International Journal of Sustainable Energy Planning and Management Vol. 26 2020 19–32

International Journal of
Sustainable Energy Planning and Management

An evaluation of the energy and environmental policy efficiency of the EU member states in a 25-year period from a Modern Portfolio Theory perspective

Paulino Martínez Fernández[a], Fernando deLlano-Paz[a*], Anxo Calvo-Silvosa[a] and Isabel Soares[b]

[a] *Department of Business, Faculty of Economics and Business, University of A Coruna, Campus de Elvina, 15071 – A Coruna, Spain.*
[b] *Economic Scientific Group and CEF.UP., University of Porto, Rua Dr. Roberto Frias, 464 – Porto, Portugal*

ABSTRACT

The European Union has been developing its energy and environmental policy for the last 30 years. Recent communications issued by the European Commission confirm the leadership of the European Union on reducing pollutant gas emissions and technological change towards a climate neutral economy. This work assesses the efficiency of European energy policy under a Modern Portfolio Theory (MPT) approach. This proposal analyses the disaggregated European power portfolio: to make a more exhaustive analysis, focusing individually on each European country along the period 1990-2015. The efficiency of the energy and environmental policy of each Member State is measured by their distance to the power generation efficient frontier. The quadratic optimization model used by MPT is complemented by a cluster analysis in order to identify different groups of EU member states according to their behaviour patterns regarding the application of their energy and environmental policies without overlooking the efficiency of that implementation. Results stand out that France, Slovakia and Sweden belong to the "leader" efficient cluster for the analysed period. In turn, Denmark, Germany, Greece and Italy show a high consistency in the application of their energy and environmental policies as they improved their positions for the considered years.

Keywords:

European Union;
Power Mix Portfolio;
Efficiency assessment;
Energy policy assessment;
Environmental policy assessment;

URL: http://doi.org/10.5278/ijsepm.3482

1. Introduction

The EU Energy and Environmental Policies have advanced in three different fronts: energy supply security, competitiveness and sustainability [1,2]. Thus, since 1990 the technological –renewable energy sources (RES)– and environmental –carbon emissions reduction and the EU Emissions Trading System (EU-ETS)– objectives that were proposed have turned the EU into the world leader in climate change abatement [3,4].

The European Union is responsible for 10% of the global greenhouse pollutant gas emissions. However, the EU is recognized as the global leader towards net-zero-greenhouse gas emissions economy since between 1990 and 2016 it has achieved a successfully double reduction of energy use by almost 2% and greenhouse emissions by 22%, while its GDP has reached an increase around 54%. The EU has recently proposed a European vision for a modern, competitive, prosperous and climate neutral economy [4]. This new energy and environmental targets proposal continues the previous framework developed from 1990 to the present.

This work is aimed to assess to what extent the efficiency of the EU energy policy has changed for the last thirty years under a Modern Portfolio Theory (MPT) perspective. Coming from Finance, this methodological approach allows to analyse the economic efficiency of

*Corresponding author e-mail: fernando.de.llano.paz@udc.es

List of Abbreviations

CSS	Carbon capture and storage technology
GDP	Gross Domestic Product
GMC	Global minimum cost portfolio
GMV	Global minimum variance (risk) portfolio
MPT	Modern portfolio theory
PV	Solar photovoltaic generation technology
RES	Renewable energy sources

a portfolio including real assets to produce electricity (electricity generation plants). It is an optimization-based technique which searches for a long-term investment decision with a minimum risk or, alternatively, a minimum cost considering a set of constraints. Thus, the optimization process that allows obtaining portfolios with the lowest risk or the lowest cost derived from electricity production is defined in the literature with a social approach [5] as well as an environmental one, typical of public energy policy: thus, the closer the portfolio is to efficiency, the lower the social effort in terms of risk or cost assumed to produce electricity, and the more effective the energy policy applied will be. In line with this proposal in terms of risk, renewable energies are preferred to emission technologies because they do not incorporate the fuel cost component, which is characterized by high volatility. Thus, the model will tend to incorporate a higher percentage of renewable energies when defining efficient portfolios with less risk. This is why the greater presence of renewable energies in a territory's portfolio will be indicative of lower risk and greater proximity to efficiency: both economic and environmental. Portfolio emissions are reduced with this greater presence of non-emitting technologies.

This work offers a new element in the electricity generation technology portfolio analysis. The European Union energy policy assessment using this methodological approach is usually presented in terms of aggregated data: just one European Union portfolio containing the overall addition of all the EU member-state electricity productions. In this work a more exhaustive analysis is proposed as the focus is individually on each member state and for the period 1990-2015. The efficiency of the energy and environmental policy of each Member State is evaluated by measuring its Euclidean distance to the power generation efficient frontier [6]. From a methodological point of view, the customary quadratic optimization of the MPT is used for this purpose. Additionally, taking into account the huge number of variables considered, all the Member States were classified by using a clustering algorithm. As a result, it is also possible to analyse different patterns with regard to the application of national energy and environmental policies without overlooking the efficiency of that implementation considering the different behaviours featuring each cluster over the studied years.

The key research question addressed by this work is if it is possible to identify clear trends when analysing the outcomes of the different energy and environmental policies implemented by the EU member states with a special focus on gas emission reductions.

As mentioned before, the efficiency of these policies is evaluated by measuring its Euclidean distance to the power generation efficient frontier. This seems to be a valid approach to draw conclusions about the economic and social efficiency of the different electricity generation technology portfolios because the methodology is setting portfolios optimising the generation cost-risk binomial in each country.

After getting this evaluation done, three clusters including all the EU countries will be set according to the cost-risk efficiency of their electricity generation technology portfolios. The following questions could be answered when going in depth with the classification provided by the cluster analysis:

- Which member states have remained in the cluster with the highest level of cost-risk efficiency in the electricity generation?
- Which ones have improved their efficiency for the studied period (1990-2015) as a result of designing and implementing successful policies under an economic and social perspective?
- Which cluster has shown the best improvement in terms of cost-risk binomial?
- How far are the different member states from the efficient positions when generating electricity and how much would this distance be worth in economic terms (Euro/MWh)?
- Which member states have achieved the biggest reductions of gas emissions over the analysed period? Do they belong to the cluster including the most efficient countries?

2. Literature review

Portfolio theory has been widely used to analyse long-term energy planning [7–16] of energy and environmental policies that condition their design on a long-term horizon. It is within this context that portfolio theory can be framed: as a methodology that offers an answer to the problem of selecting long-term investments in the field of electricity generation technologies.

So far the various analyses presented in the literature refer to the analysis of the European portfolio as a whole, but not country by country of the European Union [7–10].

In this way, the work presented aims to analyse the outcomes of energy and environmental policies implemented by the EU member states with a special focus on gas emission reductions. The proposal is based on portfolio theory and clustering analysis.

It is not the purpose of this paper to analyse each energy policy individually. We therefore propose an analysis of all the policies applied by each country based on the proximity to efficiency (efficient frontier) of the portfolios designed by these countries over time. Therefore the study of the evolution of the portfolio efficiency of each country over the period considered (1990-2015) is presented. This work is in line with [17], which uses a multi-objective interval portfolio theory approach to provide decision support tools for investing in energy efficient technologies. In this line, it is proposed to the reader to review the work of [18]diminishing social acceptance of traditional fuels, and technological innovations have led several countries to pursue energy transition strategies, typically by massive diffusion of renewable electricity supplies. The German 'Energiewende' has been successful so far in terms of deploying renewable power, mainly by applying particular feed-in tariffs, and by bundling public, academic, industrial and political support. So far though, only few EU member states proceed with a similar transition. In March 2014 CEOs of Europe's major energy companies publicly opposed a fast and thorough transformation of electricity supplies to become fully renewable. In April 2014 the European Commission published new state aid guidelines, generally mandating renewable energy support mechanisms (premiums, tenders in which a very interesting and relevant brief review of the transition process of the electrical sectors in Europe can be found.

The application of portfolio theory to the design and efficiency analysis of power generation assets is a valid methodology widely employed [7,8,11–14,19,20]. This approach considers energy planning as a problem of long-term investment selection. The portfolio evaluation is proposed considering the cost and the economic risk of selecting different energy technologies [15,21]. This proposal is aimed to determine the minimum portfolio cost or risk depending on the objective function, or the maximum power output [22]. Cunha and Ferreira [11] develop and deepen the characterization of the different types of risk inherent to an investment in a real power generation asset such as small-hydro power technology. Likewise, in [23] a good review of the concept of risk can be found in the theory of portfolios within the problem of investment selection.

According to the MPT approach, a portfolio is considered efficient if it shows the lowest cost for a given level of risk or, alternatively, if it shows the lowest risk for a determinate level of cost. The model computes the efficient frontier, which is the geometric place in the risk-cost plane where efficient portfolios lie. Every efficient portfolio is thus characterized by its risk and cost, calculated as a function of the risk and cost of the technologies involved and their participation share. This enables an efficiency assessment taking into account the distance from each member state power generation mix portfolio to this efficient frontier.

MPT is also useful for land-use planning –to allocate scarce land and improve land-use possibilities– and lowland agriculture [24,25]. Also for assessing the financial robustness of diversified forests in comparison with single-species forests [26]. Castro et al. [27] use it for dealing with the uncertainty of conservation payments to preserve wildlife respectful production. Halpern et al. [28] apply it to natural capital and social equity across space. Hildebrandt and Knoke [29] studied forest investment analysis under uncertainty with MPT. Besides, MPT is applied to water-use planning [30], and to fish management: to analyse the behaviour of the population of salmon in North America [31] or to study the performance of salmon fishery portfolios [32]. Continuing with its applications to fish, Sanchirico et al. [33] used MPT to help in the management of ecosystem-based fishery; while Edwards et al. [34] studied the management of wild fish stocks using the MPT. Finally, Kandulu et al. [35] applied MPT to assess the impact of the Australian agricultural enterprises diversification as a strategy to stay protected against the economic risk derived from climate variability.

3. Dataset and Methodology

In this section the dataset source and structure are described, along with a full description of the MPT model used.

3.1. Dataset

Detailed generation data for each country in the EU28 were used to implement the model. Data include the production in TWh for every year in the period 1990-2015 detailed by technology — nuclear, coal, natural gas, oil, wind, hydro, small hydro, offshore wind, biomass and solar photovoltaic (PV). These data were used to compute the CO_2 emissions of every country for each year of the analysed period.

These data were also transformed into generation percentages by technology, country and year in order to compute two $\mathbb{R}^{26\times 28}$ matrixes with the costs and risks of the generation portfolio for every one of the 26 years and 28 countries considered. This information will be compared with the base model and with the technological model explained in section 3.2. These two models are the footing to provide the European generation efficient frontiers.

3.2. Model and model inputs

The base model, used as a first reference for efficiency measure, is based on the Modern Portfolio Theory or MPT [36]. The MPT model proposes a quadratic optimization mathematic approach for computing efficient portfolios of financial assets. When applied to power generation, the model includes cost and risks definition for each generation technology considered. The expected cost of the portfolio $E(C_p)$ consists of the average technologies' generation cost (C_i) weighted by the participation share of each technology (x_t), as shown in Eq. (1).

$$E(c_P) = \sum_{\forall i} x_i E(c_i) \tag{1}$$

In turn, the expected risk for a portfolio is defined according to the standard deviation of each technology (σ_i) and the correlations among every couple of them, weighted by their individual shares in the portfolio, as seen in Eq. (2).

$$\sigma_P = \left(\sum_{\forall i} x_i^2 \sigma_i^2 + \sum_{\forall i \neq j} x_i x_j \sigma_i \sigma_j \rho_{ij} \right)^{1/2} \tag{2}$$

The objective function searches for the minimisation of the generation portfolio risk meeting some constraints such as the participations shares have to be positive and total one, and the cost has to be equal to a determinate one. Thus, the model can be expressed as in Eq. (3).

$$min\,\sigma_p = min\left(\sum_{\forall i} x_i^2 \sigma_i^2 + \sum_{\forall i \neq j} x_i x_j \sigma_i \sigma_j \rho_{ij} \right)^{1/2} \tag{3}$$

$$\text{subject to:} \quad \begin{cases} x_i \geq 0\,\forall i \\ \sum_{\forall i} x_i = 1 \\ E(c_P) = c^* \end{cases}$$

The technological model includes additional constraints on the participation share of each generation technology (w_i^*), following the literature [7,16] and according to the objectives of the European energy strategy. When applying MPT to power generation, the mentioned constraints incorporate both the physical generations limits by technology and the desired generation and emission policies. Thus, the technological model can be expressed as in Eq. (4).

$$min\,\sigma_p = min\left(\sum_{\forall i} x_i^2 \sigma_i^2 + \sum_{\forall i \neq j} x_i x_j \sigma_i \sigma_j \rho_{ij} \right)^{1/2} \tag{4}$$

$$\text{subject to:} \quad \begin{cases} x_i \geq 0\,\forall i \\ \sum_{\forall i} x_i = 1 \\ E(c_P) = c^* \\ x_i \leq w_i^* \end{cases}$$

The input costs, risks and CO_2 emission for the aforementioned base and technological model are shown in Table 1 [9] for every technology used: nuclear, coal, coal with carbon capture and storage (CCS), natural gas, natural gas with CCS, oil, wind, hydro, hydro (mini), offshore wind, biomass and PV.

Table 2 shows the generation limits by technology used in the technological model, taken from [10]. Besides, the joint generation share of coal, natural gas and oil must be less than the 18% of the CSS –coal and natural gas plants with CCS technology– generation.

4. Clustering the Data

The next phase was to get the information clustered by implementing the algorithm of Hartigan and Wong [37]. This algorithm searches for cluster assignments that

Table 1: costs, risks and emissions by generation technology

Technology	Cost (€/MWh)	Risk (€/MWh)	CO_2 emission (kg/MWh)
Nuclear	30.04	2.84	
Coal	52.23	5.61	734.09
Coal CCS	78.44	6.80	101.00
Natural gas	38.79	3.51	356.07
Natural gas CCS	63.60	6.67	48.67
Oil	93.17	12.48	546.46
Wind	60.69	6.46	
Hydro	38.62	10.29	
Hydro (mini)	42.95	3.59	
Offshore wind	73.81	7.21	
Biomass	96.62	12.76	1.84
PV	212.03	10.50	

Table 2: generation limits by technology

Technology	Maximum Participation Share
Nuclear	29.80%
Coal and CSS Coal	23.40%
Natural gas and CSS Natural gas	27.60%
Oil	0.80%
Wind	20.30%
Hydro	10.80%
Hydro (mini)	1.50%
Offshore wind	2.00%
Biomass	8.50%
PV	5.50%

Table 3: clustered countries

	1990	1995	2000	2005	2010	2015
Cluster 1	be bg cz de es fr lv lt lu hu nl at si sk fi se	be fr lt lu si sk se	be fr lt sk se	be bg fr lv lt lu hu si sk se	be fr lv lu hu ro si sk se	fr hu si sk se
Cluster 2	dk ee ie hr pl ro uk	bg cz de es lv hu nl at ro fi uk	bg cz de es hr lv lu hu nl at ro si fi uk	cz de es hr nl at ro fi uk	bg cz ie es hr it lt nl at fi uk	dk de gr it
Cluster 3	gr it pt	dk ee ie gr hr it pl pt	dk ee ie gr it pl pt	dk ee ie gr it pl pt	dk de ee gr pl pt	be bg cz ee ie es hr lv lt lu nl at pl pt ro fi uk

jointly minimize the sum of the squares of the distances from points to the assigned cluster centre. As a result, this methodology gave rise to a reduction of the observations as it replaced the member states observations with those ones linked to the newly created three clusters for the years included. Annex A contains further information about the clustering process.

The clustering is made according to the generation percentages in the dataset and the calculated generation costs and risks for every member state and year considered. More specifically, the technologies generation participation shares were used to calculate – according to the costs and risks presented in Table 1– the total generation cost and risk per country and year. Cluster labelled 1 contains those countries showing the least risk; cluster labelled 3 contains those countries showing the highest risk. The components of each cluster are shown in Table 3. The codes shown correspond to the ISO 3166-1 alpha-2 standard. It is worth noting that both Cyprus and Malta were excluded of the analysis due to their insular nature.

Table 3 reveals how the number of countries in each cluster, particularly in clusters labelled 1 and 3, varies throughout the period studied. While in 1995 most of the countries were included in the leader group, in 2015 that majority is assigned to the bottom of the pile. This does not necessarily implies that the EU member states as a whole are doing worse. On the contrary, it means that the efficiency improvement makes it tougher to achieve the excellence when dealing with generation efficiency. Table 3 also shows the following noteworthy facts:

- France, Slovakia and Sweden are always assigned to cluster 1.
- Hungary and Slovenia started and finished in cluster 1, after a short stay in cluster 2.
- Portugal is always assigned to cluster 3.
- Greece and Italy are the only countries that finished in a better cluster than the one in which they started.

5. Clusters' Efficiency

It is possible to depict each cluster risk-cost in a coordinate plane to obtain Figure 1. The risk and cost of each cluster are computed as the average of the risks and costs of the countries included in it. Figure 1 also shows the efficient and feasible frontiers of the aforementioned theoretical models (base and technological models). The solid line corresponds to the efficient frontier and the dashed one represents the non-efficient part of the feasible frontier. It is important to highlight that no portfolio can be found to the left of the feasible frontier.

Figure 1 shows that to a certain extent all the clusters have moved towards efficiency for the analysed years. Nevertheless, some differences arise. Cluster 3 appears to be the most regular in that movement and the one that has reduced its costs and risks further: a 19.39% reduction in cost and a 40.25% reduction in risk, as shown in Table 4. However, Cluster 2 suffered a 20.52% increase in the generation cost. Between the former ones, Cluster 1 has experienced more moderate reductions in cost (1.88%) and risk (22.91%) than Cluster 3.

Notwithstanding, as Figure 1 shows, member states are still far from the European efficiency objectives — represented by the technological model efficient frontier. Therefore, it is important to measure the distance between the 2015 clustered portfolios and the efficient frontier. For that purpose, the first step is to calculate the intersection points between the efficient frontier considered and the segments linking the coordinate origin to every cluster centroid; the second one is to measure the Euclidean distance between that intersection

Table 4: cost and risk variations through the period 1995–2015

Cluster	Cost Variation 1995–2015	Risk Variation 1995–2015
1	–1.88%	–22.91%
2	20.52%	–34.78%
3	–19.39%	–40.25%

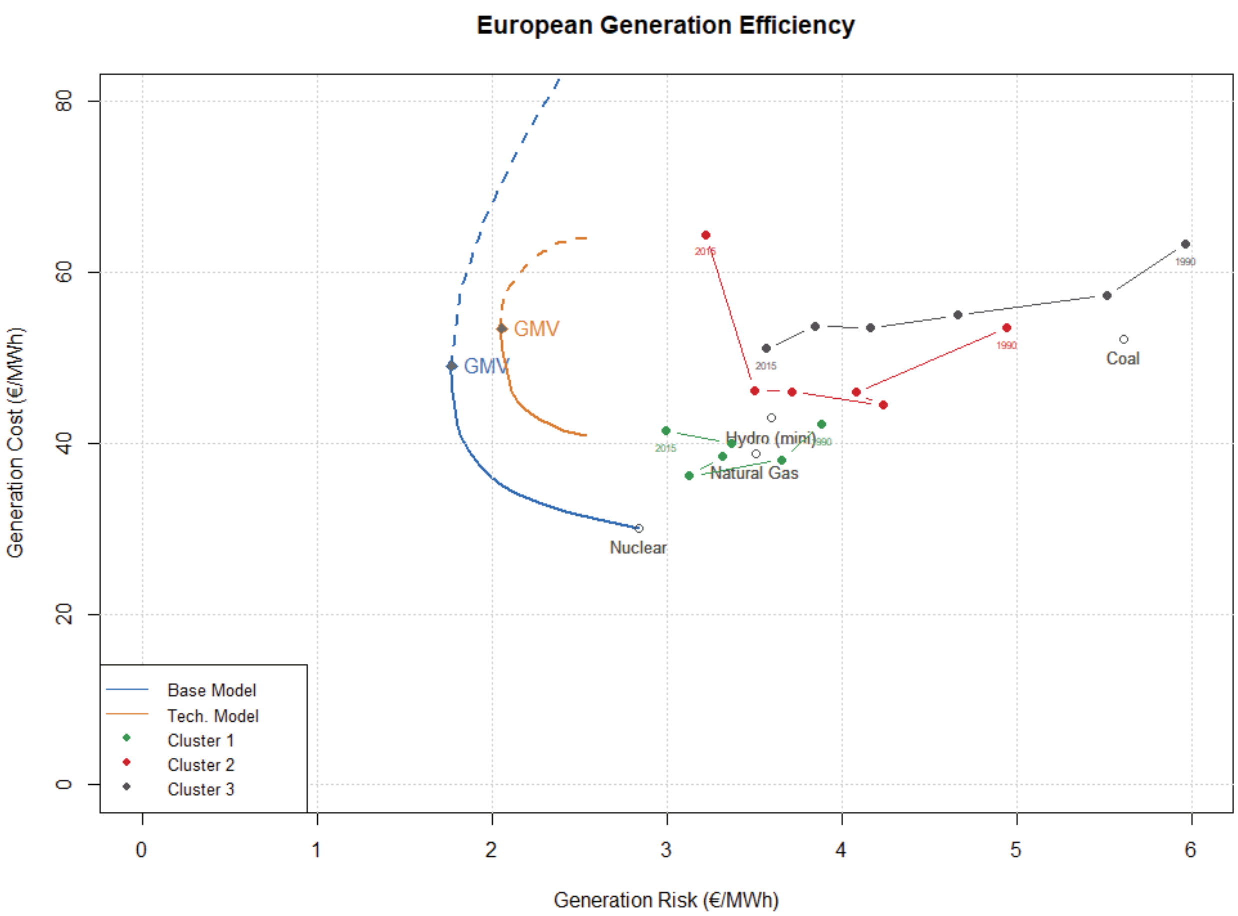

Figure 1: Efficient frontier and EU-member states Clusters (1990-2015)

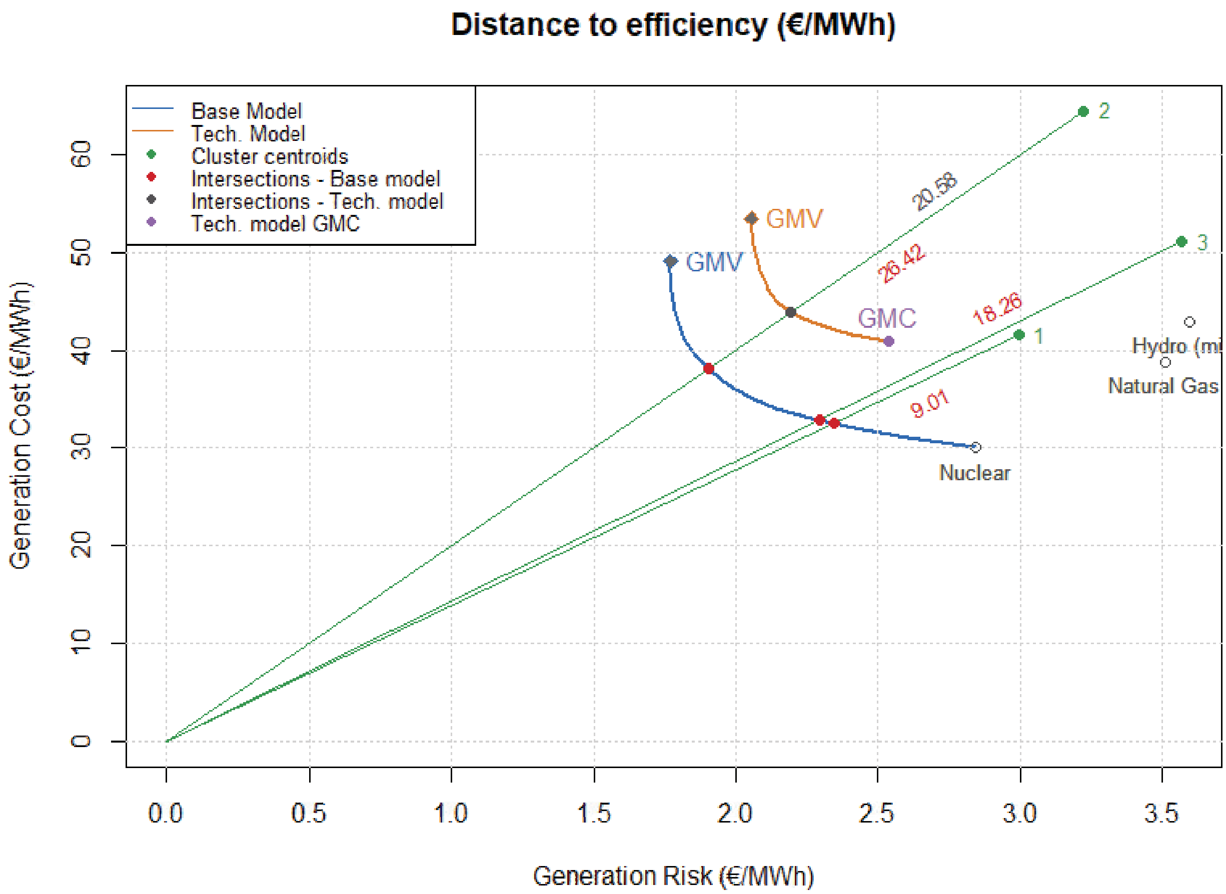

Figure 2: Distance to efficiency of the cluster centroids

Table 5: Distance from the clusters' centroids to the efficient frontier

Cluster	Base model	Technological model
1	9.01 €/MWh	0.77 €/MWh
2	26.42 €/MWh	20.58 €/MWh
3	18.26 €/MWh	10.25 €/MWh

point and the corresponding cluster centroid. Figure 2 shows that there is no intersection point between the clusters 1 and 3 and the technological model efficient frontier. Table 5 includes these distances. It is important to note that, for the technological model and clusters 1 and 3, this table shows the Euclidean distance from the cluster centroid to the technological model global minimum cost portfolio (GMC) –this is, the efficient portfolio that has the lowest cost and, consequently, the higher risk–, located in the lower-right extreme of the efficient frontier, as shown in Figure 2. The technological model GMC portfolio has a cost of 40.88 €/MWh and a risk of 2.54 €/MWh.

6. Results

This work confirms that the member states exhibit a general trend to move towards efficiency. On the basis of the clustered information, that trend is a true fact. Some member states stand out due to their leadership regarding the efficiency of their energy and environmental policies. Among them, France, Slovakia and Sweden has belonged to the leader cluster since 1990. Denmark, Germany, Greece and Italy have shown a high regularity in the efficiency of their policies for the period 1990-2015. Regarding Environment, Lithuania, Slovakia, Estonia and Denmark stand out as the member States that have reduced their pollutant emissions in the sharpest way – with an annual reduction percentage of 3.75%, much higher than the European average (0.67%).

When analysing the percentage of RES generation, France, Slovakia and Sweden show a higher average than the other member states in the period concerned. Thus, it seems that a high percentage of RES generation may improve not only the environmental efficiency but also the economic efficiency. It is also pertinent to point out that France has a large share of nuclear –non-pollutant– generation.

Denmark, Germany, Greece and Italy, for their part, exhibit as a whole a higher annual RES growth rate –5.11%– than the European average – 1.59%. The growth primarily occurs in the period 2007-2015, changing from a joint RES contribution of 10% to 23%. Again, the conclusion may be that the stronger the commitment with RES generation, the better the improvements in both environmental and economic efficiency.

CO_2 emission variation can also be analysed for the period 1990-2015. There appears to be general trend to reduce CO_2 emissions in the EU member states, although Luxembourg, Netherlands, Spain, Portugal and Ireland show a relevant increase in their emissions. On the other side, Lithuania, Denmark and Slovakia are able to reduce their CO_2 emission by more than 50%, while Estonia, Sweden, France and the United Kingdom lower their emissions by more than 40%. Interestingly, all the countries that increased their CO_2 emission throughout the period 1990-2015 were assigned to cluster number 3 in 2015.

The member states that most reduced their pollutant emissions –Lithuania, Slovakia, Estonia and Denmark– also show a higher RES share in power generation. As a matter of fact, the RES share of these member states grew at an annual percentage of 1.93% –higher than the European average of 1.59%– confirming the strategy for decarbonisation of the European generation portfolio.

7. Conclusion and Policy Implication

In this work, MPT is used to determine the efficiency of the EU power generation in the period 1990-2015. Taking into account the high number of variables considered, some of the years initially considered were discarded and finally the information was clustered due to methodological reasons. After determining the optimal number of clusters to compute, the analysis focused on three clusters in each one of the following years: 1990, 1995, 2000, 2005, 2010 and 2015. These clusters were labelled from one to three according to their efficiency, being the cluster one the most efficient and the cluster three the least efficient.

Studying how the EU member states are assigned to the different clusters provides some useful information about the risk-cost efficiency of their Energy and Environmental policies. The cluster analysis assigned France, Slovakia and Sweden to the leader cluster (one) in every year considered. Additionally, Denmark, Germany, Greece and Italy show a high consistency in the design and implementation of their policies, as they moved upwards throughout the period concerned.

With regards to the evolution of every cluster over these years, all of them have moved towards efficiency. Cluster labelled three exhibits the better performance with the highest cost and risk reductions (a 19.39% reduction in cost and a 40.25% reduction in risk). Contrary to the major trend, cluster labelled two obtains a 20.52% increase in its generation cost over the twenty-five years included in this work.

Concerning the distance from the centroid of each cluster to the efficient portfolios frontier or to the GMC portfolio of the technological model, as expected, cluster labelled one, which includes the most efficient member states, is closer to efficiency. Moreover, this analysis can even be more accurate because a measure of those distances in economic terms can also be provided: cluster number one is inefficient in less than 1€/MWh, while clusters number two and three are more than 20€/MWH and 10€/MWh far from the technological model efficient frontier, respectively.

This member-state-based analysis can be considered a valuable tool because at present the national governments are in charge of the power generation portfolio design, apart from the framework including general guidelines, recommendations and objectives issued by the EU institutions. Therefore, this analysis could be used to assess the risk-cost efficiency of the environmental and energy policies implemented by the different countries and rank them according to the aforementioned criteria.

Finally, an analysis of the power generation emissions in the different member states is also addressed. Lithuania, Slovakia, Estonia and Denmark are leaders in CO_2 emission reduction in power generation. Besides, Sweden, Slovakia and Denmark are the leaders of emission containment in the last year concerned.

Acknowledgements

We are grateful to the organizers of the "4th International Conference on Energy and Environment: bringing together Engineering and Economics", which was held on May 16th and 17th, 2019 in Guimarães (Portugal), for accepting our study for exhibition. We would also like to thank the "International Journal of Sustainable Energy Planning and Management" [38] the opportunity to make it public.

References

[1] Johansson B. Security aspects of future renewable energy systems–A short overview. Energy 2013;61:598–605. https://doi.org/10.1016/j.energy.2013.09.023.

[2] European Union. Official Journal of the European Union, 2010/C 83/01, Vol. 53 2010.

[3] EC. Communication from the Commission to the European Parliament, and the Council. European Energy Security Strategy, COM(2014) 330 final. Brussels. Belgium: 2014.

[4] EC. A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy - COM(2018) 773 final. 2018.

[5] Beurskens L, Jansen JC, Van Tilburg X, Beurskens L, Van Tilburg X. Application of portfolio analysis to the Dutch generating mix. Reference case and two renewables cases, year 2030, SE and GE scenario. Energy research Centre of the Netherlands ECN; 2006.

[6] Allan G, Eromenko I, McGregor P, Swales K. The regional electricity generation mix in Scotland: A portfolio selection approach incorporating marine technologies. Energy Policy 2011;39:6–22. https://doi.org/10.1016/j.enpol.2010.08.028.

[7] Awerbuch S, Berger M. Applying Portfolio Theory to EU Electricity Planning and Policy Making. IAEA/EET Work Pap No 03, EET 2003;3:69.

[8] Awerbuch S, Yang S. Efficient Electricity Generating Portfolios for Europe. Anal. Methods Energy Divers. Secur., Elsevier; 2007, p. 85–115. https://doi.org/10.1016/B978-0-08-056887-4.00005-6.

[9] deLlano-Paz F, Calvo-Silvosa A, Iglesias Antelo S, Soares I. The European low-carbon mix for 2030: The role of renewable energy sources in an environmentally and socially efficient approach. Renew Sustain Energy Rev 2015;48:49–61. https://doi.org/10.1016/j.rser.2015.03.032.

[10] deLlano-Paz F, Martínez Fernandez P, Soares I. Addressing 2030 EU policy framework for energy and climate: Cost, risk and energy security issues. Energy 2016;115:1347–60. https://doi.org/10.1016/j.energy.2016.01.068.

[11] Cunha J, Ferreira P. A risk analysis of small-hydro power (SHP) plants investments. Int J Sustain Energy Plan Manag 2014;2:47–62. https://doi.org/10.5278/ijsepm.2014.2.5.

[12] Kumar D, Mohanta DK, Reddy MJB. Intelligent optimization of renewable resource mixes incorporating the effect of fuel risk, fuel cost and CO2 emission. Front Energy 2015;9:91–105. https://doi.org/10.1007/s11708-015-0345-y.

[13] Jano-Ito MA, Crawford-Brown D. Investment decisions considering economic, environmental and social factors: An actors' perspective for the electricity sector of Mexico. Energy 2017;121:92–106. https://doi.org/10.1016/j.energy.2017.01.016

[14] Cucchiella F, D'Adamo I, Gastaldi M. Optimizing plant size in the planning of renewable energy portfolios. Lett Spat Resour Sci 2016;9:169–87. https://doi.org/10.1007/s12076-015-0150-6.

[15] Bhattacharya A, Kojima S. Power sector investment risk and renewable energy: A Japanese case study using portfolio risk optimization method. Energy Policy 2012;40:69–80. https://doi.org/10.1016/j.enpol.2010.09.031.

[16] Arnesano M, Carlucci AP, Laforgia D. Extension of portfolio theory application to energy planning problem – The Italian case. Energy 2012;39:112–24. https://doi.org/10.1016/j.energy.2011.06.053.

[17] Singh VK, Henriques CO, Martins AG. A multiobjective optimization approach to support end-use energy efficiency policy design – The case-study of India. Int J Sustain Energy Plan Manag 2019;23:55–68. https://doi.org/10.5278/ijsepm.2408.

[18] Verbruggen A, Di Nucci MR, Fischedick M, Haas R, Hvelplund F, Lauber V, et al. Europe's electricity regime: Restoration or thorough transition. Int J Sustain Energy Plan Manag 2015;5:57–68. https://doi.org/10.5278/ijsepm.2015.5.6.

[19] Roques F, Hiroux C, Saguan M. Optimal wind power deployment in Europe—A portfolio approach. Energy Policy 2010;38:3245–56. https://doi.org/10.1016/j.enpol.2009.07.048.

[20] Gökgöz F, Atmaca ME. Portfolio optimization under lower partial moments in emerging electricity markets: Evidence from Turkey. Renew Sustain Energy Rev 2017;67:437–49. https://doi.org/10.1016/j.rser.2016.09.029.

[21] Zhu L, Fan Y. Optimization of China's generating portfolio and policy implications based on portfolio theory. Energy 2010;35:1391–402. https://doi.org/10.1016/j.energy.2009.11.024.

[22] Cunha J, Ferreira P. Designing electricity generation portfolios using the mean-variance approach. Int J Sustain Energy Plan Manag 2014;4:17–30. https://doi.org/10.5278/ijsepm.2014.4.3.

[23] Kitzing L, Weber C. Support mechanisms for renewables: How risk exposure influences investment incentives. Int J Sustain Energy Plan Manag 2015;7:117–34. https://doi.org/10.5278/ijsepm.2015.7.9.

[24] Abson DJ, Fraser ED, Benton TG. Landscape diversity and the resilience of agricultural returns: a portfolio analysis of land-use patterns and economic returns from lowland agriculture. Agric Food Secur 2013;2:2. https://doi.org/10.1186/2048-7010-2-2.

[25] Knoke T, Paul C, Härtl F, Castro LM, Calvas B, Hildebrandt P. Optimizing agricultural land-use portfolios with scarce data—A non-stochastic model. Ecol Econ 2015;120:250–9. https://doi.org/10.1016/j.ecolecon.2015.10.021.

[26] Knoke T. Mixed forests and finance — Methodological approaches. Ecol Econ 2008;65:590–601. https://doi.org/10.1016/j.ecolecon.2007.08.009.

[27] Castro LM, Calvas B, Hildebrandt P, Knoke T. Avoiding the loss of shade coffee plantations: how to derive conservation payments for risk-averse land-users. Agrofor Syst 2013;87:331–47. https://doi.org/10.1007/s10457-012-9554-0.

[28] Halpern BS, White C, Lester SE, Costello C, Gaines SD. Using portfolio theory to assess tradeoffs between return from natural capital and social equity across space. Biol Conserv 2011;144:1499–507. https://doi.org/10.1016/j.biocon.2011.01.019.

[29] Hildebrandt P, Knoke T. Investment decisions under uncertainty—A methodological review on forest science studies. For Policy Econ 2011;13:1–15. https://doi.org/10.1016/j.forpol.2010.09.001.

[30] Marinoni O, Adkins P, Hajkowicz S. Water planning in a changing climate: Joint application of cost utility analysis and modern portfolio theory. Environ Model Softw 2011;26:18–29. https://doi.org/10.1016/j.envsoft.2010.03.001.

[31] Moore JW, McClure M, Rogers LA, Schindler DE. Synchronization and portfolio performance of threatened salmon. Conserv Lett 2010;3:340–8. https://doi.org/10.1111/j.1755-263X.2010.00119.x.

[32] Griffiths JR, Schindler DE, Armstrong JB, Scheuerell MD, Whited DC, Clark RA, et al. Performance of salmon fishery portfolios across western North America. J Appl Ecol 2014;51:1554–63. https://doi.org/10.1111/1365-2664.12341.

[33] Sanchirico JN, Smith MD, Lipton DW. An empirical approach to ecosystem-based fishery management. Ecol Econ 2008;64:586–96. https://doi.org/10.1016/j.ecolecon.2007.04.006.

[34] Edwards SF, Link JS, Rountree BP. Portfolio management of wild fish stocks. Ecol Econ 2004;49:317–29. https://doi.org/10.1016/j.ecolecon.2004.04.002.

[35] Kandulu JM, Bryan BA, King D, Connor JD. Mitigating economic risk from climate variability in rain-fed agriculture through enterprise mix diversification. Ecol Econ 2012;79:105–12. https://doi.org/10.1016/j.ecolecon.2012.04.025.

[36] Markowitz H. PORTFOLIO SELECTION*. J Finance 1952;7:77–91. https://doi.org/10.1111/j.1540-6261.1952.tb01525.x.

[37] Hartigan JA, Wong MA. Algorithm AS 136: A K-Means Clustering Algorithm. Appl Stat 1979;28:100. https://doi.org/10.2307/2346830.

[38] Ferreira P, Soares I, Johannsen R, Østergaard P. Policies for new energy challenges. Int J Sustain Energy Plan Manag 2019;26. https://doi.org/https://doi.org/10.5278/ijsepm.3552.

Annex A: clustering Information

Historical generation data by country, technology and year are used for clustering. They also are the footing to calculate the generation cost and risk of every country, technology and year. Using the information about risks and costs shown in Table 1 and, specifically, the variances-covariances matrix shown in Table A–1.

Thus, knowing the share of every electricity generation technology in every country and year, it is also possible to calculate the total generation cost and risk of every country and year using Equations (1) and (2). Results are shown in Table A–2.

The preceding tables contain the information used for clustering. Finally, all the countries considered were classified in three different clusters. Figure A–1 exhibits the sum of the squares of the distance from every point to the assigned cluster centre for all the years.

Summary of the clustering results is shown in Table A–3.

Table A–1: variances-covariances matrix used in calculations (€/MWh)

	Nuclear	Coal	Coal with CCS	Natural Gas	Natural Gas with CCS	Oil	Wind	Hydro	Hydro (mini)	Wind (offshore)	Biomass	PV
Nuclear	8.07	3.84	5.07	3.54	4.26	15.32	-0.07	-0.42	-0.46	-0.10	-6.40	0.20
Coal		31.51	7.04	4.02	4.81	20.82	-0.21	0.03	0.03	-0.31	-14.09	-0.21
Coal with CCS			46.27	5.43	6.60	27.16	-0.45	0.06	0.07	-0.68	-18.52	-0.46
Natural Gas				12.33	6.55	15.44	0.00	-0.08	-0.08	0.00	-3.16	0.05
Natural Gas with CCS					44.45	18.33	0.00	-0.16	-0.17	0.00	-3.38	0.11
Oil						155.83	-4.02	-1.95	-2.11	-6.07	-86.44	-0.16
Wind							41.69	0.94	1.01	4.68	-0.31	0.09
Hydro								105.79	3.64	1.41	-0.33	0.56
Hydro (mini)									12.92	1.53	-0.36	0.6
Wind – (offshore)										52.04	-0.48	0.13
Biomass											162.84	0.25
PV												110.27

Table A–2: generation costs by country and year

	Costs (€/MWh)						Risks (€/MWh)					
	1990	**1995**	**2000**	**2005**	**2010**	**2015**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**
be	38.0	38.1	36.7	37.5	39.2	50.3	2.7	2.7	2.5	2.5	2.3	2.2
bg	44.0	42.6	41.4	41.5	43.4	48.3	3.5	3.2	3.1	3.1	3.4	3.2
cz	47.6	47.8	47.5	45.0	46.2	50.8	4.4	4.3	4.3	3.7	3.4	3.1
dk	53.8	56.0	56.8	56.3	57.6	66.7	5.2	4.8	3.7	3.1	3.1	3.7
de	45.2	44.9	44.5	46.6	51.1	61.8	3.7	3.6	3.4	3.1	2.8	2.8
ee	54.9	52.3	51.4	51.5	54.3	55.8	5.3	5.4	5.2	5.2	4.8	4.4
ie	51.7	53.8	54.6	51.6	45.6	49.4	4.1	4.3	4.2	3.7	2.9	2.8
gr	60.5	59.8	56.6	55.8	53.6	65.9	5.5	5.4	4.8	4.5	4.0	3.6
es	44.3	46.4	47.5	47.6	49.5	56.7	3.4	3.5	3.4	3.0	2.6	2.5
fr	34.6	33.9	33.8	33.7	34.3	36.2	2.7	2.7	2.7	2.6	2.5	2.5
hr	57.3	53.8	49.0	49.1	43.5	46.6	5.9	6.5	5.7	5.5	5.8	5.4
it	67.1	67.9	57.8	50.6	48.4	63.5	6.7	7.0	5.1	3.7	3.1	2.8
cy	93.2	93.2	93.2	93.2	93.2	95.0	12.5	12.5	12.5	12.5	12.3	11.3
lv	42.1	45.1	40.7	39.8	39.7	47.6	6.3	6.9	6.3	6.3	5.1	3.9

(*Continued*)

Table A–2: (*Continued*) generation costs by country and year

	Costs (€/MWh)						Risks (€/MWh)					
	1990	**1995**	**2000**	**2005**	**2010**	**2015**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**
lt	41.5	35.5	35.5	34.1	47.8	54.5	3.4	3.0	2.8	2.6	3.5	3.0
lu	39.9	40.2	40.7	40.6	41.1	49.2	5.7	6.4	7.0	3.3	3.7	5.3
hu	41.2	47.3	45.9	41.4	42.0	42.3	3.0	3.7	3.5	2.5	2.4	2.3
mt	70.3	90.9	93.2	93.2	93.2	101.7	7.1	11.9	12.5	12.5	12.5	11.5
nl	46.0	45.7	45.3	46.5	46.0	50.1	3.3	3.2	3.1	2.9	2.9	2.9
at	44.0	44.0	43.3	44.5	45.5	48.6	6.0	6.3	6.5	5.5	5.5	5.8
pl	52.3	52.2	52.2	52.5	54.0	55.2	5.4	5.4	5.3	5.2	4.9	4.5
pt	62.5	62.9	55.8	56.6	51.2	55.3	5.6	5.4	4.3	3.8	3.4	2.9
ro	52.7	48.9	46.5	44.8	42.6	49.5	4.1	4.0	3.8	4.0	3.8	3.1
si	44.1	41.5	40.9	40.7	41.1	43.8	3.5	3.4	3.5	3.2	3.4	3.3
sk	42.1	39.9	37.0	37.6	38.7	43.0	3.0	2.9	2.7	2.7	2.7	2.4
fi	46.0	46.9	46.1	46.4	48.2	48.2	2.8	2.8	2.8	2.8	2.8	3.2
se	36.2	37.4	38.0	38.4	41.7	42.3	4.7	4.4	5.1	4.4	4.3	4.5
uk	51.6	45.8	43.0	43.8	44.3	52.1	4.5	3.4	2.9	2.9	2.7	2.3

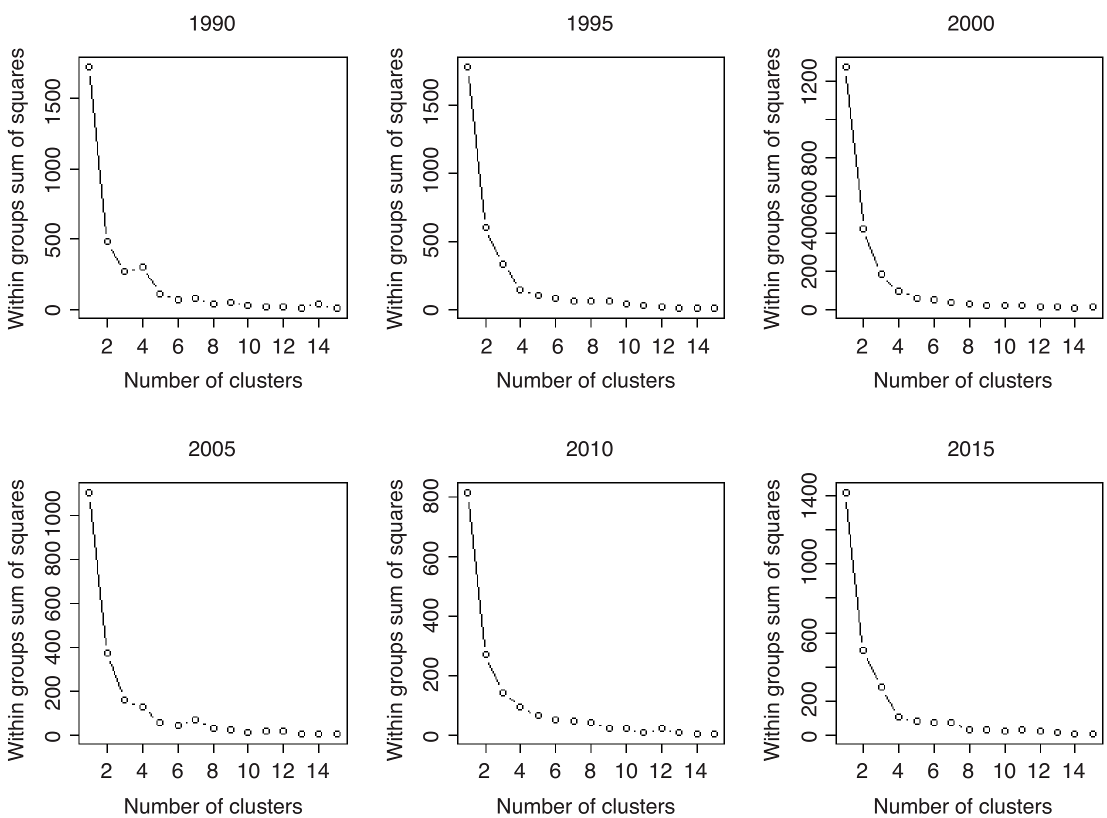

Figure A–1: sum of the squares of the distance from every point to the assigned cluster centre

Table A–3: summary of the clustering results

		Size	Centroid Risk	Centroid Cost	Sum of squares within cluster
1990	Cluster 1	16	3.88	42.30	219.92
	Cluster 2	7	4.94	53.48	28.37
	Cluster 3	3	5.97	63.36	23.51
	Sum of squares between clusters / Total sum of squares				84.2%
1995	Cluster 1	7	3.66	38.08	55.03
	Cluster 2	11	4.08	45.94	48.71
	Cluster 3	8	5.52	57.37	233.26
	Sum of squares between clusters / Total sum of squares				81.0%
2000	Cluster 1	5	3.13	36.18	15.19
	Cluster 2	14	4.24	44.44	130.77
	Cluster 3	7	4.66	55.02	37.45
	Sum of squares between clusters / Total sum of squares				85.6%
2005	Cluster 1	10	3.32	38.54	85.10
	Cluster 2	9	3.71	46.03	31.99
	Cluster 3	7	4.16	53.56	43.04
	Sum of squares between clusters / Total sum of squares				85.5%
2010	Cluster 1	9	3.37	40.04	57.80
	Cluster 2	11	3.50	46.21	53.56
	Cluster 3	6	3.85	53.64	32.65
	Sum of squares between clusters / Total sum of squares				82.3%
2015	Cluster 1	5	2.99	41.51	40.00
	Cluster 2	4	3.22	64.46	15.95
	Cluster 3	17	3.57	51.08	186.98
	Sum of squares between clusters / Total sum of squares				82.9%