Journal of Environmental Management 292 (2021) 112784

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Convergence in renewable energy sources diffusion worldwide

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ARTICLE INFO

JEL classification:
C33
O11
O13
Q20
R11

Keywords:
Renewable energy sources
Conditional convergence
Worldwide countries data set

ABSTRACT

The diffusion of renewable energy sources (RES) is a fundamental objective of the worldwide policy actions for sustainable development, at the UN level with the sustainable development goals (SDG) recommendations, to ensure access to affordable, reliable, sustainable and modern energy for all (SDG 7). Also, primary attention to RES has been given at the EU level with the new Green Deal and the new objectives of the Next Generation EU after the Covid pandemic, and at the level of national Governments worldwide. So far, there has not been an analysis of the RES convergence process across countries worldwide, given that the issue of climate change is a global externality. Previous analyses have focused on specific regions, such as EU, OECD, provinces of China. This paper fills this gap, providing new evidence on the convergence process of RES for the 176 countries that account for more than 98% of the world population, from 1990 to 2018. A common panel data set has been used to take into account countries' specific effects. Several socio-economics and political variables are introduced to test conditional convergence such as openness to trade, developments in financial markets, income distribution, level of education. The results of this new contribution reveal that there is evidence of sigma-absolute and conditional beta-convergence process for several groups of countries. Moreover, the conditional convergence analysis shows that spatial spillover effects exert rich and complex impact on convergence speed. Finally, we provide policy recommendations, highlighting that the decarbonization target in 2050 needs additional mobilization of public and private resources to pursue a common, convergence path worldwide.

1. Introduction

The diffusion of renewable energy sources (RES) is a fundamental objective of the worldwide policy actions for sustainable development. This objective is pursued at the UN level with the sustainable development goals (SDG) recommendations, at the EU level with the new Green Deal and the new objectives of the Recovery Fund action after the Covid pandemic, and the national levels worldwide.

The importance of RES is accepted in the global debate as a way to create a sustainable future energy system, in the framework of the transition toward climate-safe investment, in line with the decarbonization goals for 2050 (IRENA, 2020). The transition to a socio-economic path which is encompassing the fight to global warming, the aspirations of Agenda (2030) to zero hunger, affordable and clean energy, sustainable cities, the International Energy Agency new Scenario "NET zero emissions by 2050" (IEA, 2020) are vision based on the crucial assumption of RES diffusions in 2050. To put data in perspective, the Net zero scenario views the reductions of CO2 emissions from 33 GT in 2020 to about 20 in 2050. To this end, worldwide annual solar PV additions should increase fivefold, expanding from 110 GW in 2020 to nearly 500 GW in 2030, resulting in an increase more than double of the share of renewables in global electricity supply, from 27% in 2020 to 60% in 2030. Thus, it is crucial to be able to assess what is the path followed by all countries in the world so far and, in particular, whether the growth of RES is converging to a common goal worldwide.

In this context, it is natural to investigate the global diffusion process of RES, in the framework of the notion of macro-economic convergence, originally analyzed in Barro and Sala I Martin (1991) and Sala-I-Martin (1996). In particular, there have been recent analyses of energy intensity and RES diffusion. Among these latter we find Bai et al. (2020) and Zhu et al. (2020) in China provinces; Berk et al. (2020) on Some EU countries; Mulder and de Groot (2012), Reboredo (2015) and Demir and Cergibozan (2020) on OECD countries. Finally, worldwide this issue has been investigated, among others, by Liddle (2010) and Herrerias (2012).

Surprisingly, there is not a worldwide analysis of the RES convergence. This is particularly striking, given that the issue of climate change

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https://doi.org/10.1016/j.jenvman.2021.112784
Received 3 February 2021; Received in revised form 1 May 2021; Accepted 12 May 2021
Available online 20 May 2021

is a worldwide externality, because there is need of joint effort globally to change the energy paradigm to converge to a sustainable development path. In addition, the existing literature has analyzed the conditional convergence of RES using as conditioning covariates the traditional macroeconomic structure variables, but no analysis has been done about the impact of regulatory and policy actions on the convergence process of RES diffusion.

This paper fills this gap, aiming to assess whether there is convergence of RES at the world level in line with the relevant Sustainable Development Goals (SDG). Specifically, this is: Ensure access to affordable, reliable, sustainable, and modern energy for all, SDG 7 (UN, 2015). In this sense, the notion of convergence is a useful paradigm to assess whether RES growth dynamics bring an effective path toward climate change policies through time, between countries or regions.

The contribution to the literature is threefold. First, as stated, we analyze the notion RES convergence at the world level in a long-time span, 1990–2018, analyzing 176 countries, which represent over 98% of the world population. Second, while convergence analysis shows whether cross-country differences are increasing or reducing, this paper also analyzes the catch-up convergence, measuring the gap between a benchmark country and the others. Third, we explicitly analyze both the RES diffusion in the energy system and in the electricity system in each country. More recent literature used RES diffusion as a proxy of environmental quality. In this paper we measure RES diffusion using two variables expressed as percentages. First, we consider the usage of RES in electricity production, second the share of green energy in total energy consumption. These two variables allow us to avoid the so called "nonproportional problem" (Dietz and Rosa, 1994). This choice, while solving a methodological problem, allows us to address a relevant issue for the policy-maker, because not only the electricity system, but also the entire economy should strive for the new targets set for the year 2050. In this context, the results of this analysis have relevant policy implications for the sustainability of worldwide policy for climate change.

The rest of the paper is organized as follows. Section 2 presents a brief literature review. Section 3 shows the methods and data used in the analysis, presenting the spatial convergence model. Section 4 presents empirical results and Section 5 provides the analytical discussion. Section 6 shows some concluding remarks.

2. Literature review

In the global debate about climate change policy implementation, the RES deployment has recently become a main issue. Especially after the Paris Agreement (UNFCC, 2015) the majority of countries worldwide has laid the grounds in the commitment to the National Determined Contributions (NDC), to increase the share of non-fossil fuels in the primary energy consumption. Accordingly, comprehensive policy frameworks for RES deployment have been announced by the Governments and several tools have been developed jointly to a variety of support instruments such as: feed-in tariffs, premiums, investment incentives certificate trading for RES in the electricity sector, obligations for RES in the heating sector and renewable energy portfolio standards.

At the supranational level to ensure that the RES-targets could be reached, coordinated policy efforts and diffusion of best practices in RES policy design are implemented to support RES deployment among countries. For example, in the EU the optimization of the policy design to support as well as the evolution of cooperation mechanisms are pivotal in the policy debate. On the contrary, in the US this coordination is lacking and consequently a high disparity exists among states due to the presence of the active environmental movements and political color. These differences also reflect heterogeneity in countries, environmental degradation (Pham et al., 2020). Convergence approach is a method widely used both in environmental economics and environmental management in order to investigate the dynamic evolution among countries of several environment variables of interest. Convergence of environmental and energy legislation has also been a very debated question worldwide. In this context several authors have tried to analyze RES convergence process in terms of share in the energy mix, policy design, energy consumption, energy supply, the role of the RES in economic growth, convergence or in the innovation patterns, focusing on four different areas or countries: US, industrial countries, EU, other emerging countries. In the US the main question has been for many years the necessity of a convergence between environment and energy federal policy intervention (Davies, 2010; Wildermuth, 2011). Further, without a federal coordination, single states have pursued independent strategies to address the RES deployment (Klass, 2013; Vasseur, 2014). Among others, focusing on CO2 emission Burnett (2013) investigated conditional beta-convergence and convergence club for USA member states, from 1960 to 2009. Focusing on industrial countries, Camarero et al. (2013) analyzed convergence club for 23 OECD members, from 1960 to 2008 referring to CO2 emissions relative to energy use; de Oliveira and Bourscheidt (2017) conducted a multi-sectorial convergence analysis to test the convergence hypothesis in term of per capita GHG emission and Acar et al. (2018) have conducted a meta-analysis of the convergence of per capita carbon dioxide emissions highlighting the existence of convergence of per capita carbon dioxide emissions between richest industrialized countries, even if the results appear sensitive to the choice of data sample and convergence approach.

In addition, also among OECD countries Solarin et al. (2018) found a club convergence process using both parametric and semiparametric techniques. In the second approach, a large club is identified, including fourteen countries such as USA, France, Italy and Japan, but surprisingly not Germany. More recently the findings of Demir and Cergibozan (2020) obtained with the estimation of a generalized method of moments model show RES convergence across OECD countries and it is interesting that they find conditional convergence determined by additional exogenous country-specific variables. Related to the issue of RES convergence, de Oliveira and Bourscheidt (2017) have analyzed the emission convergence at the sector level in the main industrialized economies, Jakob et al. (2012) found that for industrialized countries the economic growth is partially decoupled from energy consumption and that above average rates of economic growth were accompanied by larger improvements in energy efficiency). On the contrary, in several developing countries a nexus between electricity consumption and GDP exists (Dey and Tareque, 2019).

In the EU, member states have developed a variety of support instruments and stronger cooperation between countries will be of mutual benefit to achieve new EU targets. According to these authors, cooperation requires a transparent policy debate by evaluating costs and benefits resulting from enhanced RES development, that is the main way to reach convergence in term of RES share. Grafström (2018) analyze the presence of convergence of invention efforts per capita in the renewable energy field across EU countries, indeed this could be considered a necessary condition to expand homogeneously the RES production among countries. The results highlight that only a beta convergence exists. Moutinho et al. (2014) focused on absolute and conditional σ and β convergence for Portugal from 1996 to 2009. Kitzing et al. (2012) focus the policy supports of most countries become more similar in the policy types applied (dominance of feed-in tariffs) and in their scope of implementation. Similar results have been obtained by Strunz et al. (2018) that find that temporary convergence in the case of policy support instrument choices and conditional convergence in terms of RES shares. However, the results suggest a divergence of public R&D subsidies targeting RES. Summarizing environmental and energy policy convergence that represents a prerequisite of RES share convergence is a process still unfinished and more efforts are required in term of participation and transparence. Differences among national policy could determine important delay in the green new deal implantation as well as carbon emission can impact on country risk (Chaudhry et al., 2020).

The focus on the EU has also analyzed the issue of renewable energy consumption convergence patterns. Several scholars have highlighted that European countries denote a remarkable converge process. Kasman and Kasman (2020) results support the convergence hypothesis in term per capita in renewable energy consumption across the EU-15 countries also highlighting the existence of a certain number of clubs. The heterogeneity in the convergence process among European countries has been also confirmed by both Maza et al. (2010) and Berk et al. (2020). Since the end of '90 convergence process has involved a higher number of countries. More recent empirical evidence also suggests that the energy mix of core EU members has a tendency to become similar in the long-run as the RES shares in primary energy consumption converge to the average level. However, large cross-country differences will likely persist for RES shares in the electricity generation in the long-term, requiring a more supportive policy intervention at national levels. As far as emerging countries' convergence analysis is concerned, others environmental phenomena have been analyzed. For example, Xue et al. (2021) investigated the convergence process of the marginal abatement cost of carbon dioxide in China at regional level; Sueyoshi and Wang (2020) analyzed the club convergence of the sustainable development worldwide while Stergiou and Kounetas (2021), by employing several convergence approaches, investigate the existence of conditional and unconditional convergence in term eco-efficiency. Xu et al. (2020) tackle the issue on unequal RES development in emerging economies.

Generally speaking, pollution mitigation also depends on many determinants that can foster RES development (Nasir et al., 2020; Nguyen et al., 2021) however, on the supply side, RES have been investigated both in term of energy mix and economic growth. Among others, Reboredo (2015) suggests divergence and dissimilar temporal patterns in the contribution of renewable energies to the energy supply. Only a small number of countries with significant and growing RES sectors display convergence. Focusing on the relationship between renewable and economic convergence, Finally, RES seem to play a positive role in term of electricity generation (Atems and Hotaling, 2018).

3. Data and methodology

3.1. Data

To empirically investigate RES convergence, we use annual data from a panel of 176 countries covering the period 1990 to 2018. The list of countries is published in the supplementary material in Science Direct. The data are drawn from different sources, as detailed in the supplementary material. Our measure of RES refers to two relevant measures of diffusion in the economy in the period 1990–2018. The first measure is the renewable electricity output as % of total electricity output, REL. This variable refers to the usage of RES in the electricity system and represents the percentage of diffusion of RES in the generation of electricity.

The second measure is the renewable energy consumption as % of total final energy consumption, REN. This variable refers to the global importance of RES in the whole economy and represents the indicator of the strategy to decarbonize the economy following the Paris Agreement. The other exogenous variables are taken from the World Economic Indicators of the World Bank https://databank.worldbank.org/home.aspx; the UN https://data.un.org/Data.aspx; the Freedom House data base: https://freedomhouse.org/. A small number of occurrences of missing and implausible data values for some periods have been estimated. The countries represent the 98% of the total world population. Table A1 in the Appendix provides some statistics that describe our dataset.

3.2. Methods

The notion of σ -convergence involves the computation of the standard deviation (s) in each t period of the variable of interest across the *N-units* considered:

$$s_t = \left[\frac{1}{N-1}\sum_{i=1}^{N}\left(X_{it}-\overline{X}_t\right)^2\right]^{(1/2)} \tag{1}$$

where X_{it} is the variable for i countries and t periods and $\overline{X}_t = \frac{1}{N}\sum_{i=1}^{N} X_{it}$ is the cross-sectional average. The analysis through time of s_t indicates convergence if it is decreasing. A formal test can be conducted regressing s_t on a time trend t, for absolute sigma-convergence and adding other covariates Z_t, for conditional σ -convergence:

$$s_t = a + bt + cZ_t + u_t \tag{2}$$

The vector Z_t may contain specific determinants for each country, such as level of GDP per capita, gross fixed capital formation as a percentage of GDP, life expectancy at birth.

Another notion of descriptive convergence is the so-called γ -convergence, first proposed by Boyle and McCarthy (1997), which allows to check the evolution of the intra-distribution mobility of countries through time. In practice, the idea is to detect whether the ranking among "good" and "lagged" performers remains stable (i.e. the last remain last and the first remains first). The rank concordance index is between zero to unity: the closer the value is to zero the greater the extent of mobility within the distribution and it is computed as:

$$\gamma_t = \frac{Var\left[\Phi_{tj} + \Phi_{1j}\right]}{Var\left[2 * \Phi_{1j}\right]} \tag{3}$$

where Var is the variance and Φ_{1j} and Φ_{tj} are the rank of country j in periods 1 and t, respectively. This indicator can be criticized because it risks to overstate the concept of convergence. In fact, it can evolve away from unity also when changes occur only at the bottom of the distribution (for instance, when the last and the next-to-last switch positions, but both remain far down the distribution).

The notion of β -convergence allows to check for the existence of different growth processes among countries processes, leading all countries to convergence to a common target. The main idea is that "laggards" grow faster than "leaders", so that the laggard can close the gap and reach the level of the leaders. Some limitations of the β -convergence approach noted in the literature (e.g. Quah, 1993) have led some economists to prefer the concept of σ -convergence. For further considerations on pros and cons of these approaches see, among others, Bai et al. (2019).

Formally, the initial level of a variable determines its growth rate together with other covariates represented by the vector Z_{it}. As noted above, convergence occurs if the laggard "runs" faster than the first:

$$\ln(X_{it} / X_{it-\tau}) = a_i + b_i \ln(X_{it-\tau}) + c_i Z_{it} + u_{it} \tag{4}$$

We refer to absolute *β-convergence* when the restriction $c_i = 0$ applies and the coefficient b_i results negative and statistically significant in eq (4). We refer to conditional β-convergence in case of negative b and significant effect of Z_{it} ($c_{it} \neq 0$). The speed of convergence S can be evaluated by computing:

$$S_i = -\frac{\ln(1+b_i)}{T} \tag{5}$$

and the half-life is:

$$H_i = \ln(2)/S_i \tag{6}$$

Note that (4) can be also estimated for all countries using panel data methods. In this case we will introduce country and time fixed effects. Note that the controls Z_{it} are variables linked to policy actions, so that we can construct counterfactual simulations, to study the effectiveness of actions aimed at enhancing the convergence process. The notion of catch-up convergence is an extension of the beta-convergence, checking whether there is a country which is a target for the others. Following

Pesaran (2007) and Nicoletti and Scarpetta (2013), it is possible to consider an autoregressive distributed lag model of order 1, i.e. ARDL (1, 1), in which the variable of each country i X_{it} and that of a country benchmark B X_{Bt} are cointegrated:

$$\ln(X_{it}) = \phi_{i1}\ln(X_{it-1}) + \phi_{i2}\ln(X_{Bt}) + \phi_{i3}\ln(X_{Bt-1}) + g_i Z_{it} + u_{it} \tag{7}$$

Note that (7) can be seen as an error correction model (ECM) equation, under the assumption of long-run homogeneity $1 - \phi_{i1} = \phi_{i2} + \phi_{i3}$, to obtain:

$$\ln\left(\frac{X_{it}}{X_{it-1}}\right) = d_i \ln\left(\frac{X_{Bt}}{X_{Bt-1}}\right) - f_i ln(X_{it-1}/X_{Bt-1}) + g_i Z_{it} + u_{it} \tag{8}$$

with the reparameterization $d_i = \phi_{i2}$, $f_i = (1 - \phi_{i1})$. Note that X_{it} is the variable of country i and X_{Bt} is the variable of the benchmark country and d_i captures the instantaneous effect of changes in the growth of the target country's and f_i indicates the pace of the closing distance between country i and the country benchmark. Finally, adding other covariates Z_{it}, we control for the conditional catch-up convergence, also controlling for the potential shortcomings of these approaches.

4. Results

The estimation of the sigma convergence shows a clear tendency of absolute convergence in the RES diffusion worldwide; this is a novel result in the literature. The path of convergence is faster for the variable REN with respect to the variable REL, as it is evident comparing the time paths in Figs. 1 and 2. It is also interesting to note that in the case of variable REL the period post big financial crisis the convergence slowed down and then accelerated after 2015, which is the year of the Paris Agreement. The sigma convergence process is clearly steady in the case of REN. The declining trend is less pronounced in the case of REL, as it is shown by the linear trend coefficient (REL = −0.18 t + 36.70), which is lower than the liner trend coefficient of REN (REN = −0.25 t + 34.31).

We show the estimation of the gamma convergence in Table 1 computed according to eq. (3). We observe that there is a clear indication of gamma convergence, i.e. of mobility for both variables related to RES diffusion. For the variables RES as percentage of electricity (REL) and RES as percentage of energy consumption (REN), the indicator gamma is diminishing through time. For the first variable is 0.92 in 2000, 0.85 in 2015 and 0.54 in 2018 and for the second variable is 0.94 in 2000, 0.88 in 2015 and 0.53 in 2018. This shows that the gamma convergence is more pronounced for the variable REL, which expresses the RES in percentage of total electricity consumption.

We have estimated the absolute beta convergence, separately for the variables REN and REL, with a time lag t = 1, with 4928 observations and t = 2 with 4752 observations (Table 2).

The test of the absolute beta convergence involves the significance of the negative coefficient of the lag variable (176 country specific effects are omitted).

The estimation of equation (4) is reported for the dependent variables defined as the growth rate of REN, labeled as Δln(REN) in the left column and the growth rate of REL, labeled as Δln(REL) in the right column, respectively. In the top panel the exogenous variable is the level with lag l = 1 and in the bottom panel with lag l = 2. We note that the coefficients of the lag values of both variables, REN_{t-j} in the left column and REL_{t-j} in the right column are negative and significant with lag j = 1,2, respectively. This supports the conclusion that there is convergence in both RES percentage of electricity and RES percentage of total energy consumption in the period 1990–2018. The speed and the half-life estimated values, for lag j = 1, 2, are reported in Table 3. The values for speed are faster than other estimates for total energy, confirming that RES diffusion is taking momentum.

We have estimated conditional beta convergence. The conditional beta convergence is tested in Table 4 (176 country specific effects are omitted). The structure of Table 4 is the same of Table 2, but now the estimation includes the vector Z_{it} of exogenous variables: the index of civil liberties (Clindex), the life expectancy at birth (Lifeexp), the gross fixed capital formation as a percentage of GDP (GFCFperc), the level of

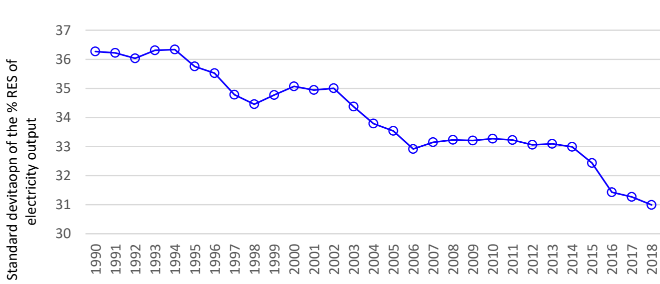

Fig. 1. Sigma-convergence - REL (RES electricity output as % of total electricity output).

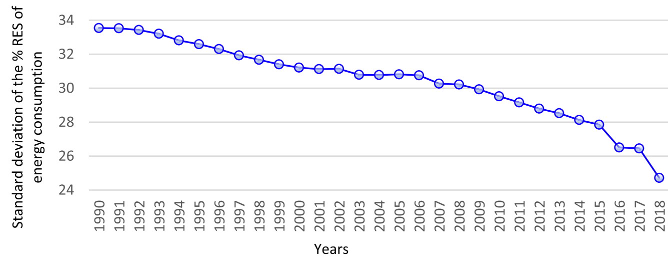

Fig. 2. Sigma-convergence - REN (RES electricity output as % of total final energy consumption).

Table 1
Gamma convergence -RES diffusion - 1990 2018.

	1990	2000	2008	2015	2018
REL (RES as a percentage of total electricity output)	1	0.92	0.90	0.85	0.54
REN (RES as a percentage of total final energy cons.)	1	0.94	0.85	0.88	0.53

Table 2
RES diffusion -Regression results-beta convergence equation (4) with $Z = 0$, lag j = 1 and j = 2.

Dep variable	Δln(REN)	Δln(REL)
lag j = 1		
N. obs. 4928		
Durbin-Watson	1.90	1.96
F (zero slopes)	1.89	3.31
R-squared	0.07	0.11
Log likelihood	−15569.20	−15748.00
Variable	Coefficient	Coefficient
Constant	8.78**	15.92**
REN_{t-j}	−0.11**	
REL_{t-j}		−0.17**
lag j = 2		
N. obs. 4752		
Durbin-Watson	1.90	1.97
F (zero slopes)	1.74	1.83
R-squared	0.06	0.08
Log likelihood	−15070.70	−15233.20
Variable	Coefficient	Coefficient
Constant	9.33**	11.24**
REN_{t-j}	−0.12**	
REL_{t-j}		−0.12**

Note: ** significant at 1% * significant at 5%.

Table 3
Absolute beta convergence - Estimated half-life and speed of convergence for lag j = 1, 2.

	j = 1	j = 2
REL (RES as a percentage of total electricity output)		
Half-life H	3.71	10.70
Speed	0.18	0.07
REN (RES as a percentage of total final energy consumption)		
Half-life H	5.92	11.31
Lambda	0.12	0.06

Table 4
RES diffusion - Conditional beta convergence eq. (4) with *Z* vector, lag j = 1, 2.

Dep variable	Δln(REN)	Δln(REL)
lag j = 1		
N. obs. 4927		
Durbin-Watson	1.93	1.96
F (zero slopes)	2.80	3.38
R-squared	0.10	0.11
Log likelihood	−15483.80	−15734.90
Variable	Coefficient	Coefficient
Constant	26.52**	16.59**
REN_{t-j}	−0.13**	
REL_{t-j}		−0.18**
$CLindex_{t-1}$	−0.01*	−0.01*
Lifeexp	−0.30**	
GFCFperc	−0.08**	−0.03*
GDPpc	8.66E-05**	8.82E-05**
lag j = 2		
N. obs. 4752		
Durbin-Watson	1.93	1.97
F (zero slopes)	2.50	1.87
R-squared	0.09	0.07
Log likelihood	−15001.60	−15227.10
Variable	Coefficient	Coefficient
Constant	25.74**	11.73**
REN_{t-j}	−0.13**	
REL_{t-j}		−0.12**
$CLindex_{t-1}$	−0.01*	−0.05*
Lifeexp	−0.29**	
GFCFperc	−0.07**	−0.03*
GDPpc	8.76E-05**	6.55E-05*

Note: ** significant at 1%; * significant a 5%.

GDP per capita (GDPpc). We note that also in this case the coefficients of the lag variables REN_{t-j} and REL_{t-j} are negative and significant with lag j = 1, 2 for both variables. It is also noticeable that the conditioning variables are significant.

In particular, we note that the coefficients of the conditioning variables are negative, reinforcing the convergence process. In other words, a lower level of liberty index, life expectancy at birth and gross fixed capital formation shares in GDP exert a boosting effect on the growth rate of RES diffusion. We note that the life expectancy is significant only for the variable RES but not for the variable REL. On the basis of a likelihood ratio test we can also infer that the conditioning variables are jointly significant. The variable GDP per capita has an opposite effect: the coefficient is positive in both REN and REL equations and hence slowing the growth rate of the diffusion of RES in the total energy system and also the growth rate of the diffusion of RES in the electricity system. These empirical results support the conclusion that there are conditional convergences in both RES percentage of electricity and RES percentage of total energy consumption in the period 1990–2018. Also, for the conditional convergence the speed and the half-life have been estimated according to lag j = 1, 2 (Table 5) confirming that the values for speed are faster than other estimates for total energy consumption.

We have also estimated the catch-up model, assuming that Germany is the leading country. In the sample period the RES share in total energy consumption in Germany (variable REN_{GE}) increased from 2% to 17% and the RES share in electricity production (variable REL_{GE}) increased from 3% to 29%. In addition, Germany has declared a very ambitious decarbonization plan to 2050, with a high target for RES diffusion (Kumar et al., 2020). We recall that the catch-up model tries to detect whether the “laggard” countries are able to reach the target country. In other words, rather than only checking for a higher speed of the “laggards”, the catch-up model examines whether the growth rate of the “laggards’ is capable of closing the gap with the benchmark. We report the cointegration summary test in Table 6, showing that most of the country variables are I(1) and that there is cointegration with Germany and the other countries. The estimation results of eq. (8) are reported in Table 7 (176 country specific dummies are omitted); to save space we report results only for l = 1.

Table 5
Conditional beta convergence - Estimated half-life and speed of convergence for lag j = 1, 2.

	j = 1	j = 2
REL (RES as a percentage of total electricity output)		
Half-life H	3.61	10.30
Lambda	0.19	0.07
REN (RES as a percentage of total final energy consumption)		
Half-life H	4.92	9.91
Lambda	0.14	0.07

We have estimated the equations without and with the exogenous effects.

The first two columns on the left reports the estimation of the growth rate of RES as percentage of total energy, Δln(REN), without and with the exogenous variables; the last two columns on the right reports the estimation of the growth rate of RES as percentage of electricity Δln (REL), without and with the exogenous variable. According to the specification of eq. (8), the covariates are the growth rate of the benchmark country, the ECM term and the exogenous vector *Z*. We observe that the coefficients of the ECM term are significant and negative for both variables (lag j = 1) i.e. $\ln(REN_i/REN_{GE})_{t-j}$ and $\ln(REL_i/REL_{GE})_{t-j}$, respectively. We note that the coefficients that refer to the catch-up are negative and significant with lag j = 1 for both variables and the majority of the conditioning variables are still significant. These results confirm that there is conditional catching-up in all LHS variables in the period 1990–2018. Furthermore, the half-life, i.e. time span necessary to catch-up 50% of the gap with the target country is around 1–2 years for the world sample. In addition, we have estimated the catch-up model of eq. (8) only on the sub-sample of the EU-27 countries (Table 8).

It is interesting to note that absolute convergence among the subgroup of EU countries is confirmed by the negative and significant coefficients of the ECM term for both variables, as shown in columns 1 and 3 with an implied half-life of around 2 years. On the contrary, the conditional catch-up process appears to be significant for REN but not for REL, as shown by LR test equals to 14.21 for REN and 4 for REL against a critical value of 9.19 (at 1% confidence level), respectively.

Table 6
RES diffusion – Catch-up convergence- Cointegration tests.

Dickey Fuller		
	REN	REL
Percentage countries I(1)	86%	89%
Engle Granger		
	(REN, REN_{GE})	(REL, REL_{GE})
	−12.83**	−14.32**

Note: ** significant at 1%.

Table 7
RES diffusion - Catch-up convergence- Germany benchmark eq. (8) - lag j = 1.

Dep variable	Δln(REN)	Δln(REN)	Δln(REL)	Δln(REL)
N. obs.	4811	4811	4140	4122
Durbin-Watson	1.89	1.91	1.95	1.96
F zero slopes	1.81	1.72	1.72	1.13
R-squared	0.04	0.07	0.04	0.03
Log likelihood	−14855.10	−14781.30	−13209.80	−13149.40
Variable	Coeff.	Coeff.	Coeff.	Coeff.
Constant	0.23**	20.22**	1.55*	7.57**
$\Delta\ln(REN)_{GE}$	−0.75**	−0.40**		
$\ln(REN_i/REN_{GE})_{t\text{-}j}$	−0.32**	−0.99**		
$\Delta\ln(REL)_{GE}$			−0.11*	−0.01
$\ln(REL_i/REL_{GE})_{t\text{-}j}$			−0.93**	−0.90**
$Clindex_{t\text{-}j}$		−0.01**		−0.02
Lifeexp		−0.34**		−0.10**
GFCFperc		−0.08**		−0.03*
GDPpc		1.7E-04*		−0.04*

Note: ** significant at 1%; * significant at 5%.

Table 8
RES diffusion - Catch-up convergence- Germany benchmark eq. (8) - lag l = 1.

Dep variable	Δln(REN)	Δln(REN)	Δln(REL)	Δln(REL)
N. obs.	666	666	563	563
Durbin-Watson	1.72	1.75	1.96	1.97
F zero slopes	1.70	1.41	1.14	1.24
R-squared	0.02	0.04	0.04	0.04
Log likelihood	−1735.50	−1728.40	−1596.30	−1594.30
Variable	Coeff.	Coeff.	Coeff.	Coeff.
Constant	0.32	25.23**	0.51	−14.91*
$\Delta\ln(REN)_{GE}$	−0.36*	0.50		
$\ln(REN_i/REN_{GE})_{t\text{-}1}$	−0.40**	−0.80**		
$\Delta\ln(REL)_{GE}$			0.31**	0.23
$\ln(REL_i/REL_{GE})_{t\text{-}1}$			−0.49**	0.52**
Clindex		0.01*		
Lifeexp		−0.31**		0.23*
GFCFperc				
GDPpc		0.87E-05		−0.71E-04**

Note: ** significant at 1%; * significant at 5%.

4.1. The sensitivity analysis

To assess the robustness of our results, we perform a sensitivity analysis and then we compare our results with the existing papers. For brevity, we only report the general findings; detailed results of these sensitivity checks are available upon request. We recall that our observation period includes the 2008 crisis, which triggered substantial changes in energy use due to economic shocks and also includes 2015, which is the year of the important Paris agreement. Consequently, we have performed a stability assessment for the sub-periods 1990–2008 and 2009–2018 and 1990 2015–2018. The rationale is that some structural characteristic of the estimated relations may have changed in the period after the 2008 crisis and/or during the period after the 2015 Paris Agreement. For sigma and gamma convergence, we note that the variance is downward sloping in Figs. 1 and 2 continuously and the gamma index is continuously decreasing in Table 1. For beta convergence, we have performed a Chow test for the above-mentioned subperiods to test the joint stability of the coefficients reported in Tables 2, 4, 7 and 8 and we cannot reject the null hypothesis of coefficient stability base on the usual F test.

Our econometrics are not fully comparable in the literature given that there is not a worldwide analysis of the RES convergence. However, some comparisons are possible referring to a specific sub-sample. For example, focusing on EU countries our results are in line with Kasman and Kasman (2020) which using our approach show that both β- and σ-convergence of per capita renewable energy consumption exist across the EU-15 countries. Analysis in developing countries confirm the results of Pfeiffer and Mulder (2013), indeed we confirm that RES diffusion requires, among others determinants, higher per capita income and educational level.

5. Discussion

The estimation results confirm that heterogeneity exists in the worldwide renewable convergence process. This is not only due to the spatial dimension, but also energy variable considered matters. In terms of gamma convergence, the process is, the more pronounced percentage of RES as total energy consumption if compared with the share of RES in total electricity output. Consumption behavior is a key factor to spur RES convergence. Hence, according to our results it is crucial to promote education and cultural change in the population to achieve a higher RES deployment. In any case our novel results underline that both energy variables considered converge over the 25 years analyzed. This is coherent with other results that refer to a club of countries, particularly in the EU and among major OECD countries. Sigma convergence is evident among EU countries also according to the strong policy intervention that has reduced the variability in the convergence path. These results are due to the successful deployment of renewables across EU Member States. In the first decade of the new millennium, several impressive structural changes have involved the European energy supply as a result of a combination of strong national policies and the general focus on renewables created by the EU legislative intervention. Furthermore, the increasing homogeneity in the EU policy instrument has increased both the sigma convergence and the speed of the process that is faster for RES, confirming that its diffusion is "taking momentum". From this point of view, it will be crucial for the policymakers to design new coordinated and harmonized environmental strategies and instruments in order to increase the speed of the convergence worldwide.

Also, since 2008 the perceived potential of renewables to economic growth among not European OECD countries has pushed policymakers to invest in green infrastructure related to energy and electricity generation. Other important measures that have positively affected renewables deployment among OECD countries have referred to the removal of the financial and technical barriers to RES investment (OECD, 2015). Focusing on the catching-up process, taking Germany as target countries results confirm that several obstacles exist acting to delay process. Data suggest that some geographical characteristics matter. In the current scenario, European countries led in term of energy technology, while Asian and American countries follow. As discussed above, the catching-up process depends on the short run by on energy policies and market opportunities and on the long run-on technology innovation and investments, consequently European countries do not suffer of structural delay.

For the emerging countries, the main obstacle refers to technological delay. It is necessary to foster green growth, combining policy instruments and green innovation process for both supply side and demand side. This means that is necessary to, develop consumers' knowledge about green energy, encouraging responsibility and the adoptions of environmentally friendly behaviors.

Among Asian countries, the main requirement also refers to a new business model that means innovation in formal education and training. For the American countries, governments need to remove obstacles to green production that is the main cause of the delay in the green industry. Of course, the impact of these measures depends on the European countries (e.g. Germany) that is expected to promote innovation in renewables sector continuously also spurred by the new paradigm of the Circular Economy that is an important issue in Europe, as evidenced by the success of the ecofriendly products among consumers.

Given the importance of the EU policy in favor of the RES and the relevance of Germany as a leading country of the EU transition strategy to RES, we have analyzed the catching-up process towards Germany of both worldwide and European countries. Recalling that the ECM process depicts an infinite gradual adjustment mechanism, the estimation results confirm the existence of a convergence process. Furthermore, the catching-up analysis shows that Germany may represent a somewhat easy target to reach at the world level. Focusing the analysis on EU countries a significant convergence process toward Germany is confirmed. Nevertheless, the low significance of the conditional catching-up process, while the absolute convergence is significant, is an indication that the policies strive of all EU members is a common effort, as shown by the estimation, and it is not a differentiated behavior of some cluster of countries. Note that the half-life of the catch-up process is about 2 years for REL and 3 years for REN, respectively. This confirms that the strategy to decarbonize the electricity sector has a relatively higher momentum in the EU, with respect to the strategy to diffuse RES in the whole economic system.

6. Conclusions

The paper has provided a comprehensive analysis worldwide of the process of convergence of the diffusion of RES in 176 countries. We show as a novel result that there is convergence worldwide. So far, there has not been an analysis of the RES convergence process across countries worldwide, given that the issue of climate change is a global externality. Previous analyses have focused on specific regions, such as the EU, OECD, and provinces of China. Several socio-economics and political variables are introduced to test conditional convergence such as openness to trade, developments of financial markets, income distribution, level of education.

The introduction into the analysis of these variables allows to control the convergence process in term of institutional and social issues. Our measure of RES refers to two relevant measures of RES diffusion in the economy: 1) renewable electricity output as % of total electricity output as proxy of the usage of RES in the electricity system; 2) the share of renewable energy in term of total energy consumption as a proxy of the importance of the RES in the whole economy. Three processes have been analyzed: sigma, beta, and catching-up convergences. In the last case the leader country has been Germany. The results highlight that sigma-absolute and conditional beta-convergence process for several groups of countries exist. The half-life, a measure of the time span necessary to catch-up with the target country is around 1–2 years for the world sample. This shows that Germany may represent a somewhat easy target to reach at the world level. Focusing on EU the conditional catch-up process appears to be scarcely significant, while the absolute process is significant. This is an indication that the policy strive of all EU members is a common effort, as shown by the estimation, and it is not a differentiated behavior of some cluster of countries. A limitation of this study is that it is considering RES as an aggregate, while there are relevant differences in technologies, localization, social costs related to the impact on the local environment, as documented by the well-known issues of resistance to wind and solar installations at the local level. A possible line for future research could be to disaggregate RES and consider separately the diffusion paths of wind, PV, biomass for electricity and, in addition, RES for transportation and residential heating; this is crucial also because it is well known that different technologies also imply different social acceptability. In turn, social acceptability conditions the political process of adoption of policies in favor of RES diffusion.

In view of the new challenging target of decarbonization for the year 2050 it is of paramount importance to understand whether the path designed in the new scenarios is affordable. The new decarbonization policy aiming at Net zero emissions calls for something like a fivefold increase in RES investment in the next three decades (IEA, 2020). This means a speeding up of the investment process, which is unprecedented in comparison to the historical experience that we have estimated. This paper provides to firms a clear indication of the additional investment effort that has to be taken to pursue a common, convergence path worldwide. Firms need from the public decision-makers a huge mobilization of public and private resources to support viable transition to the new Net zero society, with public funding that will have to anticipate private funding to allow the private sector to adequately address this transition. A new technological development in strategic sectors must accompany the investment effort to the diffusion levels of RES. In this context, we provide the policymakers at the world level with a useful tool to design an appropriate amount of policy actions to modify the speed of RES diffusion across the entire world. Indeed, it is very likely that the ecological transition will also require an adjustment of the rates of convergence among countries.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Table A1
Main descriptive statistics - 5104 data points (176 countries x 29 years)

var	Mean	Std. Dev.	Minimum	Maximum	1st Qrt.	Median	3rd Qrt.
REL	34.99	34.11	0.00	100.00	3.50	22.59	62.04
REN	33.01	30.71	0.00	99.76	6.09	22.44	56.01
GFCF/GDP	22.64	7.66	−2.42	93.55	18.19	21.97	25.88
GDPpc	11912.23	17476.28	164.34	111968.35	1282.76	4115.21	13349.38
Lifeexp	68.37	9.86	26.17	84.93	61.94	70.89	75.69
Clindex	34.38	14.07	0.00	48.00	24.00	40.00	45.00

var	Variance	Skewness	Kurtosis
REL	1163.17	0.64	−1.00
REN	943.10	0.70	−0.88
GFCF/GDP	58.66	1.04	4.13
GDPpc	3.05E+08	2.21	5.22

(*continued on next page*)

Table A1 (*continued*)

var	Variance	Skewness	Kurtosis
Lifeexp	97.32	−0.80	−0.04
Clindex	197.83	−1.02	0.06

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112784.

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