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Regional development trajectories of renewable energy: Evidence from French regions

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A B S T R A C T

This article aims to study the regional development of renewable energies (RE) in France over the period 1990–2015. As a first step, Principal Component Analysis was used on the collected data, which led to a classification of RE's development into four sub-periods. The first two sub-periods (1990–1994) and (1995–2003) are characterized by a strong dependence on hydro, thermal, and fossil energies. The third sub-period (2004–2011) shows the development of new RE sources. In the last sub-period (2012–2015), RE's use in transport and heating sectors has grown significantly. In a second step, we carried out a Hierarchical Ascendant Classification (HAC) on each sub-period to highlight the similarities and differences between regions in terms of diversification of the energy mix. The results show that 16 regions followed a similar path over the 1990–2015 period because of an initial favorable condition for sharing RE consumptions. Other regions (Auvergne, Aquitaine, Burgundy, Franche-Comté, Poitou Charentes, and Lorraine) experienced more contrasting trajectories in their RE development.

1. Introduction

During the 1990s, environmental issues became a significant concern for political decision-makers. Considering the threats linked to climate change, it appeared essential to reduce energy consumption, limit the use of polluting energies, and encourage the development of low-carbon sources. The development of nuclear and RE energy sources should make it possible to significantly reduce future greenhouse gas emissions [1,2]. Nuclear energy plays a crucial role in long-term economic development and environmental strategies. It has allowed meeting countries' energy needs with rapidly growing energy demand [3]. For instance, it allowed France to be one of the countries with the lowest greenhouse gas emissions globally. However, nuclear power's growth faces a triple challenge: operational safety, the disposal of radioactive waste, and the risk of proliferation of nuclear materials. Plus, nuclear energy faces the public acceptance challenge [4]. Therefore, the energy transition must be mainly oriented towards RE.

The energy transition to low-carbon technology is now a dominant paradigm in energy-related public policies. Torvanger and Meadowcroft [5]; Shrimali and Kniefel [6]; and Aklin and Urpelainen [7] underline the importance of public policy orientation in supporting energy transition and RE deployment. Fostering the development of RE requires a radical technological transformation of the global energy system. It also needs a rapid implementation of policies to encourage concerted and coordinated efforts to integrate global concerns into local and national policies. Fossil fuels continue to dominate the energy system mainly due to market failure, which leads to ignoring the cost of their negative externalities (Unruh, 2000). Due to centuries of industrial development, fossil fuels have huge structural advantages, making them more mature than sustainable alternative RE such as solar and wind energy. These disadvantages are further reinforced by fossil fuel subsidies [8]). Therefore, government action is needed to support energy transition trajectories [9]; Loorbach, 2010). RE's development requires implementing incentives to offset costs that are much higher than those of "conventional" energies, predominantly nuclear [10]. In this context, most European Union countries introduced a feed-in tariff mechanism at the beginning of the 2000s to encourage RE's development. Renewable electricity benefits from a guaranteed remunerative price, set by the public authorities, and a feed-in tariff under a long-term contract with the traditional operator [11]. Besides, the climate-energy legislative package, adopted on December 12, 2008, by the European Council, sets a target of 20% of RE in final energy consumption by 2020. By adopting the Energy Transition Law for Green Growth (Law No. 2015-992) on August 17, 2015, France committed to increasing the share of RE to 23% of gross final energy consumption in 2020 and 32% by 2030.

Achieving such targets requires local and regional authorities' active participation and competencies [12]. Indeed, RE is strongly linked to territory since it constitutes a decentralized energy production mode

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that uses local natural resources. In France, energy policy is historically a centralized policy due to French electricity production's national character. Consequently, thinking about the decentralization of energy production ends up becoming almost taboo because it is systematically interpreted as a challenge to the central state [13]. However, the appearance of RE sources in the French electricity mix is disturbing this situation. The decentralization of the organization of these energies is a necessity for their development. Thus, local authorities have gradually assumed greater responsibility in this field. During the 1980s and especially in the 1990s, increasing usage of ecological theories in society and the political world has been observed through green parties' participation in certain governments. The attention paid by the state to energy savings and the development of renewable production sources has reinforced the role of the regions in energy policy.

The current context of energy issues has made urgent the territorialization of energy policy. In decentralization, the legislator has favored local governance with an operational planning level regionally based. Indeed, since 1998, the regions have initiated various policies in the field of sustainable development. They were already involved (with ADEME) in energy savings and energy distribution networks. Nevertheless, in 2007, they were given real competencies, particularly in planning (Regional Air Climate and Energy Plan, Regional Wind Energy Plan, Territorial Climate and Energy Plan, Regional Ecological Coherence Plan, Etc.).

The energy transition is at the heart of environmental concerns and the planning of local and national energy policies. Therefore, it is essential to understand its historical origins and adopt an evolutionary analysis that reveals this transition's temporal mechanisms. Taking a temporal approach in studying the energy transition process allows a better understanding of the conflicting nature of this transition's current political implementation (Labussière and Baere, 2007). In fact, to better understand regional efforts in terms of promoting RE, we have adopted a dynamic approach to studying RE's regional development over the period 1990–2015. The temporal dimension is crucial in energy due to significant delays between the decision to invest in equipment, the installation of this equipment, and energy production. The approach adopted is based on a multidimensional data analysis that considers the characteristics defined by the selected variables. Based on the similarity of these characteristics, we can proceed to group the regions to establish a typology. The usual analyses on annual data do not allow an overall analysis of the regions and their characteristics because these analyses are carried out separately (year by year) and do not consider the possibility of having a common temporal structure. Therefore, the global evolution of the regions will be studied by a temporal analysis carried out on aggregated data. The originality of this work is linked to the regional scale chosen for the analysis; the work carried out to date concerns only national data [14]; Ntanos et al. [15]; Bersalli et al. [16].

2. Literature review

RE technologies for electricity generation are a central pillar of energy sector decarbonization strategies worldwide. Public policies to promote their diffusion have been in place in developed economies since 1980, and, since the 2000s, a growing number of emerging countries began implemented such policies. In December 2008, the European Council and the European Parliament agreed on a final compromise for a new European renewable energy directive. Actually, European Union Directive 2009/28/EC established that the share of RE in the final energy consumption should reach a target of 20% by 2020 in European Union (EU) countries. Many authors have been interested in the evolution of RE development policies at the European level. We begin by outlining the main studies that have focused on how RE is developed in the European Countries during our same analysis period (1990–2015). Then, a literature approach is presented on the impact of RE on the economic growth of countries.

Zhou et al. [17] tried to understand RE policy adoption and evolution in Europe. Going beyond the traditional analysis of individual policies, he compared alternative models of diffusion processes in 30 European countries to understand the role of coercion, emulation, competition, and learning. The findings suggest that external forces' impact varies across policy instrument groups and along the policy development timeline. Initial RE policy adoptions are mainly driven by European Union (EU) coercive power, competition pressure from economic peers, and policy learning from intergovernmental organizations, while subsequent policy evolution is more heavily influenced by EU coercion and regional emulation. Mehedintu et al. [18] analyzed the share of renewable energy consumption in final energy consumption using data for EU 28. The positive impact of the EU Directive in increasing this share was proved by means of a perturbed regression model. Forecasts of this share for the 2020 horizon were obtained, all showing that the EU target is yet to be reached. After, four groups of EU-countries were considered, according to the final energy consumption. Empirical estimations of RE share into the final energy consumption showed an increasing trend for all groups while providing forecasts quite different from those of the EU.

Bersalli et al. [16] proposed an econometric analysis of RE policies' effectiveness, based on panel data for 20 Latin American and 30 European countries over 20 years. The results converge for the influence of promotion policies in general: they have a positive and statistically significant effect on RE investment, being the principal determinant in both regions. Nevertheless, tax incentives are insufficient to assure the deployment of RE technologies. They also highlighted specificities in policy approaches and motivations across both areas and explains why auction became the main instrument in Latin American countries.

However, most of these studies have only focused on cross-country comparisons; research on regions is more limited or almost non-existent. This article aims precisely to remedy this shortcoming by proposing a contribution focusing on the French regions. RE is the fourth largest energy source after nuclear power, oil products, and gas. Consequently, the country aims to reach 32% of RE in its gross consumption by 2030. To meet this ambitious target and diversify the country's energy mix, the French government has put different goals to be accomplished for each region, notably within the framework of the Regional Climate Air Energy Schemes.

Nowadays, RE investments are accelerating in many developed economies. The enormous energy potential and the high availability at national and local levels make RE a vital option with many advantages for states and regions [19]. However, many factors influence the use of these new energy sources. At the national level, the key elements are energy prices, energy production, energy dependence, economic growth, trade openness, and the volume of greenhouse gas emissions. Besides, countries' development levels significantly influence the degree of interaction between these factors [20].

At the regional level, the study of RE consumption a recent field of research. RE is spread all over France, but the different regions are not equal in the race to develop RE. Indeed, as a result of the differences in terms of potential, some regions have been forerunners and leaders in RE's development. Comparing energy consumption or production between regions is not relevant to assess their respective performances. Indeed, the observed disparities reflect structural specificities of the economic structure, natural resources, or even climate differences []. Thus, understanding the differences in consumption or production is crucial for the successful activation of the levers of energy policy at the local level. However, the major challenge facing any energy policy in the 21st century is balancing the mitigation of environmental degradation and the achievement of sustainable economic growth.

The empirical literature on the impact of RE on economic growth is relatively new. It has focused mainly on the relationship between economic growth, nuclear energy consumption, RE consumption, and CO2 emissions. Studies on this causal link constitute a significant area of interest within our field of research. The relationship between economic growth (GDP) and RE consumption in different regions has been studied in various works using diverse methods and data.

Most of the studies of this causal link confirm the existence of a relationship between economic growth and RE consumption on the one hand and between this variable and CO2 emissions on the other hand. Increases in real GDP per capita and CO2 emissions per capita seem to be the main drivers of renewable energy consumption, which has a positive impact on economic growth.

Apergis and Payne [21]; Pao and Fu [22]; and Ben Jebli et al. [23] show the existence of bidirectional causality between RE consumption and real GDP per capita, while for Apergis et Danuletiu [24]; the relationship is unidirectional from RE consumption to real GDP per capita. In the same analytical framework, Ntanos et al. [15] examined the relationship between energy consumption deriving from RE sources and countries' economic growth expressed as GDP per capita concerning 25 European countries. His results show a higher correlation between RE consumption and the economic development of countries of higher GDP than those of lower GDP. Saad, W., & Taleb, A [25]. also analyzed and compared the short-run and long-run relationship between RE consumption and economic growth but in only 12 EU countries. Their findings indicate unidirectional causality running from economic growth to renewable energy consumption in the short run and a bidirectional causal relationship between the variables in the long run. This result is also found by Soava et al. [26]; who examined the causal relationship between economic growth and renewable energy consumption using data for 28 countries of the EU. The empirical results suggest a positive impact of renewable energy consumption on economic growth and emphasize bidirectional or unidirectional Granger causalities between the two macroeconomic indicators for each country in the panel.

Finally, Kasperowicz et al. [27] examined the long-run relationship between renewable energy consumption and economic growth within the traditional production function framework in 29 European countries from 1995 to 2016. The study found a long-term equilibrium relationship between economic growth and renewable energy consumption and that RE consumption has a positive impact on economic growth. The results suggest that the use of renewable energy as a global commodity in the process of economic growth is highly significant.

These results justify the political decisions of the EU concerning the necessity of increasing the RE consumption and prove that this type of energy consumption has a strong positive impact on economic growth. RE development is favorable to economic growth, and that RE development policies cannot delay economic growth. The outcomes also confirm that economic growth is crucial to provide the resources needed for sustainable development. Therefore, policies to promote renewables can provide for economic growth, increase renewables, reduce greenhouse gas (GHG) emissions, and ensure important sustainable development goals. We assume that economic growth at the regional level can also lead to an increase in RE consumption.

Apergis and Payne [21]; Saint Akadiri et al. [28]; and Menegaki, A. N [29]. introduce an environmental dimension in the analysis of RE consumption. Apergis et al. [14] indicate that short-term nuclear power consumption plays an essential role in reducing CO2 emissions. The long-run estimates suggest a statistically significant positive relationship between emissions and RE consumption. Saint Akadiri et al. [28] applied an autoregressive distributed lag (ARDL) methodology to a panel data of 28 European Union (EU-28) countries over the period 1995–2015. The study confirms a positive and significant long-run nexus among environmental sustainability, RE consumption, and economic growth in the EU-28 countries. Besides, empirical results indicate that real gross fixed capital formation, carbon emissions, and other environmental factors are principal determinants of long-run growth in the EU. Menegaki, A. N [29]. studied the causal relationship between economic growth and renewable energy for 27 European countries in a multivariate panel framework over 1997–2007 using a random effect model. Empirical results do not confirm causality between renewable energy consumption and GDP, although panel causality tests unfold short-run relationships between renewable energy and greenhouse gas emissions and employment.

Also, other results from Menyah and Rufael [30] and Apergis et al. [14] indicate that short-term nuclear power consumption plays a vital role in reducing CO2 emissions, while Ben Jebli et al. [23] and Ben Jebli et Ben Youssef [31]; showed a unidirectional causality from CO2 emissions to RE consumption. In this context, Tiwari [32] confirms that a positive shock on RE consumption reduces CO2 emissions. The rest of the studies reveal that RE consumption does not contribute to the reduction of emissions. The lack of adequate storage technology can explain this to overcome the intermittency problems associated with using the new energy technologies, forcing power producers to rely on emissions-generating energy sources to meet demand.

Panayotou [33] and Stern [34] emphasized the economic structure's impact on energy consumption. Indeed, a robust sectoral specialization measured by a high degree of industrialization explains the contrasting levels of energy consumption between countries. Indeed, being polluting and very energy-intensive, industrial production has also been highlighted in many studies as determining energy consumption. In this perspective, Wang et al. [35] have shown that industrialization increases CO2 emissions and energy consumption in China. At the regional level, we estimate that highly industrialized regions will consume more energy from fossil or nuclear sources than from renewable sources.

3. Data and preliminary analysis

3.1. Data

We aim to establish French region typology in terms of the energy mix and RE's development over the period 1990–2015. The regional specificities are measured using variables representing the weight of RE in final consumption, the shares of the different sources (hydraulic, wind, photovoltaic, thermal, and biomass) in the production of renewable electricity, the weight of nuclear and fossil fuels, the per capita consumption of biofuels in transport and biomass and solar thermal energy in heat. We have also retained energy intensity as a regional structural indicator. All these so-called active variables, characteristics of RE development, are described in Table 1. We collected data from the Regional Directorate of Environment, Planning and Housing, and the Observation and Statistics Service.

3.2. Evolution of active variables over the period 1990–2015

This section adopts a double approach, both temporal and spatial, to highlight possible temporal and spatial disparities in RE development in France. First, we will present descriptive statistics of all active variables, calculated over the period 1990–2015 for all regions. In the same framework, we will perform a temporal analysis of spatially aggregated data, i.e., the average annual evolution of all regions' active variables. Second, we will adopt a spatial approach to spatially aggregated data to highlight regional disparities in terms of RE development over the 1990–2015 period. To study RE development's temporal dimension, we consider annual averages of variables calculated over all regions. Summary statistics are reported in Table 2.

Analysis of the means and dispersion indicators for the active variables reveals substantial temporal disparities (see Table 3). The average share of RE in final energy consumption reaches 11% for the whole period 1990–2015; it varies from 6% in 2002 to 25% in 2015. If we consider the coefficient of variation, which compares the level of homogeneity or relative dispersion of the data around the average, it varies from 9% for the Energy intensity to 118% for the share corresponding to wind electricity. We note a high coefficient of variation for RE's share in final energy consumption (52%) and the photovoltaic (62%) in total renewable electricity production. These numbers show a large temporal variability of RE's shares in France over the period 1990–2015.

Fig. 1 shows the evolution of RE's shares in total electricity

Table 1
Characteristics of RE development.

Abbreviation	Variable	Definition
Share.RE.TFEC	The share of RE in total final energy consumption (%)	The sum of the consumption of wind, solar, hydro and biomass energy divided by the total final energy consumption.
Share.REL.TEP	The share of renewable electricity [a] (REL) in total primary electricity production (TPEP) (%)	The sum of wind, photovoltaic, thermal and hydroelectric electricity production and electricity from bioenergy divided by the TPEP
RELP.cap	REL production per capita (Gwh/capita)	The sum of wind, photovoltaic, thermal and hydroelectric electricity production and electricity produced from biomass divided by the number of inhabitants of the region.
TPEP.cap	TPEP per capita (Gwh/cap)	Electricity generated from fossil, nuclear and renewable sources divided by the number of inhabitants of the region
NEP.cap	Nuclear electricity production per capita (Gwh/capita)	
FFC.cap	Fossil fuel consumption per capita (Ktoe/cap)	The sum of the consumption of coal, oil products and natural gas divided by the number of inhabitants of the region.
Share.hydr.ELRP	The share of hydroelectric electricity production in the production of REL (%)	Hydroelectric electricity production divided by total REL production
Share.wind.ELRP	The share of wind electricity production in the production of REL (%)	wind electricity production divided by total REL production
Share.phot.ELRP	The share of photovoltaic electricity production in the production of REL (%)	photovoltaic electricity production divided by total REL production
Share.therm.ELRP	The share of thermal electricity production in the production of REL (%)	Thermal electricity production (electricity produced from biomass (cogeneration), solar energy and geothermal energy) divided by total REL production.
Share.biom.ELRP	The share of electricity generated by the biomass energy [b] in the production of REL (%)	Electricity production from biomass divided by total REL production.
Cons.RH.cap	Per capita consumption of renewable heat[c] (Ktoe/cap)	The consumption of renewable heat (wood energy and solar thermal energy) divided by the number of inhabitants of the region.
Cons.Biof.cap	Biofuel consumption per capita (Ktoe/cap)	Biofuel consumption divided by the number of inhabitants of the region
EI	Energy intensity (Toe/1000 €)	The ratio of final energy consumption to gross domestic product, volumes

[a] The total production of REL (hydro, wind, photovoltaic, thermal and biomass) is used to calculate the share of REL in total electricity (Share.REL.TEP), to calculate the per capita production of REL (RELP.cap) and also to calculate all shares of RE in the total production of REL.

[b] The production of electricity from biomass comes from wood-fired boilers, waste incineration factories and plant or animal materials (cogeneration) and biogas production by methanisation. Only electricity produced from wood boilers and methanisation is counted. Electricity from cogeneration is counted as thermal electricity.

[c] The consumption of renewable heat is the sum of three heating consumptions: wood energy (biomass energy), solar thermal energy and geothermal energy (variable not available).

Table 2
Summary temporal statistics.

	Mean	Min	Max	Standard deviation	Coefficient of Variation
Share.RE.TFEC	11%	6%	25%	6%	52%
Share.REL.TEP	31%	25%	45%	6%	20%
Share.hydr.ELRP	57%	36%	71%	13%	22%
Share.wind.ELRP	11%	0%	33%	13%	118%
Share.phot.ELRP	5%	0%	10%	3%	62%
Share.therm.ELRP	13%	10%	14%	1%	11%
Share.biom.ELRP	14%	10%	16%	2%	15%
Cons.RH.cap	1,80E-04	1,34E-04	2,22E-04	2,30E-05	13%
Cons.Biof.cap	3,02E-05	8,43E-06	5,90E-05	1,48E-05	49%
FFC.cap	1,75E-03	1,24E-03	2,01E-03	1,94E-04	11%
RELP.cap	1,48E-03	1,20E-03	1,96E-03	1,69E-04	11%
TPEP.cap	9,03E-03	7,53E-03	1,39E-02	1,16E-03	13%
NEP.cap	6,83E-03	6,52E-04	1,20E-02	1,73E-03	25%
EI	9,96E-02	8,51E-02	1,13E-01	8,61E-03	9%

Table 3
Summary regional statistics.

	Mean	Min	Max	Standard deviation	Coefficient of Variation
Share.RE.TFEC	11%	1%	60%	9%	83%
Share.REL.TEP	31%%	0%	99%	30%	97%
Share.hydr.ELRP	57%	0%	100%	36%	63%
Share.wind.ELRP	11%	0%	87%	20%	187%
Share.phot.ELRP	5%%	0%	54%	8%	146%
Share.therm.ELRP	13%	0%	54%	15%	118%
Share.biom.ELRP	14%	0%	60%	15%	112%
Cons.RH.cap	1,80E-04	1,00E-05	6,50E-04	1,07E-04	59%
Cons.Biof.cap	3,02E-05	0	1,41E-04	2,15E-05	71%
FFC.cap	1,75E-03	8,00E-04	3,20E-03	4,14E-04	24%
RELP.cap	1,49E-03	0	0,0066	1,60E-03	108%
TPEP.cap	9,03E-03	1,00E-04	1,20E-01	1,01E-02	112%
NEP.cap	6,83E-03	0	1,21E-01	1,05E-02	154%
EI	9,97E-02	3,20E-02	1,77E-01	2,38E-02	24%

production and overall energy consumption, while Fig. 2 shows the growth of RE in total electricity production (annual regional averages).

The evolutions of the shares of RE in final energy consumption and total primary electricity production show steady growth over the period 1990–2015, i.e., 201% and 79%, respectively. We note that over the

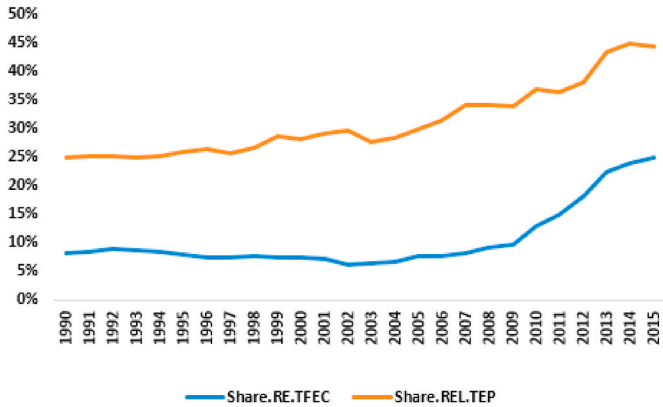

Fig. 1. Evolution of RE shares in total electricity production and in total energy consumption (annual regional averages).

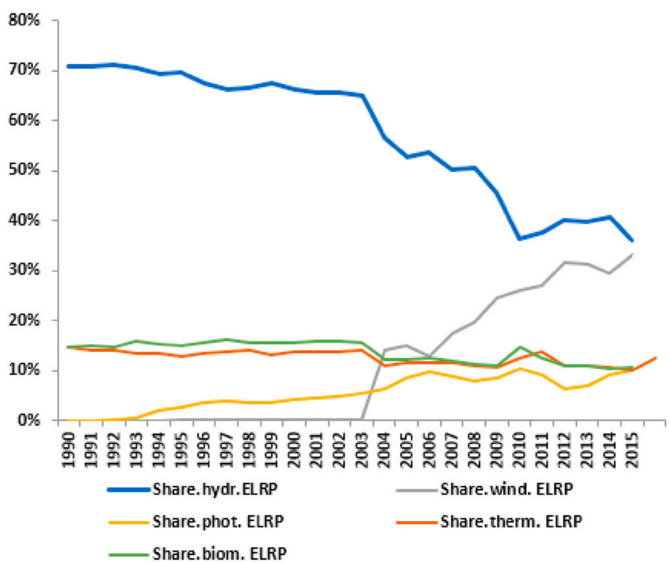

Fig. 2. Evolution of the shares of the RE energy sectors in the total production (annual regional averages).

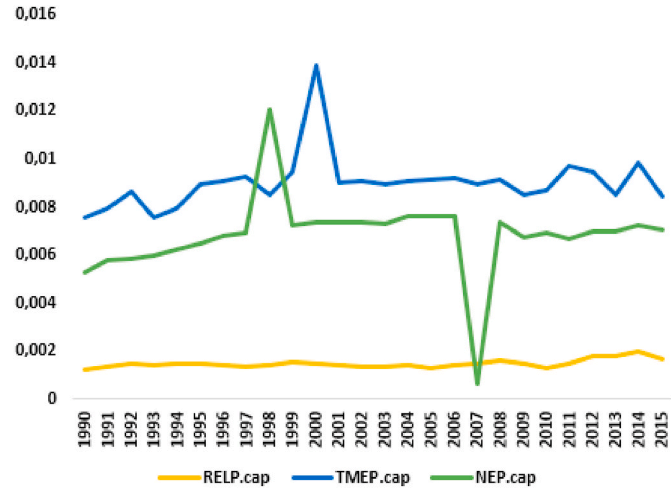

Fig. 3. Evolution of total electricity production, renewable electricity and nuclear electricity per capita (annual regional averages).

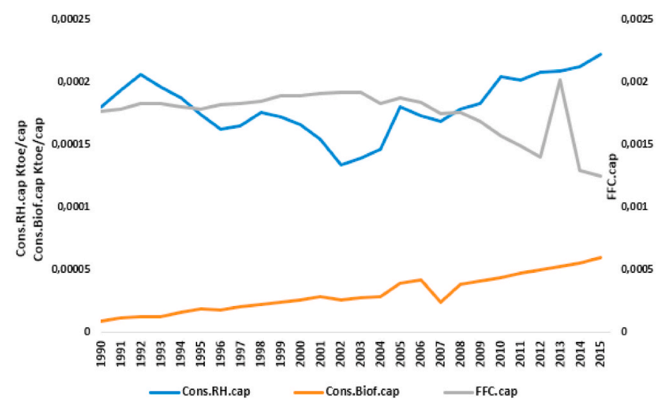

Fig. 4. Evolution of per capita consumption of renewable heat, biofuels and fossil fuels (annual regional averages).

period, except for hydropower, the average shares of the various RE sources in total production of RE increased sharply. Hydropower, which benefits from a mature technology that offers a potential already widely exploited in France, hardly evolves any more on a national scale. Its share in electricity production has been strongly decreasing since 2003 due to the emergence of new RE sources.

A large part of the new RE sectors' growth comes from the development of wind and solar photovoltaic farms. The exponential growth of the wind energy sector between 2003 and 2015 is particularly noticeable from 2005 (the reference year of the (EU) Directive 2015/1513). For these sectors, as for hydropower, the temporal disparities in capacity are incredibly significant. However, in electricity production, the shares of biomass and thermal have remained stagnant over our study period. From 1990 to 2003, there was a slight regression in the use of biomass for heating and stagnation of solar thermal. The evolutions of biomass and thermal shares in renewable electricity production remained close to the averages, i.e., respectively 14 and 13% over the period 1990–2015. Figs. 3 and 4 present the evolutions of per capita energy production and consumption over 1990–2015.

The temporal disparities are very pronounced. Indeed, the production of renewable electricity is much lower than that of nuclear, on which the total production of primary power depends mostly. The two curves of the evolution of nuclear electricity production and total electricity (Fig. 3) represent this dependence on nuclear power. On the other hand, the per capita consumption of fossil fuels has decreased by 29% (Fig. 4). The use of renewable heat is increasing by 23% compared to 1990. The development of the biofuel sector is spectacular and steady over the period. Indeed, per capita consumption has increased by 600% over the period 1990–2015.

3.3. Regional disparities in RE development over the period 1990–2015

In the following lines, we will adopt a spatial approach to temporally aggregated data to highlight local disparities in RE development over the period 1990–2015. We consider the regional averages of the variables calculated from the twenty-six years considered in our sample.

The figures below perfectly illustrate these differences in terms of RE consumption. We first present the regional summary statistics.

Analysis of the averages and dispersion indicators of the active variables reveals substantial disparities between regions. The average share of RE in final energy consumption reaches 11% for 1990–2015. It varied from 1% in Ile-de-France in 1998 to 60% for Limousin in 2015. If we consider the coefficient of variation, it varies from 24% for energy intensity and fossil fuel consumption per capita to 187% for wind power share in the total renewable electricity production. We also note a very high coefficient of variation for the percentage of RE in final energy consumption (83%) as well as for the shares of biomass (112%), wind (187%), photovoltaic (146%), and thermal (118%) in total renewable electricity production, which shows a very contrasted regional development of RE.

Fig. 6 highlights strong regional specificities over the period 1990–2015. Each region has a different renewable energy production potential that should enable France to reach 32% of renewable energy in gross final energy consumption by 2030. To achieve this goal, the development of renewable electricity production is at the heart of France's strategy. In recent years, the various support measures have led to a significant change in the quantity produced and its distribution. Indeed, new sectors have been developed, such as wind power and, more recently, photovoltaic solar energy.

The Limousin, Corse, Auvergne, Rhône-Alpes, Franche-Comté, and Midi-Pyrénées regions show the best results in terms of the share of RE in final consumption (Fig. 5). These regions have, as shown in Fig. 6, a high potential for hydropower production. This abundant resource allows them to produce a large amount of renewable electricity and cover a large share of their final consumption. The Champagne-Ardenne, Basse-Normandie, Picardie, Lorraine, and Centre regions are particularly characterized by many "new" RE sources installed. Indeed, renewable electricity production in these regions comes mainly from wind power in which these regions are mostly involved.

Photovoltaic electricity is not only developed in the south-east of France (Provence-Alpes-Côte d'Azur, Languedoc-Roussillon, Aquitaine, and Corse) but also in the regions of Bourgogne, Poitou-Charentes, and Pays de la Loire. These regions have large spaces suitable for the installation of solar panel equipment. Finally, specific areas, notably Ile-de-France, the French overseas departments (OD), and Haute-Normandie, are highly specialized in producing electricity from biomass and thermal sources. These two renewable energies play a significant role in supplying the heating system in these three regions.

In conclusion, the dual approach adopted in this research enables us to highlight temporal and spatial disparities in RE's development in France. The temporal analysis of spatially aggregated data reveals a large temporal variability of RE's shares in France during the period 1990–2015. Indeed, apart from hydropower production, primary production in other sectors has sharply increased since 2003. The spatial approach based on temporally aggregated data revealed territorial disparities and a very contrasted regional development of RE over the 1990–2015 period reflecting each region's different RE production potentials.

4. Methodology and empirical results

We use multidimensional analysis methods to study the regions' involvement in the energy transition and their performance in RE development. The first step is to analyze the dynamics of French regions over the period 1990–2015 to identify sub-periods of RE development.

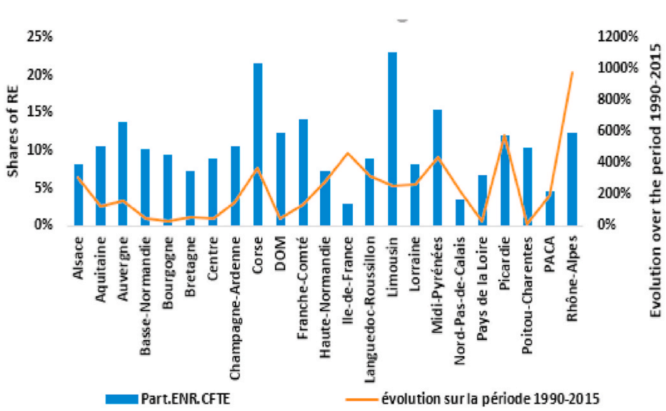

Fig. 5. RE shares in final energy consumption by region (average from 1990 to 2015). **Note:** The variable "Evolution over the period 1990–2015 " represents the growth rate over the period 1990–2015 of the share of RE in final energy consumption for each region.

In the second step, we establish a typology of RE development in France for each sub-period to highlight the similarities and differences between regions regarding the diversification of the regional energy mix (production and consumption by energy source).

4.1. Methodology

The approach adopted is based on a combination of multidimensional evolutionary data analysis methods considering the regions' energy characteristics and their evolution over the period 1999–2015. The usual analyses on annual data do not allow for overall analysis since they are carried out separately (year by year), they do not consider the possibility of a standard structure over time. Therefore, the evolution of regions' classes for each sub-period is studied using a temporal analysis performed on aggregated data (averages over time for each sub-period). This analysis highlights the common structure of groups of variables observed for the same individuals (22 metropolitan regions). This method's originality lies in the weighting of the variables, which balances the influence of the various groups of variables. This method makes it possible to consider all the groups on an equal basis. This balance is necessary because groups of variables always differ according to the variables' structure, including their interrelationships. It provides representations of regions and variables that can be interpreted according to a standard principal component analysis (PCA).

Before explaining the rest of the methodology, it seems useful to motivate the method's choice. To analyze a set of variables and synthesize the information that emerges from them, we can choose between two data analysis methods: principal component analysis (PCA) or Exploratory Factor Analysis (EFA). Calculations for both PCA and EFA involve matrix algebra and matrices of Eigenvectors and Eigenvalues. PCA is a variable reduction technique used when variables are highly correlated. It Reduces the number of observed variables to a smaller number of principal components, which account for most of the observed variables' variance. Simultaneously, EFA is a variable reduction technique that identifies the number of latent constructs and the underlying factor structure of a set of variables. It Hypothesizes an underlying construct; a variable not measured directly, and estimates factors that influence observed variables' responses. This method is traditionally used to explore the possible underlying factor structure of a set of measured variables without imposing any preconceived structure on the outcome [36]. The difference between PCA and EFA in mathematical terms is found in the values put in the correlation matrix's diagonal. In PCA, 1.00s are put in the diagonal, meaning that all of the matrix's variances are to be accounted for (including variance unique to each variable, variance common among variables, and error variance). That would, therefore, by definition, include all of the variances in the variables. In contrast, in EFA, the commonalities are put in the diagonal, meaning that only the variance shared with other variables is accounted for (excluding variance unique to each variable and error variance). That would, therefore, by definition, include the only variance that is common among the variables.

The difference between PCA and EFA in conceptual terms is that PCA analyzes variance and EFA analyzes covariance [37]. Thus, EFA is used to exclude unique and error variances to see what is going on in the covariance, or common variance, as in situations where there is a theory drawn from previous research about the relationships among the variables. PCA is performed without a theory to explore what patterns emerge in the data (in all of the variance). In our case, our objective is to classify regions according to their behavior in terms of renewable energy development. We do not have a theoretical framework for comparison or a model to follow. Our goal is to derive profiles of regions from a highly correlated variable. The most appropriate method for our study is, therefore, principal component analysis.

In a first step, we begin by identifying the sub-periods of the development of RE. We use PCA to group the years of the 1990–2015 period into homogeneous classes or sub-periods. In a second step, we use a

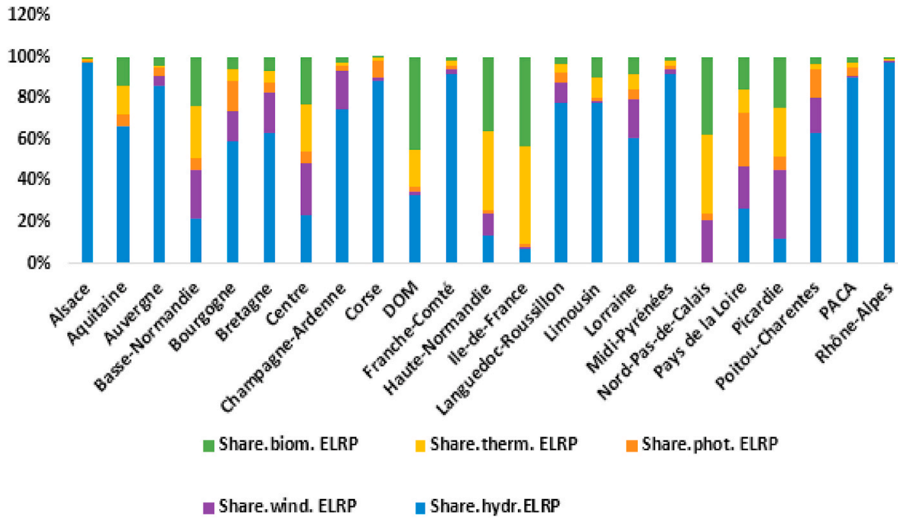

Fig. 6. Percentage of renewable electricity generation by energy source (average from 1990 to 2015).

Hierarchical Ascendant Classification (HAC) according to the Ward criterion[1] on the significant factors of the Principal Component Analysis (PCA) of average annual rates of RE development variables. This methodological linking of factorial and clustering methods constitutes an instrument for statistical observation and structural analysis of data.

4.2. Dynamics of RE development over the period 1990–2015

To analyze RE development dynamics over the 1990–2015 period, we study the average annual evolution of the energy variables (the 14 active variables) for all French regions (metropolitan and OD). In this analysis, the years play the role of "individuals" and the average annual values of the variables' function. We apply cluster analysis to group the 1990–2015 period into homogeneous classes or sub-periods. More accurately, an HCA was used on the significant factors of the average annual variables' PCA. The temporal variability of the active variables noted in the previous section justifies using the PCA standardized over the years. The dendrogram in Fig. 7 represents the hierarchical tree of years. Table 4 summarizes the main results characterizing the chosen partition into four sub-periods obtained from the hierarchical tree.

The established classification highlights four sub-periods of RE development. The first is spread over four years (1990–1994) and is characterized by a strong dependence on hydropower and thermal energy. These two energies are among the most mature renewable energies for producing electricity. Indeed, the development of hydropower in France dates back to the post-World War II years (between 1946 and 1960) when the question of independence regarding the supply of raw materials, particularly coal, appeared to be of little strategic importance. The development of hydropower was then favored [38]. Consequently, hydropower plants between 1946 and 1960 produced 60% of electricity. This first sub-period is also characterized by the non-existence of new renewable energy sources, notably wind and photovoltaic energy, whose development only took off in the 2000s. Therefore, the share of renewable energy in electricity production remains relatively low during this period. We observe that 74% of the period's net electricity production was generated by nuclear power compared to only 15% of RE production. General De Gaulle initiated the development of this sector in the 1950s and 1960s. France's first civil nuclear program began in the third five-year plan (1957–1961). The 1973 oil crisis accelerated the commitments. The impact of this shock led the Messmer government

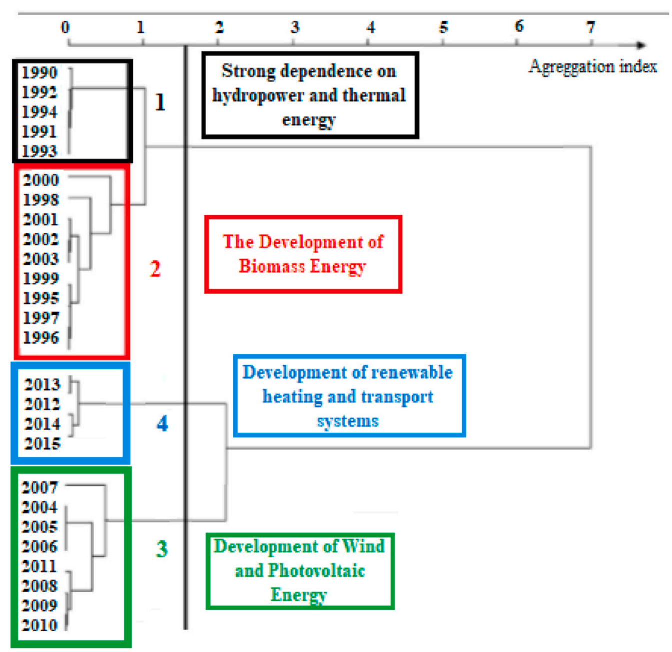

Fig. 7. Cluster dendrogram of years over the period 1990 to 2015 of the 23 regions.

to initiate a nuclear power construction program to ensure the country's energy independence [39]. Financial and human resources were then mobilized in this direction to the detriment of RE, except for hydropower, which was developed at an early stage. Finally, we underline that biofuels' low consumption marks this first sub-period with the drop in oil prices after the oil counter-shock of 1986, which continued to attract consumers and industrialists at biofuels' cost.

During the second period (1995–2003), the energy mix was still not very diversified. It was heavily dependent on fossil fuels, hydropower, and thermal power. However, we observe the emergence of biomass, whose average share rose from 15.3% in the first sub-period to 37.4% in the second period. Biomass, used as a biofuel to produce heat and electricity, experienced strong growth during the 1990s. At the international level, this period was marked by the adoption of the Kyoto Protocol. Indeed, in 1997 the United Nations Framework Convention on Climate Change (UNFCCC) was adopted, reflecting the commitment of stakeholders (ratifying the protocol) to reduce greenhouse gas

[1] Generalized Ward's Criteria, i.e. aggregation based on the criterion of the loss of minimal inertia.

Table 4
Synthetic partition into four sub-periods.

	Class 1	Class 2	Class 3	Class 5
	Strong dependence on hydropower and thermal energy	The Development of Biomass Energy	Development of Wind and Photovoltaic Energy	Development of renewable heating and transport systems
Duration	5 years	9 years	8 years	4 years
Years	1990 to 1994	1995 to 2003	2004 to 2011	2012 to 2015
Profile (+)	+ Share.hydr. ELRP + Share. therm. ELRP	+ Share.biom. ELRP + Share.hydr. ELRP + Share. therm. ELRP + FFC.cap	+ Share.phot. ELRP + Share.wind. ELRP	+ Share.RE. TFEC + RELP.cap + Share.REL. TEP + Share.wind. ELRP +Cons.Biof.cap + Cons.RH.cap
Anti-Profile (−)	- Share.wind. ELRP - Share.phot. ELRP - Share.REL. TEP - Cons.Biof. cap	- Share.REL. TEP - Share.RE. TFEC - Share.wind. ELRP - Cons.RH.cap	- Share.therm. ELRP - Share.hydr. ELRP - Share.biom. ELRP	- FFC.cap - Share.therm. ELRP - Share.hydr. ELRP - Share.biom. ELRP

Note: Variables are significant at the level of 5.

emissions. The European Union has played a leading role in this field: it ratified the Kyoto Protocol in 2002 and made an ambitious commitment to reduce its GHG emissions by 8% in 2012 compared to 1990 levels. In this context, France has moved towards increasing the use of renewable energy sources, particularly biomass. During this period, the energy use of biomass has been marked by the exploitation of bagasse and thermal power plants (Bilionière, 2011). This period is also characterized by low consumption of RE sources, whether to produce electricity (small share of wind power in renewable electricity production) or heat (low consumption of renewable heat). Indeed, fossil fuels continue to dominate the energy mix thanks to relatively stable oil prices during this period.

During the second period (1995–2003), the energy mix was still not very diversified. It was heavily dependent on fossil fuels, hydropower, and thermal power. However, we observe the emergence of biomass, whose average share rose from 15.3% in the first sub-period to 37.4% in the second period. Biomass, used as a biofuel to produce heat and electricity, experienced strong growth. The third period running from 2004 to 2011, is distinguished by developing two new RE sources: wind and photovoltaic energy. Since 2005, France has adopted a proactive policy to promote RE sources to diversify the renewable energy mix. As a result, besides hydropower, biomass, and thermal energy, wind and photovoltaic energy production have become part of the energy mix. Almost non-existent in the electricity capacity mix in 2000, both at the French and European levels, these two technologies have found their place, next to hydropower, in electricity production. This period was marked by the adoption of laws promoting the use of RE. Indeed, the Law of 13 July 2005, known as the POPE[2] law, is the first to set targets for promoting renewable energies. This law is based on the transposition of European directives into national law. The Programming Act of 3 August 2009 on the Grenelle Environment Forum's implementation set a target of 23% renewable energies in final energy consumption by 2020 in line with European objectives. In addition to these laws encouraging the use of new renewable electricity sources, the offshore wind energy sector was exclusively supported via an initial call for tenders launched in 2005. On the other hand, the average shares of conventional hydraulic, biomass, and thermal energy in renewable electricity production are significantly lower than those of the overall period.

The last sub-period (2012–2015) is marked by the rise of new RE sectors, notably wind and biofuels. In addition to power generation, renewable heat and transport systems are rapidly growing. Regarding electricity, the development of wind power is growing at a higher rate than other renewable energy sources (hydro, biomass, and thermal). The shares of RE in total electricity production and total energy consumption, and the per capita production of renewable electricity are higher than the average over the overall period. The rise in oil prices has mainly driven the development of the renewable transport system. Biofuels have become more and more economically attractive over the last period. The production of renewable heat has also been developed with the heating fund's support, which, according to the Ministry of the Environment, Energy and the Sea (MEEM), was to reach 420 million euros in 2017. Thus, it will be possible to achieve the target of more than 50% of renewable heat by 2023 (compared to 2014)[3]. We observe that all French regions have adopted the Regional Climate Air Energy Schemes during this last period, whose major commitment is RE's development. This scheme is entirely in line with the law on energy transition for green growth (LTECV) adopted in 2015, which sets an ambitious target of 32% RE in gross final energy consumption by 2030.

In conclusion, the classification method adopted allows us to identify four sub-periods of RE development. In what follows, we will focus on analyzing the regions' trajectories in terms of RE development by identifying classes of areas with similar energy profiles for each sub-period.

4.3. Regional development trajectories of RE over the period 1990–2015

In this paragraph, we focus our attention on RE's regional development trajectories in France over the period 1990–2015. To do so, we construct French regions typology in terms of the 14 variables considered over each sub-period.

Table 5 summarizes the main results of the chosen partition's characterization into three homogeneous classes obtained from the cut of the hierarchical tree in Fig. 7. The temporal evolution of RE development in the French regions identified four homogeneous sub-periods with distinct profiles. We note that the three evolutionary analyses of the French areas show certain stability in the region's trajectories. Indeed, the four typologies present three homogeneous classes with almost identical profiles and anti-profiles. Except for Bourgogne, Champagne-Ardenne, Pays de la Loire, Picardie, and Poitou-Charentes, which followed different paths in RE development, the rest of the regions followed almost identical paths over the 1990–2015 period.

The first class includes 11 regions over the whole period, namely Alsace, Aquitaine, Auvergne, Bretagne, Corse, Franche-Comté, Languedoc-Roussillon, Limousin, Midi-Pyrénées, PACA, and Rhône-Alpes. This class also includes Bourgogne and Poitou-Charentes in the first two sub-periods, while Champagne-Ardenne and Lorraine are included in the 1995–2003 sub-period. Picardie and Pays de la Loire joined the first class in the 2012–2015 sub-period. This class is characterized by a high share of hydropower and low percentages of biomass and thermal electricity in total renewable electricity in all sub-periods. These regions have set an ambitious target for RE beyond 20% of renewable energy in total energy consumption. The Limousin and Midi-Pyrénées regions are mainly involved with respective goals of 55% and 38%. This "historical" orientation towards hydropower leads to a high share of renewable electricity in the total power production and a significantly higher per capita renewable electricity production than the other classes' average. As a result, these regions show low nuclear

[2] Programmation fixant les Orientations de la Politique Énergétique: Programming Act setting the Orientations of Energy Policy).

[3] This objective is included in the framework of the multiannual programming for energy (MPE).WW.

Table 5
Regional development trajectories of RE in the French regions over the four sub-periods.

		1990 to 1994		1995 to 2003		2004 to 2011		2012 to 2015
Class 1	+Share.hydr (90–94) +Share.REL.TEP (90–94) +RELP.cap (92–94) -NEP.cap (90–94) -FFC.cap (90–94) -Share.therm 92 -Share.biom 92	Alsace Aquitaine Auvergne Bourgogne Bretagne Corse F−Comté L−Rous Limousin M−Pyr P−Char PACA R−Alpes	+Share.hydr (95–03) -Share.therm (95–00) -Share.biom (95 et 99)	Alsace Aquitaine Auvergne Bourgogne Bretagne C−Ardenne Corse F−Comté L−Rous Limousin Lorraine M−Pyr P−Char PACA R−Alpes	+Share.hydr (04–11) +Share.REL.TEP (04–11) +RELP.cap (04–11) - FFC.cap (04–11) - Share.biom (04–09) - Share.therm (04–09) -Share.wind (04–08)	Alsace Aquitaine Auvergne Bretagne Corse F−Comté Limousin L−Rous M−Pyr PACA R−Alpes	+Share.hydr (12–15) +Share.RE.TFEC (12–15) +RELP.cap (12–15) +Share.phot (14–15) +Share.REL.TEP (12–15) -NEP.cap (12–15) - Share.therm (12–15) -Share.biom (95 et 99) -Share.wind (12–15)	Alsace Aquitaine Auvergne Bourgogne Bretagne Corse F−Comté L−Rous Limousin M−Pyr PACA Picardie PDLL R−Alpes
Class 2	+Share.biom (93 and 94) -Share.hydr 94 -Cons.RH.cap (90–94)	DOM IDF PDLL Picardie	+Share.biom (95–03) +Share.therm (95–03) -Share.hydr (97–03)	PDLL Picardie	+Share.biom (04–11) +Share.therm (05–11) -EI (04–11) -Cons.Biof.cap (04–07)	DOM IDF	+Share.biom (12–15) +Share.therm (12–15) -EI (12–15)	DOM IDF
Class 3	+Share.therm (90–94) +NEP.cap (90–94) + TMEP.cap (90–94) +FFC.cap (90–94) +EI (90–94) -Share.hydr (90 et 91) -Share.REL.TEP (90–94)	B−Norm C−Ardenne Centre H−Norm Lorraine NPDC	+NEP.cap (95–03) +TMEP.cap (95–03) -Share.REL.TEP (95–03) -Share.hydr 03	B−Norm Centre H−Norm NPDC	+Share.wind (09–11) +Share.phot 06 +FFC.cap (04–08) +NEP.cap (04–11) -Share.REL.TEP (04–08) -Share.hydr (09–11)	B−Norm Bourgogne C−Ardenne Centre H−Norm Lorraine NPDC P−Char PDLL Picardie	+Share.wind (12–15) +Share.phot (13–15) +NEP.cap (12–15) +TMEP.cap (12–15) -Share.REL.TEP (12–15) -Share.hydr 15	B−Norm C−Ardenne Centre H−Norm NPDC P−Char Lorraine

electricity production levels and fossil fuel consumption in the first and last two sub-periods.

The second class includes Ile-de-France and the French OD for the entire period. Pays de la Loire and Picardie also belong to this class only for the first two sub-periods. The characterization of the second class is relatively stable over the four sub-periods. Indeed, this class is characterized by leadership for both biomass and thermal energy over the period 1995–2015. In this context, particular attention was devoted to the wood energy and solid biofuels sectors within the framework of the SRCAE of Ile-de-France. Consequently, specific objectives were defined in terms of the development of biomass for combustion. Hydraulic energy appears to be underdeveloped in these regions. However, the other sectors, in particular biomass and solar thermal energy, are rapidly expanding. We also point out that these regions show a high sectoral specificity translated by a low energy intensity over the 2004–2015 period. They were less industrialized and more oriented towards services. Indeed, Ile de France shows a strong sector specificity with a robust service-oriented economy. The OD also present similar characteristics to those of Ile de France in terms of RE development. In particular, they stand out for the importance of bioenergy and thermal energy in electricity production, low hydroelectricity production, and low energy intensity.

The third class is made up of four regions over the four sub-periods, specifically Basse-Normandie, Centre, Haute-Normandie, and Nord-Pas-de-Calais. Champagne-Ardenne and Lorraine are also attached to this class in the first, third and fourth sub-periods. The regions Pays de la Loire and Picardie joined the third class in the 2004–2011 sub-period, while Poitou-Charentes left the first class to belong to the third in the third and fourth sub-periods. The characterization of this class is stable over the whole period. Per capita, nuclear, and primary electricity productions are well above the respective averages of the regions making up the other classes. As a result, RE's electricity production is poorly advanced because of the limited development potential for hydropower. However, since 2004, these regions have been making enormous efforts to create new sectors, especially wind and photovoltaic energy.

The trajectories of the regions are relatively stable. Only five areas changed class between 1990 and 2015. Bourgogne moved from class 1, characterized by high hydropower production over the period 1990–1994, to class 3, characterized by a high nuclear potential over 2004 to 2011. Bourgogne does not have a nuclear power plant on its territory, so the change in class corresponds to a similarity between its profile and class 3. Indeed, classes 1 and 3 have only one common variable in their profile: the share of photovoltaic electricity production in renewable electricity. This share is a variable constituting class 3 in the third sub-period and class 1 in the fourth sub-period. In fact, alongside hydropower, the photovoltaic solar sector took off in the region in the second half of the 2000s. This same region joined its first class of classification over the period 2012–2015, which groups the leading producers of hydroelectricity. Champagne-Ardenne and Lorraine left the third class, which is distinguished by strong nuclear production, to join the first class over the period 1995–2003. The regions regained their position in class 3 as of 2004 thanks to wind power generation development. Indeed, Champagne-Ardenne has the largest total installed wind farm compared to the rest of the areas. Pays de la Loire and Picardie moved from class 2, characterized by considerable development of the thermal and biomass sectors, to class 3 over the period 2004–2011, mainly involved in the wind sector development. Then they joined the first class over the last sub-period, which shows the best results in terms of RE development. Indeed, the shares of RE in the final energy consumption and the total electricity production and renewable electricity production per capita are significantly higher than those of the other classes.

Finally, we show that RE development's trajectory is well underway over the 2012–2015 period, as we are witnessing the ramp-up of new RE sectors. Moreover, regions' involvement in the event of new RE sectors seems more reliable as the areas do not benefit from historical advantages linked to the hydraulic industry's presence. We notice that this energy is relatively concentrated in Corse, Midi-Pyrénées, Alsace, and Rhône-Alpes throughout the identified sub-periods, thanks to the territorial amenities favoring this type of energy (mountains and rivers). Simultaneously, other regions have made more considerable efforts to develop new sectors, particularly wind and photovoltaic energy.

The production of the two renewable electricity sectors (wind and photovoltaic) is rapidly expanding. It has increased substantially since 2004. Its recent development has slightly reduced the gap between regions regarding the share of renewable electricity in total electricity production (which varies from 0.78% % in Île-de-France to 82% in Franche-Comté for the entire period). These two sectors have been experiencing a particular dynamic since 2005, thanks to the incentives put in place by the public authorities (subsidies and tax benefits). The sharp rise in power between 2004 and 2015 of these new energies, particularly wind power, is beginning to change the electricity mix in certain regions, notably Bretagne, Lorraine, Centre, and Picardie. However, the dynamics generated by these new energies are quite different from one region to another; some of them (Alsace, Corse, Limousin) have remained away from any development of the new sectors over the entire period.

5. Conclusion and discussion

The French regions show a hybrid integration of the energy problem in public policies. The evolution of their relationship with energy is in line with European experiences and the national incentive for transition. In this paper, we focused on the environmental dimension of French regions' dynamics by studying RE's regional development over the period 1990–2015. To approach the territories' potentialities in terms of RE promotion, we carried out typologies of all the regions using variables related to energy consumption and production. The objective is to look at energy transition and adaptation to climate change at the regional level. These typologies aim to define behavioral profiles of the regions based on the combined analysis of energy variables.

In the first step, the classification method adopted allowed us to identify four sub-periods of RE development. The first one was spread over four years (1990–1994), and it was marked by a high dependence on hydro and thermal energy. During the second period (1995–2003), the energy mix was still a little diversified, mostly based on fossil fuels, hydropower, and thermal energy with the emergence of biomass energy. The third period ran from 2004 to 2011 and was outlined by developing two new RE sources: wind and photovoltaic energy. Furthermore, in the last sub-period (2012–2015), we noticed RE's diversification. Alongside electricity production, renewable heat and transport systems were rapidly increasing.

In the second step, we identified three distinct types of RE development profiles over the four sub-periods to highlight the similarities and dissimilarities between regions in terms of diversification of the energy mix concerning the regions' energy balances. We highlighted specific stability in the trajectories of the areas except for Bourgogne, Champagne-Ardenne, Pays de la Loire, Picardie, and Poitou-Charentes, which have experienced more contrasted trajectories in terms of RE development. The other 18 regions followed a similar path over the 1990–2015 period. This very stable structure reveals that the disparities between regions at the beginning of the 1990s persisted throughout the period. Areas where the initial situation was favorable in terms of RE consumption share, reinforced this situation, while others (except for Picardie and Pays de la Loire) failed to catch up. These two regions successfully integrated the best-performing regions in the last sub-period in terms of RE development. This result is mostly due to the development of the wind energy sector in both regions. Indeed, Pays de la Loire has a real wind energy potential. In contrast, Picardie, whose nature is favorable to the development of wind energy, supports the development of eco-activities and structures in the wind energy sector connected with a mobilized industrial sector.

The regions of the first class show low levels of nuclear electricity production and fossil fuel consumption in the first and last two sub-periods. They are more oriented towards hydropower, which leads to a high share of renewable electricity in the total power production and a significantly higher per capita renewable electricity production than the average of the other classes. Regions of the second class are less industrialized and more oriented towards services. In particular, they stand out for the importance of bioenergy and thermal energy in electricity production, low hydroelectricity production, and low energy intensity. These results are concordant with those of Panayotou [33]; Stern [34]; and Wang et al. [35]; who show that robust sectoral specialization measured by a high degree of industrialization explains the contrasting levels of energy consumption between countries.

We underscore that despite different paths, the French region's RE development performance is in line with the national policy since, in 2015, 48% of the areas have already exceeded the 20% RE target in final energy consumption. However, these unevenly distributed efforts have enabled France to reach the 23% target set by the Energy Transition Law for Green Growth for 2020. To achieve the 2030 objectives, it is essential to distribute the regions' efforts equitably and set specific goals for the new RE sectors. Given that France's hydropower potential is already well exploited, promising RE are wood energy, geothermal energy, biofuels, biogas, waste-to-energy, wind, and solar photovoltaic energy. Among these electrical energies, onshore wind power and, more recently, solar photovoltaic are the most competitive green energies. Although these new sectors' share is still limited, their development has considerably modified the regions' energy supply. Other energies must become even more competitive, especially in the fields of heat and electricity. Indeed, the French Court of Auditors [40] has highlighted the imbalance in financial support, which mainly benefits renewable electrical energies at the thermal ones' expense.

We offer several recommendations to promote RE's regional development to reduce France's carbon footprint and increase its energy efficiency. First, it appears necessary to better target public policies and spending in order to guarantee a sustainable and efficient allocation of energy resources:

- By promoting RE's use in transport and heating because GHG emissions continue to grow in the transport and tertiary residential sectors, efforts should be particularly sustained in highly urbanized regions;
- By enhancing each region's energy potential and concentrating subsidies on sectors having a comparative "climatic" advantage, it would be desirable for specific regional objectives to be defined at the national level for the new RE sectors according to geographic and climatic characteristics;
- By ensuring better coordination of regional, national and European policies. As the electricity grids are interconnected at the European level, establishing a European energy policy would make it possible to manage the intermittence of new RE better and increase energy efficiency.

Second, it seems necessary that the management of the energy transition be carried out at the national or even European level to ensure overall consistency, funding, and public support systems must be long-term to provide a clear and readable framework favoring investments. In this context, developing a strategy to promote RE, especially new technologies (wind and photovoltaic energy), must be done in line with the European vision. While photovoltaic and wind energy were almost absent in the French energy mix in 2000, they have had a strong foothold in Europe. Already in 1991, Denmark installed the world's first offshore. Germany introduced, in the same year, Europe's first 'feed-in-tariff' for renewables. By 2000, Europe accounted for more than 70% of all wind power installed globally and 20% of global solar photovoltaic installations. In 2000 the world's first large-scale wind farm, 'Horns Rev' saw the light – also this time in Denmark. Europe also became the largest market for solar photovoltaics by covering more than 70% of the market by 2008. In the same year, the Olmedilla Photovoltaic Park in Spain – a 60-MW power plant, making it the largest in the world – generated enough solar energy to power 40 000 homes per year. As the rest of the world is increasingly using and producing renewables, Europe has continued to be a frontrunner. In July 2019, Portugal achieved the lowest cost of a solar photovoltaics park worldwide – a record that still holds today.

Finally, although they are key players in the transition energy, local authorities have not been provided with additional resources to ensure their mission. The allocation to the regions of resources dedicated to the development of RE could accelerate RE's development in the territories and help reach the objectives set by the energy transition law for green growth. This recommendation is confirmed by Bersalli et al. [16]; who showed that promotion policies have a positive and statistically significant effect on RE investment in 20 Latin American and 30 European countries.

In conclusion, throughout this article, we have been able to analyze the regional evolution of RE over the period 1990–2015. However, like all research work, this article has its limits. Indeed, we did not include variables related to the production costs per sector and the structuring of public support systems by lack of data. The regional differences could provide different answers in terms of the development of the RE. It should be noted that such an in-depth study requires data that are not available. Finally, the construction of an explanatory econometric model of the evolution of consumption for each RE source could provide valuable additional information to the extent that the different RE sectors are closely linked to local natural resources (wood, water …). Therefore, the introduction of geographic variables in these models could explain the contrasting levels of RE consumption between regions.

Authorship contributions

F. Roussafi;: Conception and design of study, acquisition of data, analysis and/or interpretation of data, Drafting the manuscript, revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published.

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.

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