUS)

In fact, unlike batteries, even though patenting activity for hydrogen and fuel cells almost doubled over the period 2000-2009, these technologies continue to generate significant patenting activity (around 19,000 IPFs since 2010), albeit at a slower pace over the last decade. Furthermore, compared with the battery or hydrogen sectors, the number of patents filed in the smart grid field appears to be significantly lower, with a stable average of around 1,000 IPFs per year over the period 2010-2019 (IEA, 2021).

However, it should be noted that patenting in the field of smart grids is a more recent phenomenon, with an average of only 200 IPFs filed per year between 2000 and 2009. On the other hand, EPO predicts that this growth will continue, supported by the relentless and innovative introduction of new digital platforms, including the Internet of Things, 5G communication networks, cloud computing and artificial intelligence (Yann, et al., 2020).

The place of technological innovation in the economy :

The literature on innovation is vast and interdisciplinary. It includes economists, sociologists and political scientists. It plays an important role in understanding the mechanisms of innovation, while also helping to shape economic and industrial policies that promote economic growth and social well-being. Broadly speaking, the economics of innovation aims to focus on the economic determinants of innovation. It explores the relationship between mechanisms and economies of scale on the one hand, and innovation on the other (Guellec, 1999).

Moreover, the importance of innovation as a vector of societal and economic transformation is not new to economic theory. Indeed, the literature on the economics of innovation dates back to the ideas of Josef Schumpeter in the early 1940s. Schumpeter (1942) describes three stages in the process of technical change: invention, innovation and diffusion. Invention involves developing a new product for the first time. Once the new product is on the market, the innovation phase begins. The invention and innovation processes are guided by R&D. Finally, diffusion occurs when the new product, or technology, is adopted by economic agents and becomes widely used in various activities (Jaffe, et al., 2003).

Generally speaking, macroeconomic literature has developed on the basis of the above-mentioned concepts - invention, innovation and diffusion - to produce models of global economic growth based on technological progress (Romer, 1990; Grossman & Helpman, 1994 and Solow, 2000).

In economic literature, innovation is a central and fundamental issue. It is considered one of the main vectors of economic growth.

In classical economic thought, the concept of innovation, as it is defined and studied today, did not occupy a prominent place. Nevertheless, this is not to say that these economists entirely neglected the concept of innovation. Adam Smith (1776) suggested that individuals seeking to optimize their own interests could contribute indirectly to innovation by stimulating economic growth. On the other hand, Ricardo's analysis of competition and comparative advantage can be conceived indirectly as an economic environment conducive to innovation and economic performance.

In neo-classical theory, innovation plays a crucial role in economic growth and productivity. Although neoclassical economists did not develop a dedicated theory of innovation, they recognized its importance and incorporated it implicitly into their economic analysis. Among the neo-classical theorists, and although he did not focus explicitly on innovation, Solow (1956)

reported a positive link between technological progress and economic growth. He highlighted the importance of exogenous technical progress in economic growth, and showed how technical progress contributes to an increase in the overall productivity of factors of production.

Endogenous growth theories join earlier theories in recognizing that technical progress is the engine of growth. However, these theories go beyond their predecessors in two respects. Firstly, they consider technical progress to be the result of remunerated, and therefore endogenous, economic activity. Secondly, they model forms of technology and their evolution in a richer way (Guellec & Ralle, 2003).

As part of this new theory of economic growth, Romer (1990) explicitly links technological progress to economic growth. He considers that technological innovation is itself the result of individual behavior stimulated by market incentives, which in turn contributes to wealth accumulation.

As part of the new growth theory, Aghion et al (1998) defend the idea that the volume of labor allocated to innovation and to innovative firms improves technological progress and hence the economy's productivity.

Furthermore, the development of Schumpeter's theory of innovation led to the emergence of new classical Schumpeterian growth theorists (Omri, 2020). These supported the idea that knowledge accumulation, innovation and research and development (R&D) are essential factors in promoting economic growth (e.g. Aghion et al. 1998; Howitt, 1999).

In summary, it's worth noting that classical and neoclassical economists have not paid as much attention to innovation, compared to proponents of endogenous growth. Indeed, neoclassical economists regard innovation as an external factor influencing economic growth and productivity. They focus instead on institutional contexts and economic incentives capable of stimulating innovation. As for endogenous growth theorists, they explain economic growth in terms of factors internal to the economy, notably the accumulation of human and physical capital, but also technological innovation.

Brief overview of empirical literature: technological innovation and renewable energies

In recent decades, empirical literature on renewable energies has attracted growing scientific interest. Although several potential determinants of renewable energy development have been examined, only 4% of articles have focused on technological innovation (Bourcet, 2020).

For the most part, the indicators used to assess technological innovation are the total number of patent applications or actual R&D expenditure in the energy sector (Chen & Lei, 2018; Irandoust, 2016), as well as the stock of patents (Johnstone, et al., 2017; Zheng, et al., 2021; Lin & Zhu, 2019; and Kruse & Wetzel, 2016).

Today, very few studies have analyzed the impact of technological innovation on the development of renewable energies. For example, Popp et al (2011) studied the mechanisms of technological innovation in 26 OECD countries between 1991 and 2004, using panel regression models. They used the number of patents relating to renewable energy technologies as an indicator of investment in the renewable energy sector. They found that technological innovation could indeed promote investment in renewable energies. Following Popp et al. (2011), Geng and Ji (2016) attempted to examine the mechanism of influence of technological innovation on renewable energy development within six major developed countries. Their empirical results revealed a long-term equilibrium relationship between renewable energy consumption, technological innovation

and other external factors. Irandoust (2016) has attempted to examine the relationship between renewable energy consumption, technological innovation, economic growth and CO2 emissions in the four Nordic countries. The results of this study indicate the presence of a unidirectional causality running from technological innovation to renewable energy. These results suggest, among other things, that technological innovation contributes effectively to the growth of renewable energies.

Furthermore, He et al (2018) studied the impact of technological innovation on renewable energy at provincial level in China. The results show that technology research and development (R&D) are the main determinants of renewable energy progress. The authors argued that technology spending played an important role in the development of renewable energies. In contrast, Palage et al (2019) conducted a study aimed at examining the impact of innovation support policies on the development of renewable energies. To this end, they used data relating to patent applications in 13 countries over the period 1978-2008. Similar to the findings of He et al. (2018), the authors found that the development of new energy technologies has a more profound impact on the progress of renewable energies. In addition, Xie et al (2020) investigated whether or not the development of new technologies increases the consumption of renewable energies. The findings reveal that the development of new technologies has a significant impact on renewable energy consumption.

To understand how technological innovation promotes renewable electricity generation, Zheng et al (2021) analyzed the effect of technological innovation on renewable energy development, for a panel of 30 Chinese provinces. The results of this study revealed that a 1% increase in the rate of technological innovation leads to a 0.411% increase in the rate of renewable energy use within a given province, and that this increase has a contagion effect on other neighboring provinces due to technology diffusion. In contrast, Khan et al (2022) demonstrated the causal link between technological innovations and renewable energies in the German context. The results of this study showed that technological innovations exert both a positive and a negative influence on renewable energies, depending on different sub-samples.

Empirical strategy and descriptive statistics

Data:

In this study, we use annual time series from 2000 to 2020 for ten selected economies in the South: Brazil, Chile, China, Colombia, India, Mexico, Morocco, Peru, South Africa and Tunisia. To meet our objective, our business model is as follows:

$$TER_{it} = F (IT_{it}, X_{it})$$

Where TER denotes the vector of dependent variables used as indicators of the energy transition in the selected economies, namely RELE, RELES and EI. IT refers to technological innovation. X_{it} denotes the vector of other explanatory variables, including CO2, OIL, REMIT and FDI.

The RELE variable refers to the level of renewable electricity production measured in terajoules. RELES represents the percentage share of renewable energies in the electricity mix. Finally, EI refers to the intensity of energy use, expressed as the amount of energy used to produce one unit of GDP. Our main variable of interest, IT, refers to technological innovation. In the context of our study, IT measures the number of international patents for enabling and cross-cutting technologies including smart grids and storage batteries, CCUS, etc. Table 1 below provides a description of the data.

Table 1 Description and sources of data

Variables	Definition	Measure	Sources
RELE	Renewable power generation	Terawatt hours	BP Statistical Review
RELES	Share of renewables in the electricity mix	En percentage	
EI	Energy intensity	kg equivalent petrol par \$ US	EIA
IT	Technological innovation	Nombre des brevets	INSPIRE(IRENA)
CO2	CO2 emissions	tones métrics par habitant	WDI
REMIT	personal remittances received		WDI
OIL	The international price of crude oil	\$ US constants 2010	BP Statistics
IDE	Foreign direct investment		WDI

Explanatory variables include emissions of carbon dioxide (CO2) in metric tons per capita. The international price of crude oil (OIL) in 2010 US dollars per barrel. Foreign direct investment (FDI) inflows and personal remittances received (REMIT), in constant 2010 US dollars.

Econometric model

As the aim of this paper is to investigate the role of technological innovation (TI) in the renewable energy transition (RET) process, we will examine the effect of the development of new enabling energy technologies, as indicators of TI, on the various measures of RET. The regression model is as follows:

$$\text{Ln}Y_{it} = \eta_i + \alpha_0 + \alpha_1 \text{Ln}IT_{it} + \alpha_2 \text{Ln}X_{it} + \varepsilon_{it}$$

Where indices i , t and ε denote individual cross-sectional units, respectively, countries, time, namely years, and the error term. η_i are country fixed effects. $\text{Ln}Y$ denotes the vector of dependent variables used as TER indicators, in the selected economies, expressed in natural logarithm, namely LnRELE , LnRELES and LnEI . The variable LnRELE refers to the level of electricity production. LnRELES represents the percentage share of renewable energies in the electricity mix. Finally, LnEI refers to the intensity of energy use. This particular variable reflects the efficiency of energy use, with higher values of EI corresponding to lower efficiencies of energy use, and vice versa. LnIT stands for technological innovation. It should be noted that this is linked to a country's interest in developing new technologies, which can be quantified using a quantitative statistic such as the number of patents. Given the codified nature of patents, patenting activity can serve as an indicator of technological innovation. Indeed, an increase in patent applications implies that companies and individuals are interested in implementing new technologies. Furthermore, this study specifically takes into account the effects of environmental deterioration, changes in the relative prices of energy resources and also incorporates different sources of international fund inflows, introducing certain relevant control variables ($\text{Ln}X$) as a set of explanatory variables. Explanatory variables include LnCO_2 , carbon dioxide (CO2) emissions in metric tons per capita. LnOIL , the international price of crude oil (OIL) in 2010 US dollars per barrel, used as an indicator of the price of non-renewable energy resources. LnFDI and LnREMIT represent, respectively, foreign direct investment inflows and personal remittances received.

Empirical methodology

In order to study the effect of technological innovation (TI) on energy transition (RET), we mainly use two-stage least squares (2SLS) estimation techniques in panel data. This estimation technique can be applied to overcome the endogeneity problem. In addition, the endogeneity

problem in panel data is likely to arise due to the presence of a correlation between the error term and one or more explanatory variables. Nevertheless, the use of the 2SLS estimation technique can provide a solution to the problem of model endogeneity by incorporating instrumental variables (IV) (Angrist & Imbens, 1995; Baum, 2006).

As mentioned above, using the IV approach to manage endogeneity requires that the appropriate instruments are available to identify the model. The appropriate instrument should be significantly correlated with the endogenous variable, the orthogonality condition should be satisfied, and the instrument should be excluded from the model in such a way that its effect on the response variable is only indirect (Baum, et al., 2012). However, it is often difficult to find suitable instruments that simultaneously satisfy these conditions, making it a significant dilemma when using IV estimators in most applied research (Stock, et al., 2002). Therefore, overcoming this issue, with our study we use the two-stage least squares (2SLS) technique of Lewbel (2012), which is applicable when identification sources, including suitable external instruments, are unavailable or weak.

In addition, Lewbel's (2012) 2SLS approach has been applied in numerous empirical studies, as for example the work of Acheampong, et al., (2021), Appau et al., (2019) or Churchill and Smyth, (2020). Finally, using the Driscoll-Kraay estimation technique, we check the robustness of the results.

Results and robustness analysis

Results and implications

Table 2, below, presents the results of our estimations using Lewbel's 2SLS estimator for the aggregate sample. As shown in Table 14, for models (1) and (2), the elasticities between the development of new enabling technologies and the transition to renewable energies are statistically significant and positive. A 1% increase in IT leads to an equivalent increase of 0.15% in renewable electricity production and 0.064% in the share of renewables in the energy mix.

Table 2 Lewbel 2SLS results for the aggregate sample.

	LnRELE (1)	LnRELES (2)	LnEI (3)
LnIT	0.151*** (0.048)	0.064* (0.034)	-0.028*** (0.009)
Control variables	Yes	Yes	Yes
Country Fixed effect	Yes	Yes	Yes
F-stat	13.7	13.7	13.7
Observations	210	210	210
Standard deviations in brackets, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$			

Furthermore, the regression results obtained by model (3) suggest that the development of new enabling technologies should be promoted in order to increase energy use efficiency levels in the panel of countries selected in this study. The results of the regression conducted by this model indicate that the estimated coefficient of LnIT is negative and statistically significant, implying that in these countries, the development of enabling technologies can be effective in reducing primary energy use intensities, in other words, reducing the amount of energy required to produce a unit of output. A 1% increase (or decrease) in IT leads to a 0.03% decrease (or increase) in EI levels on average, all other things being equal. This particular result of the regression analysis indicates that

policies to encourage the development of enabling technologies can be relatively effective in ensuring indirect energy conservation by progressively reducing overall energy demands in these economies. Furthermore, the negative relationship between technological innovation and energy intensity is also linked to patenting policies in these countries. Indeed, the relaxation of the latter encourages the spread of enabling energy technologies and, consequently, more efficient use of energy.

In summary, the different implications of the results of the three models support the idea that technological innovation promotes the development of renewable energies and improves energy efficiency in the selected countries. Given the different economic and environmental conditions in most countries, the impact of technological innovation on the development of renewable energies in these countries may have a different weight. However, the existence of actions undertaken in these countries can stimulate technological innovation and thus favor the development of renewable energies.

Consequently, each country should increase its investment in R&D in the field of renewable energies and implement appropriate energy policies, such as strengthening the transfer of renewable energy technologies, in order to stimulate technological innovation in favor of the development of renewable energies.

Robustness analysis

In this final section, we test the robustness of the results using the Driscoll-Kraay estimator. The estimation technique of Driscoll and Kraay (1998), which is based on a non-parametric estimator of the time series covariance matrix, assumes that the error structure is heteroskedastic, self-correlated up to a certain lag and possibly correlated between groups (Acheampong, et al., 2021). In addition, the non-parametric Driscoll-Kraay estimator produces robust results with regard to cross-sectional and time dependence (Hoechle, 2007). The Driscoll-Kraay estimation technique is also capable of handling missing data series and works with balanced and unbalanced panels (Hoechle, 2007). The results of the direct effect of the Driscoll-Kraay estimator are presented in Table 3, below.

Table 3 Driscoll-Kraay robustness results for the aggregate sample

	LnRELE	LnRELES	LnEI
LnIT	0.262*** (0.030)	0.088*** (0.018)	-0.039*** (0.005)
Control variables	Yes	Yes	Yes
Country Fixed effect	Yes	Yes	Yes
Constant	7.65e-09 (0.030)	-4.27e-08 (0.022)	-4.84e-09 (0.003)
Observations	210	210	210

The results of the Driscoll-Kraay estimator are consistent with Lewbel's 2SLS results in terms of signs. The robustness results confirm the existence of a positive and statistically significant relationship between the development of NTECH, renewable electricity production and the share of RE in the energy mix. They also confirm the presence of a negative relationship between NTECH and EI.

Conclusion:

Today, economic development depends on the availability of energy resources and environmental sustainability. In this respect, the transition to renewable energies can be a useful lever for achieving sustainable development, reducing dependence on fossil fuels and meeting energy demand while promoting economic growth. On the other hand, the relatively high cost of renewable energies means that they are still less widely used than fossil fuels. What's more, renewable sources are highly dependent on weather conditions, and their output is intermittent and uncertain. As a result, the development of renewable energies has become a global challenge, requiring the adoption of certain energy policy reforms in order to strengthen the presence of renewable energies in the energy mix. On the other hand, it is always possible to stimulate their development through technological innovation.

At the empirical level, the endogeneity problems that may arise between the energy transition indicators and the various explanatory variables retained in our model were dealt with using Lewbel's (2012) 2SLS instrumental variable method. To examine the robustness of our results, we used the Driscoll-Kraay (1998) estimator. Overall, our results confirm that technological innovation in the energy sector favors the development of renewable energies.

Our work thus allows us to conclude that technological innovation plays an essential role in stimulating the development of renewable energies to meet energy demand and optimize the energy system (Chen & Lei, 2018). However, technological innovations can accelerate the development of the renewable energy sector. (Popp, et al., 2011).

As our results suggest that new enabling energy technologies contribute significantly to the development of renewable energies, this allows us to make several energy policy recommendations. Firstly, in order to speed up the energy transition process and encourage the deployment of renewable energies, by tackling the problems of intermittency, it has become essential for the government to step up its technological R&D efforts to stimulate the rapid development of technological innovation. Indeed, enabling technologies can help develop the new energies needed to meet the targets set to combat climate change.

Finally, it's important to point out that modern renewable energies (wind and solar power), as variable energy sources, will be the cornerstones of energy supply in the future. For this reason, integrating these renewable energy sources into the energy infrastructure is a major challenge. As a result, weather-dependent production methods need to be harmonized. To achieve this, we need to modernize the current energy infrastructure, while building a smart grid with greater renewable energy storage capacity.

Appendix. 1 : Lewbel 2SLS results for the aggregate sample.

	LnRELE (1)	LnRELES (2)	LnEI (3)
LnIT	0.151*** (0.048)	0.064* (0.034)	-0.028*** (0.009)
LnCO2	-0.055** (0.028)	-0.044** (0.019)	0.005 (0.005)
LnFDI	0.165 (0.108)	-0.026 (0.075)	-0.065*** (0.020)
LnREMIT	-0.008 (0.014)	-0.008 (0.010)	0.000 (0.003)
LnOIL	-0.119 (0.078)	-0.130** (0.054)	0.028** (0.014)
Country Fixed effect	Yes	Yes	Yes
F-stat	13.7	13.7	13.7
Observations	210	210	210

Standard deviations in brackets, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Appendix. 2 : Driscoll-Kraay robustness results for the aggregate sample

	LnRELE	LnRELES	LnEI
LnIT	0.262*** (0.030)	0.088*** (0.018)	-0.039*** (0.005)
LnCO2	-0.035** (0.013)	-0.039*** (0.012)	0.003 (0.002)
LnFDI	-0.035 (0.080)	-0.070 (0.058)	-0.046*** (0.016)
LnREMIT	-0.027* (0.015)	-0.012** (0.005)	0.002 (0.002)
LnOIL	-0.144*** (0.049)	-0.135*** (0.040)	0.031*** (0.009)
Country Fixed effect	Yes	Yes	Yes
Constant	7.65e-09 (0.030)	-4.27e-08 (0.022)	-4.84e-09 (0.003)
Observations	210	210	210

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