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IMPACTS OF DECENTRALISED POWER GENERATION ON DISTRIBUTION NETWORKS:

A statistical typology of european countries

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The development of decentralised sources of power produced out of renewable energies has been triggering far-reaching consequences for DSOs over the past decade. Our paper benchmarks across more than 20 European countries the impact of the development of renewables on the physical characteristics of power distribution networks and on their investments. It builds quantitative indicators about the dynamics of installed capacity of and generation from renewable sources of electricity, electric independence, quality of electric distribution, the amount of smart grids investments, DSOs capital expenditures, the length of the distribution networks, overall costs of power networks paid by private agents, and electric losses, all in relation with the development of decentralised generation. The heterogeneity of these indicators across Europe appears to be wide notably because of physical constraints, historic legacies or policy and regulatory choices. A cluster analysis allows for deriving 5 groups of countries that display statistically homogenous characteristics. Our results may provide decision makers and regulators with a tool helping them to concentrate on the main issues specific to their countries as compared to the European median, and to look for possible solutions in the experience of other clusters which are shown to perform better for some indicators.

JEL codes: C38 – L94 – Q42.

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1. Introduction

Low carbon transitions trigger far-reaching consequences for Distribution System Operators (DSOs) in the power sector. They fuel an accelerated development of geographically decentralised sources of power produced out of renewable energies. These effects may vary substantially across countries, however, notably because of physical constraints, historic legacies or policy choices. This paper investigates this heterogeneity on European data and statistically determines homogenous groups across countries where transitions trigger similar influences on DSOs.

The development of renewable energies to lessen carbon emissions profoundly modifies the engineering of power networks and the economics of DSOs. Up to recently, DSOs received the electricity to be distributed mainly – if not almost exclusively - from transport networks connected to large production facilities. The rise in renewables involved by low carbon transitions has been triggering numerous new units of production, geographically disseminated, that are directly connected to distribution networks (henceforth, DG for "Decentralised Generation/Generators"). Accordingly, the business model of DSO is profoundly transformed nowadays in European countries. This holds all the more as the European Energy Policy promotes intermittent renewable energy sources as a way to mitigate environmental damages and increase security of supply, thus fostering the development of DGs in the long-run.

The recent empirical litterature has analysed many different aspects of the consequences of low carbon transitions on DSOs. McDonald (2008) analyses the switch from passive network management with one-way flows to active management with two-way flows. Martin (2009) investigates the market design implications of such a change in the paradigm of power distribution. Coelli, Gautier, Perelman and Saplacan-Pop (2013) as well as Giannakis, Jamasb and Pollitt (2004) analyze the quality of power distribution when DG increases. A more specialized literature has also been focusing on the financial implications of developing DG for DSOs. For instance, Jamasb, Orea and Pollitt (2012) estimate the marginal cost of quality improvement of power distribution in UK. Méndez Quezada *et al.* (2006) deal with the effect on losses in distribution network when DG are on the rise.

Papers are less numerous, though, as concerns the influence of renewables on DSOs' own investments. Cossent, Gomez and Frias (2009) analyse the costs for the power distribution activity flowing from higher DG through higher network investments and reinforcements in the short-term. Blokhuis *et al.* (2011) deals with the specific network investments required by higher peak loads. The literature providing with a cross-country, systematic benchmark of the impacts of developping renewables on DSOs and on their investments is even more scarce. Cali, Ropenus and Schroder (2009) provide with a cross-country study of the interactions between DG and DSOs in West Denmark, Germany, Netherlands, Spain and UK, but they do not focus particularly on DSOs investments.

In this context, our paper contributes to the existing litterature insofar as it benchmarks systematically across more than 20 European countries the impacts of the development of renewables on the physical characteristics of power distribution networks and on their investments. To do so, it builds on a large spectrum of databases on DSO activities for the last decade about the dynamics of installed capacities of and generation of electricity from renewable energies, electric independence, quality of electric distribution, the amount of smart grids investments, DSOs capital expenditures (CAPEX), the length of the distribution networks, overall costs of power networks paid by private agents, and electric losses. It refers to an extensive litterature on all these points. It analyses in details to what extent the effects on DSOs of low-carbon transitions may differ subtantially from one country to another, notably because of physical constraints, historic legacies or policy choices.

We then apply a cluster analysis that statistically yields 5 homogeneous groups of countries. Cluster 1 (Austria, Finland, Slovakia) is characterized, on average over the recent years, by a relatively rapidly increasing size of the distribution network though small increases in installed capacities of and power generation out of renewables. Cluster 2 (Denmark, France, Norway) shows relatively small increases in installed capacities of and power generation out of renewables as compared to the European median, increasing network losses though relatively slowly increasing network size, and rapidly increasing network costs for households. Cluster 3 (United Kingdom, Hungary) is identified by relatively large increases in installed capacities of and power generation out of renewables, but decreasing electricity losses on distribution networks and decreasing network costs for households. Cluster 4 (Germany, Poland) is characterized by relatively large increases in installed capacities of and power generation out of renewables, low investments in smart grids, relatively slowly increasing capital expenditures in power networks and decreasing network losses. In Cluster 5 (Netherlands, Belgium, Ireland), there are relatively large increases in installed capacities of and power generation out of renewables, a rapidly increasing size of distribution networks, and rapidly increasing network costs for households. These results have policy implications: the 5 clusters determined in this paper, which mirror policy choices, may in turn call for future policy choices.

The structure of the paper is as follows. Section 2 describes the data. Section 3 deals with the set of indicators computed from these data. Section 4 presents the cluster analysis and its results. Section 5 concludes with some policy issues.

2. Data issues

Our database relies primarily on four large and representative data sources for the power sector: the Eurostat database, the Joint Research Center of the European Commission database, the NRGExpert T&D database and the Council of European Energy Regulators data. We checked the consistency of these data with those provided by the US Energy Information Administration (EIA) Statistics, OECD data, reports of National Regulatory Authorities, Eurobserv'ER data and Enerdata.

We focus on the countries of the European Union. Due to the availability of the data, we restrict the analysis to 23 countries: Austria (AT), Belgium (BE), Bulgaria (BG), Czech Republic (CZ), Denmark (DK), Spain (ES), Finland (FI), France (FR), Germany (DE), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), The Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SL), Sweden (SE), United Kingdom (UK). The rationale for focusing on EU countries is threefold. First, the EU has set a target of 20% final energy consumption from renewable sources by 2020, which accounts for a significant development of DG over the past decades. Second, data on power networks are relatively detailed in Europe for the last 10/15 years. Third, Europe displays a large variety of situations given the diversity of physical constraints and historical legacies.

The Eurostat database provides with renewable electricity installed capacity, renewable electricity generation, total electricity installed capacity, network losses, average household network costs and electric independence:

- The compound annual growth rates of total power *installed capacity* and installed capacity from renewable sources are computed from 2002 to 2013. Year 2002 broadly corresponds for most of European countries (with the exception of Scandinavian countries) to the beginning of their low-carbon energy transitions. Our definition of renewable sources of electricity enshrines hydroelectricity.[1] For the sake of data comparability, data for installed capacities are divided by GDP so as to neutralize the effect of size of a country on the size of its power distribution network. Accordingly, power capacities are measured in Watt per euro of GDP. We checked the consistency of these data with those provided by the U.S. EIA Statistics and OECD data.[2]

[1] In the Eurostat database, biomass data were not available. We thus rely on Eurostat's definition to compute biomass capacity. Biomass is defined by biogas, wood and wood waste, organic urban waste (data were found on Eurostat as well).
[2] As concerns installed capacity for Romania, we used the U.S. Energy Information Administration Statistics due to some data inconsistency. We checked these data by using IEA data and the National Regulatory Authority of Romania.

- Renewable electricity *generation* was computed from 2002 to 2012 (with data for 2013 unavailable at time of writing). We checked the consistency of these data with those provided by the U.S. EIA Statistics, OECD data and Eurobserv'ER data.
- A compound annual growth rate of *network losses* was computed from 2002 to 2012. The only data available on losses concern transport and distribution overall, with no data available for distribution losses only. We checked the consistency of these data with those provided by the U.S. EIA Statistics, OECD data and several National Regulatory Authorities reports.
- The compound annual growth rate of an *average household network costs* is computed over 2008-2013, since data were unavailable for previous years.[3] Finally, data consistency was checked by using several National Regulatory Authorities report.
- Electric independence from 2002 to 2013 was calculated by using the definition of INSEE (French national statistical institute) as the ratio between gross electricity generation and gross inland electricity consumption (*i.e.*, gross electricity generation plus net imports). These data are extracted from Eurostat. A rate above 100% reflects a positive export balance.

The Smart Electricity Systems and Interoperability team of the Joint Research Center, which is part of the Energy Security, Systems and Market unit at the JRC Institute for Energy and Transport, performs data gathering and processing especially as concerns Smart grids. From the Joint Research Center data, we extracted *Smart grids investments*, especially Smart grids investments in distributed energy resources and renewable energy sources application. We computed the compound annual growth rate of Smart grids investments in distributed energy resources and RES application from 2008 to 2013. Because of breaks in series, data from 2002 to 2007 were not taken into account.

The NRGExpert T&D database provides with consistent data on *network capital expenditures* (CAPEX), transmission and distribution line length. Their CAPEX concern the whole power network and distribution CAPEX alone was nowhere to be found in a cross-country and coherent database. Available data only provide with CAPEX for both TSOs and DSOs, and not for each type of operator separately. However, this drawback may not be too detrimental for our results. Most investments related with renewables on electric networks are supported by DSOs, and many European DSOs in Europe also operate on some high voltage networks. We computed the compound annual growth rate of network's CAPEX from 2008 to 2013 and distribution line length from 2009 to 2013. Data for previous periods were not available. Data consistency was checked and sometimes improved by using several National Regulatory Authorities reports.

The Council of European Energy Regulators Benchmarking Report on the continuity of supply provides with data on the *quality of electricity distribution*, *i.e.* the System Average Interruption Duration Index (SAIDI).[4] According to the Council of European Energy Regulators, SAIDI is representative of the average interruption time on low-voltage networks. We computed from these data the compound annual growth rate of system average interruption duration index excluding exceptional events from 2008 to 2012.

Overall the database was used in order to compute 10 indicators summarized in Table 1 and described in section 3.

[3] Since the definition applied by Eurostat for a household concerns consumers between 2.5 and 5 MWh but is not consistent with data for some countries, we used Enerdata along with Eurostat data on network costs for each country depending on their consumption band.

[4] Cf. *CEER Benchmarking Report 5.1 on the continuity of electricity supply*, February 2014. SAIDI assesses the average interruption time on LV network. This index is used internationally for assessing electric grid reliability.

3. Effects on power distribution networks of developing renewables: factors of cross-country heterogeneity

We assess the impact on DSOs of a rising share of renewables in the mix using 10 indicators grouped in 3 sets:

- The "**energy variables**" refer to aggregate characteristics of the power system the distribution network is enshrined into. This set comprises **4 indicators**: a) the installed capacity in the power sector, b) the installed capacity of renewable electricity, c) the electricity *generation* from renewable sources and d) the national independence as concerns electricity;
- The "**network variables**" encompass data related with the physical characteristics of the distribution network. This set comprises **3 indicators**: a) the quality of electricity distribution; b) the size/length of the distribution networks; c) the distribution losses;
- The "**financial variables**" refer to networks expenditures. This set comprises **3 indicators**: a) the smart grids investments; b) the networks' capital expenditures (CAPEX), c) the overall network costs paid by households.

The 10 indicators are taken in *average annual variation*. In this section, we conduct a pairwise analysis. In each European country, the characteristics of energy systems are assessed in relation with the development of renewable energy.[5] Table 1 provides with a summary of the 10 indicators used in this paper, and the associated code that will be used in the graphs in this article.

3.1. Energy variables

3.1.1 Fraction of renewable sources of electricity in the total supply of electricity

Figure 1 shows the average annual growth rate of the installed capacity in the whole power sector and for renewables only.

- (upper left-hand corner): countries appearing in the lower right-hand corner have a relatively low progression of renewables combined with a relatively rapid rise in total installed electric capacity. In **Austria**, the relatively subdued increase of renewables in the electric mix applies to a large base, *i.e.*, to a country where renewables account for most of the electricity generation (around 75%). Accordingly, in absolute terms, this subdued growth rate is coherent with quite a significant amount of new utilities installed.

- (upper right-hand corner): countries appearing in the upper right-hand corner have been experiencing a development of renewables relatively more intense than the median of our panel, which has contributed to a fraction of electricity in the overall energy mix that is relatively higher than the median. Most of these countries have been implementing a low-carbon transition policy relying heavily on renewables. This is notably the case for **Germany** (see Morris and Pehnt, 2014).

- (lower right-hand corner): countries appearing in the lower right-hand corner have been experiencing a relatively intense low-carbon transition with a strong development of renewables, while the level of renewables in the energy mix has remained relatively subdued. In **Hungary**, installed capacities in renewables (wind, biomass) have increased by 18% per year on average over the last decade (admittedly from a very low basis at the beginning of the period). It has benefitted from a feed-in tariffs system (*Metàr*) and a multiplication of PV facilities (Hungarian National Regulatory Authority, 2014).

[5] In the pairwise analysis, the evolution of each pair of indicators is compared on the same period. Notice that the sample period varies from one pair to another due to a lack of data. We did not consider the shortest common period to all indicators (2009-2012). This would have led to a loss of interesting information, since many countries have launched their energy transition for decades.

- (lower left-hand corner): in countries appearing in the lower left-hand corner, the progression of power facilities has been lower than the European median and the development of renewables has remained more subdued than the European median. This is notably the case for **France**. For different reasons, this is also the case for **Norway**, **Denmark** and **Finland** where the share of renewables in the mix has already been relatively high from the 1990's onwards.

3.1.2. Renewable sources of electricity and power independence

In all countries, a rise in intermittent sources of production of electricity may trigger two effects on the security of supply and electric independence: an upward effect because electricity out of renewables is produced on the national territory (see Ölz, Kirchner and Sims, 2007) and a downward effect because intermittent sources of energy require back-up producers which can be located out of the country.

Figure 2 compares from 2002 to 2013 the dynamics of renewables in the electric mix with the evolution of an indicator of electric independence (see European Commission, 2014a; Table 8):

- (upper left-hand corner): countries with a relatively subdued development of renewables and increasing electric independence: this is for instance the case for **Latvia** which tries to lessen a historic legacy materialising in still a high dependency on imports of energy from Russia (Simkus, 2012). This is partly achieved by an already advanced development of renewables in this country (European Commission, 2013).[6]

- (upper right-hand corner): countries with a relatively strong development of renewables and increasing electric independence – as in **Germany** which exports electricity from time to time, mainly to the Netherlands and Austria (Bayer, 2015), and has monitored a vigorous rise in renewables (Morris and Pehnt, 2014).

- (lower right-hand corner): countries with a relatively high progression of renewables combined with a rapid decline in electric independence. **Hungary**'s quest for diminishing its dependence on imports of fossil fuels from its eastern neighbouring countries has resulted in the construction of a nuclear power plant in Paks (Observ'ER *et al.*, 2013) and the development of cogeneration. However, peak demand has increased sizeably, as during the summers when air-conditioning systems are working and account for significant imports of electricity. These peaks have not been met by the plant and its relatively unflexible planning of production (see European Commission, 2013). Moreover, though Hungary's installed power generation capacity can theoretically meet its demand, the country has imported around 10% on average of its electricity because the cost of imports has been cheaper than the domestic production costs (see Regional Center for Energy Policy Research, 2014).

- (lower left-hand corner): countries with a relatively low progression of renewables combined with a decline in electric independence. **Slovakia**, which has already a relatively high fraction of its energy coming from renewables, has closed two nuclear sites in 2006 and 2008 (Bohunice) for safety reasons. This has been mechanically weighing on its electric independency, all the more so as peak demand has also been on the rise, as in Hungary.

Overall, this indicator suggests that the relationship between renewable sources of energy and power independence, which may theoretically reflect two opposite mechanisms, can also in practice be blurred by factors related with policy choices or historical heritages.

3.2. Network variables

3.2.1. Renewable sources of electricity and quality of electricity distribution

In all countries, the intermittent nature of renewables might also deteriorate the quality of distribution of electricity as measured by the System Average Interruption Duration Index (SAIDI) (see Wang, 2008). However, the literature tends to suggest that renewables technologies, if adequately located,

[6] The annual average of installed capacity *in level* in Latvia is far above the European median.

sized and selected in terms of technology and system configuration, can provide a benefit to the power quality of the system (Vilchez and Stenzel, 2013). In any case, DSOs, in order to prevent outages and their associated costs, may either increase maintenance or invest more, for instance by replacing overhead lines by underground lines (Coelli *et al.*, 2013).

Figure 3 compares the dynamics of renewables with the evolution of the quality distribution from 2008 to 2012.

- (upper left-hand corner): countries where the intensity in renewables of the electric sector is already high (and thus does not progress sizeably) and where the quality of distribution of electricity has worsened. This is the case of **Lithuania.** Eurobserver' *et al.* (2013) suggest that the increase of the Lithuanian SAIDI may stem from the geographical situation of wind power in this country. The onshore wind resources in Lithuania are mostly located in the Western part of the country (*e.g.*, coastal areas near the Baltic Seas). However, due to historical reasons, the power grid in this area is weak and cannot transfer large enough amounts of power, less even intermittent electricity with peak periods (Poblocka *et al.*, 2011).
- (upper right-hand corner): countries where the intensity in renewables of the electric sector increases more than the European median, and where the quality of distribution of electricity has worsened (*i.e.*, the SAIDI has declined).
- (lower right-hand corner): countries where the intensity in renewables of the electric sector progresses more than the European median and where the quality of distribution of electricity has increased. **Germany** enjoys one of the lowest SAIDI in Europe. Accuracy in data gathering, prediction, and grid management practices may account for this result (New Jersey for Renewable Energy and Efficiency) which may have been achieved at a cost (*i.e.*, undergrounding of low-voltage (LV) and medium-voltage (MV) cables). Another factor may come from the dominance of wind power in German renewable sources of power, with more or less constant profile during the day (see de Joode *et al.*, 2009).
- (lower left-hand corner): in other countries, the intensity in renewables of the power sector expands less than the European median and the quality of distribution of electricity has increased. Despite the large amounts of wind capacity in **Denmark**, the intermittent character of wind power did not cause major incidents on the network, thanks to large district-heating, interconnection and demand-side management capacity (Slingerland *et al.*, 2015).

Overall, this indicator suggests that engineering as well as geographic factors significantly impact the magnitude of the effect of rising DG on the quality of power distribution.

3.2.2. Renewable sources of electricity and size of the distribution networks

In most cases, the development of renewables tends to bolster the density of the electric distribution network (IEA, 2011) because of units of production scattered on a territory that can be far from consumption places (Miri-Larimi *et al.*, 2012). This holds all the more as intermittent electricity sources require a relatively high-capacity network connection relative to the amount of energy they produce annually, compared to baseload forms of generation. However, the influence of renewable sources of electricity on the size of the distribution network also depends on the geographic dispersion of DG units as compared to the one of consumption centers.

Figure 4 depicts, from 2009 to 2013, the dynamics of both the development of renewables in the electric mix and the dynamics of the size of the distribution network.

- (upper left-hand corner): countries with a relatively slower increase of renewables in the electric mix but a relatively more rapidly increasing size of the distribution network as compared to the European median. In **Austria**, a significant amount of new biomass utilities have been installed, that connect to the distribution grid and trigger sizeable extensions of the power network at the local level (European Parliament, 2012).

- (upper right-hand corner): countries with a relatively rapid increase of renewables in the electric mix and also in the size of the distribution network. This is observed for instance in **Italy** where many new photovoltaic units of production have been connecting to the distribution grid.
- (lower right-hand corner): countries with a relatively rapid increase of renewables in the electric mix but a relatively slow increase of the size of the distribution grid. This may stem either from renewable units of production directly connected to the transmission grid, as large offshore wind farms in **Denmark** (Agora EnergieWende, 2013; Danish Ministry of Climate, Energy and Building, 2012) or large amounts of renewable capacity connected to the distribution grid with some underdevelopment of the transport networks that currently needs to be catched up, as in **Germany** where 97% of renewable electricity capacity is connected to the distribution grid (see Anaya and Pollitt, 2014; Ackermann, 2013; E-Bridge, OFFIS, Institute fur Elektrische Anlagen und Energiewirtschaft, 2014).
- (lower left-hand corner): countries with a relatively slow increase of renewables in the electric mix and a relatively slow increase of the size of the distribution grid. This is the case for **Nordic countries** where a large part of the electricity from renewable sources is produced in the northern areas while the consumption centers are located in the south parts, implying that the power supplied through transmission network gather most of the energy produced by DG (see Hansson and Carlsson, 2014). In other countries (such as France, Spain, Hungary), renewables units of production are not located too far from consumption centers, thus alleviating the need for increasing the density of the distribution network.

Overall, this indicator suggests that geographical factors (*i.e.*, the localization of DG units as compared to consumption areas) and policy choices (*i.e.*, the size of DG units implying a connection to the transport grid) may influence the impact of rising renewables on the density of the distribution grid.

3.2.3. Renewable sources of electricity and changes in distribution losses

Around 5% of electrical energy on average is lost in distribution networks (Shaw *et al.*, 2010) and the number of transformation steps in a power grid can account for almost half of network losses (Targosz, 2008). Mendez *et al.* (2006) argue that the development of renewables tends, at an early stage of penetration, to lessen network losses - when the local supply remains smaller than the local demand. In that case, the path from generation to consumption on distribution networks is indeed shortened on average. However, the effect is reversed for higher degrees of penetration on renewables, when local supply gets higher than local demand, involving a distribution of the surplus in farther areas and increase in network losses (see Cossent *et al.*, 2009). In that case, the possible higher dissemination of generation units fostered by renewables may influence the losses incurred by distribution networks. Mendez *et al.* (2006) additionally suggest that these effects on losses in the distribution grid are also related with the technology of the renewable sources of electricity, with wind power increasing more rapidly the amount of losses whereas photovoltaic allowing for diminishing losses even for a relatively high degree of penetration.

Figure 5 suggests that:

- (upper left-hand corner): countries with a relatively slow increase of renewables in the electric generation mix and an increase of electric network losses. This is the case for **Portugal**, due notably to overall inefficiencies of the distribution grid (Morales Pedraza, 2015). In **Austria**, energy losses are not considered as controllable OPEX by the regulator; they are accordingly covered completely by the tariff with no scheme encouraging the DSOs to reduce the losses (Mendez Quezada *et al.*, 2006).
- (upper right-hand corner): countries with a relatively rapid increase of renewables in the electric generation mix and a positive increase of electric network losses. Interestingly, relatively few European countries can be classified in this standard category (except **Belgium**).

- (lower right-hand corner): countries with a relatively rapid increase of renewables in the electric generation mix and a decrease of electric network losses. In the **UK**, the regulator adopted in the early 2000s an incentive framework so as to encourage the DSOs to lessen their power losses (Ofgem, 2003 or Jamasb and Pollitt, 2007).
- (lower left-hand corner): countries with a relatively slow increase of renewables in the electric generation mix and a decrease of electric network losses. **Latvian**'s network losses have been decreasing steadily since 1996, thanks to an efficient policy framework (Ministry of the Environment of the Republic of Latvia, 2006).

The last two sub-cases – *i.e.*, countries experiencing decreasing electric network losses – refer to countries (as Czech Republic, Lithuania, Bulgaria, Hungary and Poland) which have enforced regulatory caps for energy losses, with fines if not met and no adjustment in case of unexpected rise in DG (Mendez Quezada *et al.*, 2006).

Overall, this indicator suggests that the impact on electric losses of rising DGs may be significantly influenced by regulation.

3.3. Financial variables

3.3.1 Renewable sources of electricity and smart grids investments

The potential mismatch between demand and supply of electricity complicates the balancing of power networks. The need for precisely knowing the dynamics of the load at a disaggregated level is reinforced for DSOs when more sources of renewable energy are connected to the distribution network. Here smart grids investments can play a leading role in helping the DSO to keep actively managing its network through load management for instance (de Joode *et al.*, 2009 or Bialek and Pollitt, 2007). Smart grids technologies help substantially power distribution networks in facing the implications of increasing DG.

Figure 6 compares the dynamics of renewables with smart grids investments:

- (upper left-hand corner): the upper left-hand corner of Figure 6 contains countries with a relatively rapid dynamics of smart grids investments but a relatively lower increase of renewables in the electric mix. This characterises **Romania** (*e.g.* in the industrial park in Ghimbav, Brasov) along with most countries around the Danube region in Central Europe (REKK and Danube Region Strategy Energy, 2013).
- (upper right-hand corner): other European countries experience a relatively rapid rise in smart grids investments and also a relatively stronger increase of renewables in the electric mix. This appears to be the case of **Denmark** where wind energy penetration in the grid has strongly increased and required a stronger control of the grid with active power control and frequency regulation, reactive power control and voltage regulation, restoration of grid services after power outages, wind prediction, mix between direct and alternative current, smart charging of electric vehicles and demand-response control of heating loads, or micro-grids, to give some examples (Covrig *et al.*, 2014; de Joode *et al.*, 2010; Samad and Annaswamy, 2011). In the **UK**, a Low Carbon Networks fund allows up to £500m support to DSO projects such as smart grids project (IEA, 2011). **Czech Republic** has been implementing a sizeable program for increasing photovoltaic electricity and smart grids investments, through the ČEZ project and the experimental project in Vrchlabí.
- (lower right-hand corner): countries with a relatively subdued development of smart grids investments but a relatively stronger increase of renewables in the electric mix. In **Germany**, a survey from Steria Mummert, a consulting firm which polled 100 German utility, showed a relative lack of interest in investing in smart-grids technologies (St.John, 2012). Bichler (2012) suggests that some characteristics of the regulation may play a role in this lack of interest.

- (lower left-hand corner): countries with a relatively subdued development of smart grids investments and a relatively lower increase of renewables in the electric mix. It is the case in **Finland** where the energy transition has been triggered since decades - in Finnish distribution companies, automation and ICT systems in network operation have been well integrated since the 80's (such as Supervisory Control and Data Acquisition) (see Jarventausta *et al.*, 2011). Finland invested a lot during the past decades and is now investing relatively less than other European countries as its smart grids R&D is already well advanced.

Overall, this indicator shows that a rise in DG does not mechanically trigger vigorous investments in smart grids for DSOs, and that the heterogeneity of the situations mainly mirrors policy and regulatory factors.

3.3.2. Renewable sources of electricity and networks' capital expenditures (CAPEX)

The integration of renewables in the distribution grid requires increasing investments of DSOs, not only related with smart grids, but also - and more prominently - with the reinforcement of existing lines, the construction of new distribution lines, the development of possible technologies of storage... The investments necessary to accommodate DG in the distribution network will depend on technical factors - penetration, location and concentration of renewables as underlined in KEMA (2011) or balancing method (Blokhuis et al., 2011). They also depend on the characteristics of the regulation as concerns the inclusion of CAPEX in the regulated tariffs (ABS Energy Research, 2006) or some policy choices in end-use technologies as electric vehicles. A rise in DG may imply in some cases a reduced need for network capacity, especially if DG is geographically located near final consumers (see Martin, 2009).

Figure 7 compares the dynamics of renewables with networks' capital expenditures from 2009 to 2013:

- (upper left-hand corner): countries with a relatively slow increase of renewables in the electric mix but relatively rapidly increasing CAPEX. This is the case for instance of **Austria** (Energie-control Austria, 2014) where the fraction of renewables in the electric mix is already high and where the needs for renewing power lines, extending capacity to lessen congestions account for a significant rise in CAPEX in electric networks so as to guarantee supply security in the future. While until recently much of this spending was going to the ultra-high and high voltage grids, in 2012 the focus switched to expanding and modernizing the electricity distribution grid (Energie-Control Austria, 2014).

- (upper right-hand corner): countries with a relatively rapid increase of renewables in the electric mix and also in the CAPEX invested in electric networks. This rather intuitive case concerns the **United Kingdom** for instance, which has implemented strong regulatory incentives for DSOs to invest in the grid in case of rising DG. For instance, the Innovation Funding Incentive (IFI) permits DSOs to spend up to 0.5% of its revenues on eligible IFI projects related with any distribution system asset management aspect. The Registered Power Zones (RPZ) mechanism increases the DSOs incentives to connect DG (see Cossent *et al.*, 2009).

- (lower right-hand corner): countries with a relatively rapid increase of renewables in the electric mix but stable or even declining CAPEX. In **Germany**, DSOs as well as TSOs investments over the recent past are relatively depressed as compared to the European median (Bundesnetzagentur, 2013 and 2014) partly because the weighted average cost of capital set by the regulator is lower than in most other European countries. In **Denmark**, the regulation (with an *ex post* evaluation of the efficiency of investments and a frontier shift in the x-factor) tends to delay the DSO investments related with the rise in DG. Moreover, Niesten (2010) argues that the tariff does not enshrine any significant injection component and relies essentially on a fee for power taken out of the grid (and for power put on the grid).

- (lower left-hand corner): countries with a relatively slow increase of renewables in the electric mix over recent years and stable or even declining CAPEX. This is the case for **Spain**, in line with a specific national context in the electric sector, characterised over the recent period by a sizeable contraction of investments in the sector and the existence of an important tariff deficit (Cossent *et al.*, 2011; Robinson, 2013*)*. Another specific case is **Norway** where the network is already well-adapted to a production stemming mainly from hydroelectricity and does not require massive new investments (Norwegian Water Resources and Energy Directorate, 2014).

Overall, this indicator shows that the impact on DSOs investments of rising renewables is closely related with regulatory choices, while some historical heritage may also play a significant role in specific countries.

3.3.3. Renewable sources of electricity and overall network costs paid by households

Network costs include mainly capital expenditures but also operations, maintenance and refurbishment costs, as well as grid losses, costs for measurement and billing at the retail level. Figure 8 compares the dynamics of renewable and overall network costs paid by an average household from 2008 to 2013:

- (upper left-hand corner): countries with a relatively slow increase of renewables in the electric mix but a rapid increase of the average household network cost. The case for **Spain** mirrors problems of governance in the power sector along with some historical heritage -with, among other factors, a relatively weak connectivity between Spain and France interacting badly with high production of solar electricity in Spain (on this point, see Parr, 2015).
- (upper right-hand corner): countries with a relatively rapid increase of renewables in the electric mix and also in the average household network cost. In **Belgium** and **Denmark**, the development on a large-scale of offshore wind facilities account for rapidly increasing network costs (Lehtonen and Nye, 2009). In Denmark, the 24% rise in network costs (2007-2013) corresponds to the installation over the same period of an additional 700MW of off-shore wind (roughly 20% of the wind installed base).
- (lower right-hand corner): countries with a relatively rapid increase of renewables in the electric mix but a relatively slow increase (or even a decrease) of the average household network cost. This is the case for **United Kingdom** where, among other factors, the regulator had a clear policy with most renewables connected to MV/HV transmission networks having to cover most of the implied connection costs. Though a high penetration of RES, **Germany** has also seen little change to network charges even if around 42GW of RES were installed, much of which connected to the distribution network. However, this reflects a decrease from 2009 to 2011 and a rise in 2012 and 2013. Sizeable rises are to be expected in the next years (Bundesnetzagentur, 2014), not least because of the impact on the tariff of declining volumes of power distributed.
- (lower left-hand corner): countries with a relatively small increase of renewables in the electric mix and a relatively slow increase or decrease of the average household network cost.

Overall, data suggest that increasing DG may not mechanically weigh on the overall network costs paid by the average household, and that policy and regulation may play a significant role in offsetting the consequences of rising DG on the network costs paid by households.

4. Cluster analysis: defining statistically homogeneous European countries as concerns the effects of low carbon transition policies on DSOs

A cluster analysis is conducted so as to statistically identify countries with similar characteristics in terms of the effects of low-carbon transition policies on DSOs. This analysis relies on the indicators computed and commented on in section 3.

4.1. Methodology

We rely on a K-means clustering method to partition the European countries in homogenous groups (or clusters). This algorithm finds a partition in which countries within each cluster are as close to each other as possible, and as far from countries in other clusters as possible.[7]

Formally, let $X = \{x_i\}$, $i = 1, \dots, n$ be a set of d-dimensional points to be partitioned in K clusters, $C = \{c_k, k = 1, \dots, K\}$. In the paper, X represents the set of n countries characterized by d variables (the installed capacity in renewable energy, in power energy etc…). The center of the cluster k denoted m_k is obtained as the variables' average values of all objects in c_k. The squared error between the empirical mean of a cluster c_k and the points x_i in the cluster c_k is given by $SSE_k = \sum_{x_i \in c_k} \|x_i - m_k\|^2$. The k-means algorithm partitions the n points such that the overall sum of the squared error for the K clusters, $\sum_{k=1}^{K} SSE_k$, is minimized. In the paper, the Euclidian distance is used to determine the distance between each country/points and the center of the associated cluster.[8]

To find the optimal partition, the following procedure is applied recursively. A first partition is performed around K randomly selected centroids. Each point is assigned to the cluster whose center is the closest. New centers are then recalculated for each cluster, by averaging the points in the cluster. A new partition is obtained around these new centers and so on until the partition does not vary from one iteration to the other. To deal with the sensitivity of the results to the initial clusters' centers, we re-initiate 100 times the k-means algorithm with different initial partitions and keep the partition with the smallest squared error.

Again, 23 countries are incorporated in our analysis. Data are standardized. Missing observations for some countries are replaced by the average value of the variable, and thus might not bias the results.

The algorithm is applied to two partitions of variables. In a first step, we consider the whole set of indicators. In a second step, we consider separately the 3 sets of variables analyzed in section 3, *i.e.*, the "energy variables" set (4 indicators), the "network variables" set (3 indicators) and the "financial variables" set (3 indicators). The implementation of the algorithm in the second step is more reliable. It allows the identification of groups of countries with the same characteristics in terms of energy or distribution of electricity, while the partitioning of the whole set of variables gives a whole picture on the countries. Accordingly, we run the k-means algorithm for 4 sets of variables and consequently select countries who appear recurrently in each cluster analysis for each of these 4 sets.

Prior to the cluster analysis, we need to choose a number of clusters. Several criteria can be used for this purpose. In this paper, we rely on the Calinski-Harabasz index. This criterion is based on the comparison of the variability within the clusters and between the clusters. This criterion is defined as follows for n observations and K clusters:

$$CH(K) = \frac{B(K)/(k-1)}{W(K)/(n-k)}$$

where $B(K) = \sum_{k=1}^{K} n_k \|m_k - m\|^2$ is the overall between-cluster variance and $W(k) = \sum_{k=1}^{K} \sum_{x \in c_k} \|x - m_k\|^2$ is the overall within-cluster variance with m_k the centroid of c_k the cluster k, n_k the number of objects (countries) in c_k and m the overall mean of all data. Again, the Euclidian distance $\|\bullet\|^2$ is used as a distance metric. To have objects as similar as possible inside the clusters and as distinct as possible with the objects in the other clusters, we choose the number of clusters K that maximizes $CH(K)$.

The optimal number of clusters obtained with this criterion is equal to 5 for all the sets of variables, except for the set of "network variables" for which the criterion is maximized for a number of clusters equal to 4. However, the second best choice in term of the CH criterion is 5. Hence, we consider 5 clusters in all cases to compare all partitions more easily.

[7] See Jain (2010) for a review of this method and some extensions.

[8] The Euclidian distance is the square root of the sum of the squared differences in the values of the variables. For instance, the distance between the two countries A and B with regards to three variables x, y and z is given by $\|A - B\|^2 = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2}$.

4.2. Results

In each of the 4 above-mentioned applications of the k-means algorithm, we select the 5 groups as provided by the algorithm. Figure 9 provides with the detailed results of the k-means algorithm, in a graphical fashion, for the simulation on the whole set of variables described by pair of variables.[9] Table 2 summarizes the results obtained with the cluster analysis on the 4 sets of variables. Noteworthily, it appears that:

a) Austria, Finland and Slovakia belong to the same group in the 4 sets out of the 4 tested with the k-means algorithm;

b) Denmark, France and Norway belong to the same group in 3 sets out of 4;

c) Hungary and UK belong to the same group in 3 sets out of 4;

d) Germany and Poland belong to the same group in 3 sets out of 4;

e) Belgium, Ireland and the Netherlands belong to the same group in 3 sets out of 4.

These results consequently allow for defining 5 groups of countries with relatively homogenous features as concerns the impact of low-carbon transitions on their power distribution networks: Austria-Finland-Slovakia; Denmark-France-Norway; United Kingdom–Hungary; Germany-Poland; Netherland-Belgium-Ireland. For illustrative purpose, Figure 10 displays 5 radar charts, one for each group of countries with relatively homogenous features. The similarity of the countries in each group is evident on this figure.

Thus our method allows for classifying 13 European countries in a clear, statistically defined typology of distribution networks, according to the impacts of low-carbon transition policies on DSO's. By definition, countries belonging to the same cluster must not necessarily have *all* features in common as concern all the characteristics of their distribution network and of their low-carbon transition policies. In this context, Table 3 lists the main characteristics of each cluster:

In the first two groups, the capacities of and power generation out of renewables increase relatively slowly:

- **Cluster 1** (Austria, Finland, Slovakia) is characterized, on average over the recent years, by a relatively rapidly increasing size of the distribution network though small increases in installed capacities of and power generation out of renewables.[10]

- **Cluster 2** (Denmark, France, Norway) also displays relatively small increases in installed capacities of and power generation out of renewables as compared to the European median, but has increasing network losses though relatively slowly increasing network size, and rapidly increasing network costs for households.

By contrast, in the last three groups, the capacities of and power generation out of renewables grow rapidly:

- **Cluster 3** (United Kingdom, Hungary) is characterized, on average over the recent years, by relatively large increases in installed capacities of and power generation out of renewables, but decreasing electricity losses on distribution networks and decreasing network costs for households.

- **Cluster 4** (Germany, Poland) is also characterized, on average over the recent years, by relatively large increases in installed capacities of and power generation out of renewables and decreasing network losses, but exhibits low investments in smart grids, relatively slowly increasing capital expenditures in power networks.

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[9] The results obtained on the three subsets of variables are available upon request.

[10] The *level* of the fraction of electricity produced out of renewables is relatively high in Austria and Finland and relatively low in Slovakia.

- **Cluster 5** (Netherlands, Belgium, Ireland) exhibits, on average over the recent years, relatively large increases in installed capacities of and power generation out of renewables, a rapidly increasing size of distribution networks, rising electricity network losses, and rapidly increasing network costs for households.

4.3. Discussion

Our results can feed into some normative analysis. For instance, a normative approach would suggest that Cluster 3 experiences desirable characteristics since it contains countries which develop rapidly the fraction of renewables in their energy mix at a network cost that is kept in check. Countries in Cluster 4 might contemplate the advantages of investing more in their distribution networks. Such normative interpretations of our results should in any case remain cautious. For instance, the energy mix in most countries in Cluster 1 and 2 has already a relatively low content in carbon emissions. Hence the need for developing renewables may not be as strongly needed as it is in other countries. Comparisons of financial variables can also usefully take account of specific factors at the national level. This may be for instance the case of a growing need to replace old lines, which mechanically pushes up network costs without the DSO being necessarily fully responsible for this situation.

Our results (esp. Table 3) seem best used as a tool helping decision makers and regulators to concentrate on the issues specific to their countries as compared to the European median, and to find for possible solutions by looking in the experience of other clusters performing better for some indicator. For instance, countries of Cluster 5 could be willing to adopt some of the features of the regulation of countries in Cluster 3 so as to increase the economic efficiency of their DSOs. Countries of cluster 2 may benefit from the experience of Cluster 4 as far as network losses are concerned. Countries that are not included in a specific cluster can benefit from our analysis insofar as it provides them with a set of empirical stylized facts about other countries. The cluster analysis thus implicitly delivers useful guidelines for thinking about the business and engineering models of DSOs in each European country.

5. Conclusion

The accelerated development of decentralised sources of power produced out of renewable energies has been triggering far-reaching consequences for DSOs over the past decade. Our paper benchmarks systematically across most European countries the impact of the development of renewables on the physical characteristics of power distribution networks and on their investments. It builds on a large spectrum of databases on DSO activities so as to build indicators about the dynamics of installed capacity of and generation from renewable sources of electricity, electric independence, quality of electric distribution, the amount of smart grids investments, DSOs capital expenditures (CAPEX), the length of the distribution networks, overall costs of power networks paid by private agents, and electric losses. It appears that the heterogeneity of these indicators across Europe is wide notably because of physical constraints, historic legacies or policy choices. A cluster analysis then allows for deriving 5 groups of countries that are relatively homogenous in this context.

These results have policy implications. The 5 clusters identified in this paper mirror policy choices but may in turn call for future policy choices. For instance, countries of cluster 5 seem to correspond to the standardly assumed consequences of low-carbon transitions policies on DSO's, with rapidly rising network costs for instance. From the latter point of view, the situation of countries in cluster 3 seems globally more satisfying. Eventually, countries in cluster 1 are less currently involved in a low-carbon transition as far as their DSO's are concerned. Our statistically-driven typology of European DSO's can provide decision makers with a useful – and original - road-map by offering points of references and comparisons.

Appendices

Table 1. The 10 indicators and their code

Indicator	Code
Compound annual growth rate (%) of…	
… electric installed capacity	X1
... installed capacity of renewable electricity	X2
... electric independence	X3
... investments in smart grids for DER & RES integration	X4
... CAPEX in power networks	X5
... distribution network length	X6
... electricity network losses	X7
... net electricity generation from renewable sources	X8
... total system average interruption duration index *(excl. exceptional events)*	X9
... average household network costs	X10

Notes: This table gives the 10 indicators analysed in the paper, as well as their code used in the graphs.

Table 2. Results of the cluster analysis for each set of variables (number of groups: 5)

(NB: Figure 9 provides with a detailed presentation of the results on the 1st set of variables)

	Homogenous group 1	Homogenous group 2	Homogenous group 3	Homogenous group 4	Homogenous group 5
1st set: all 10 indicators	Austria, Denmark, Finland, France, Norway, Romania, Slovakia, Slovenia, Sweden	Belgium, Bulgary, Czech Republic, Germany, Ireland, Italy, Netherlands, Poland	Portugal, Spain	Hungary, UK	Latvia, Lithuania
2nd set: energy variables	Austria, Bulgaria, Denmark, Finland, France, Latvia, Norway, Romania, Slovakia, Slovenia	Belgium, Ireland, Netherlands, Poland, UK	Portugal, Spain, Czech Republic, Germany, Italy	Hungary	Lithuania, Sweden
3rd set: network variables	Austria, Belgium, Finland, Ireland, Italy, Netherlands, Romania, Slovakia, Slovenia	Czech Republic, Bulgaria, Germany, Hungary, Poland, Sweden, UK	Portugal, Spain	Denmark, France, Norway	Latvia, Lithuania
4th set: financial variables	Austria, Belgium, Czech Republic, Denmark, Finland, France, Lithuania, Netherlands, Slovakia, Sweden	Bulgaria, Ireland, Italy, Portugal	Spain	Hungary, Romania, UK	Germany, Latvia, Norway, Poland, Slovakia

Notes: This table provides the partition of countries obtained for 4 sets of variables, 5 being the optimal number of clusters considered. In the first case, we consider the whole set of variables. Other cases correspond to the algorithm being applied separately to each of the 3 sets of variables analysed in section3, namely, "energy variables", network variables" and "financial variables".

Table 3. Main characteristics of each cluster

	Cluster n°	1	2	3	4	5
	Countries in the cluster	Austria, Finland, Slovakia	Denmark, France, Norway	United Kingdom, Hungary	Germany, Poland	Netherland, Belgium, Ireland
Compound annual growth rate (%) of…						
X1	*… electric installed capacity*	rising	slowly increasing	rising	rising	rapidly increasing
X2	*... installed capacity of renewable electricity*	slowly increasing	slowly increasing	rapidly increasing	rapidly increasing	rapidly increasing
X3	*... electric independence*	decreasing	decreasing	decreasing		decreasing
X4	*... investments in smart grids for DER & RES integration*	rising		rising	decreasing	
X5	*... CAPEX in power networks*	rapidly increasing		rapidly increasing	slowly decreasing	
X6	*... distribution network length*	rapidly increasing	slowly increasing	slowly increasing	slowly increasing	rapidly increasing
X7	*... electricity network losses*	rising	rising	decreasing	decreasing	rising
X8	*... net electricity generation from renewable sources*	slowly increasing	slowly increasing	rapidly increasing	rapidly increasing	rapidly increasing
X9	*... total system average interruption duration index (excl. exceptional events)*	decreasing	decreasing	decreasing	decreasing	
X10	*... average household network costs*	slowly increasing	rapidly increasing	decreasing		rapidly increasing

Notes: Cells with no data correspond to cases where the situation of each country in the cluster can slightly differ one with another.

Figure 1. Electrical mix and renewables

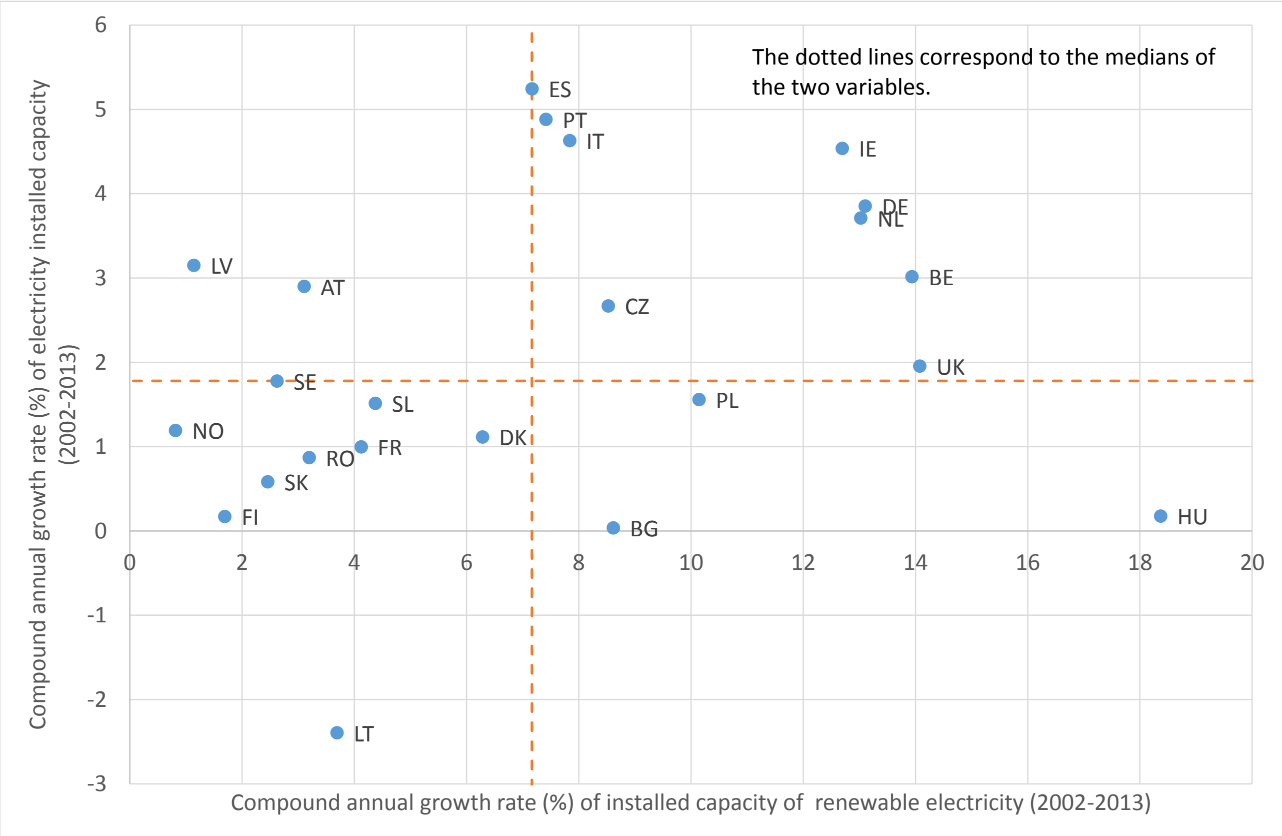


Figure 2. Renewable energy sources and electric independence

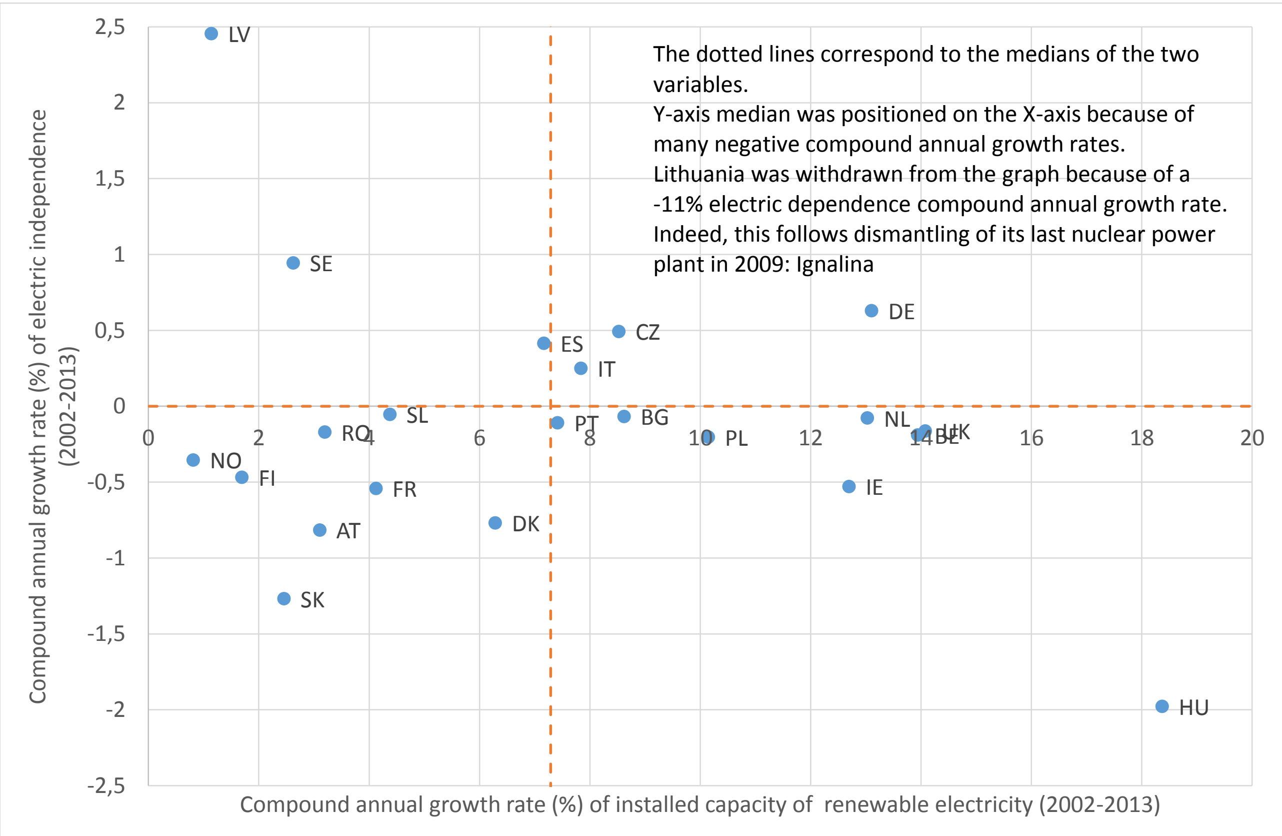


Figure 3. Renewables integration and System Average Interruption Duration Index (excluding exceptional events)

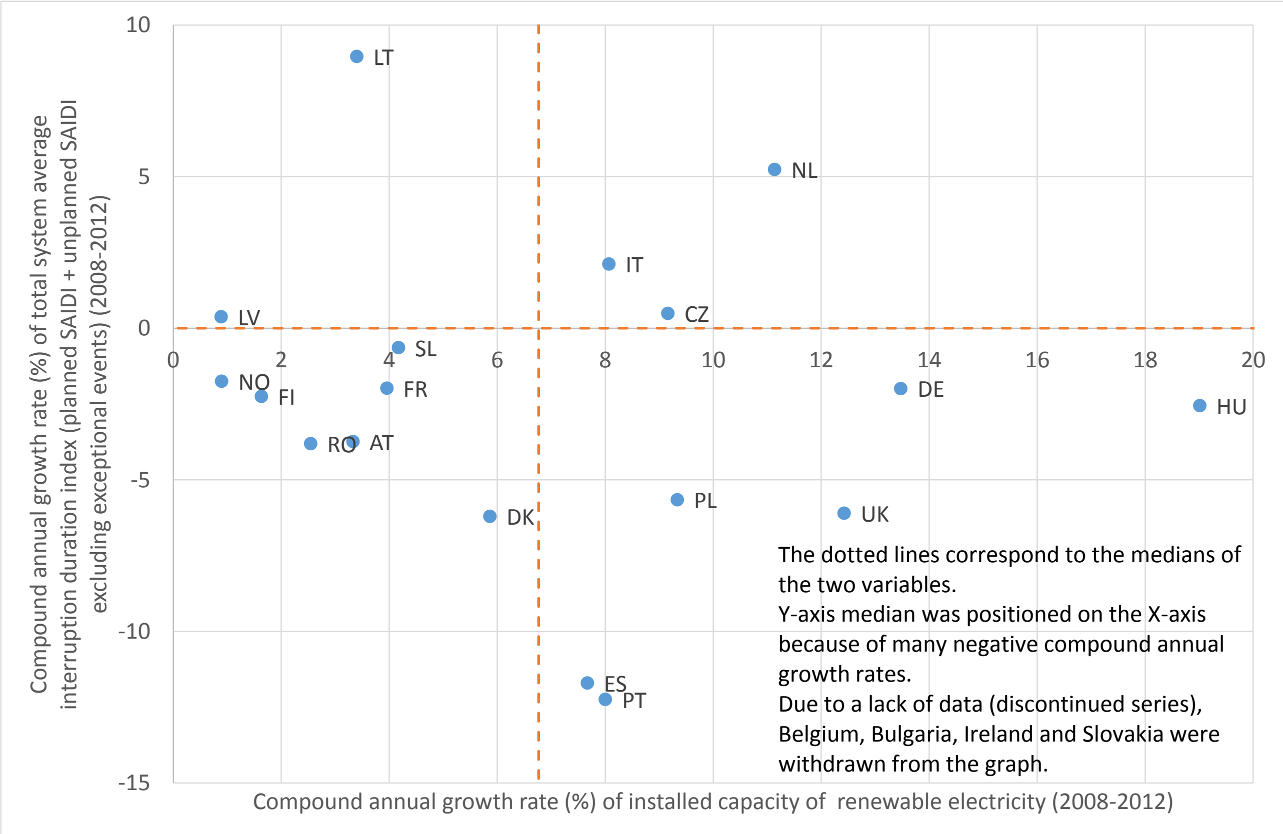


Figure 4. Increase in distribution network size and Renewable energy sources

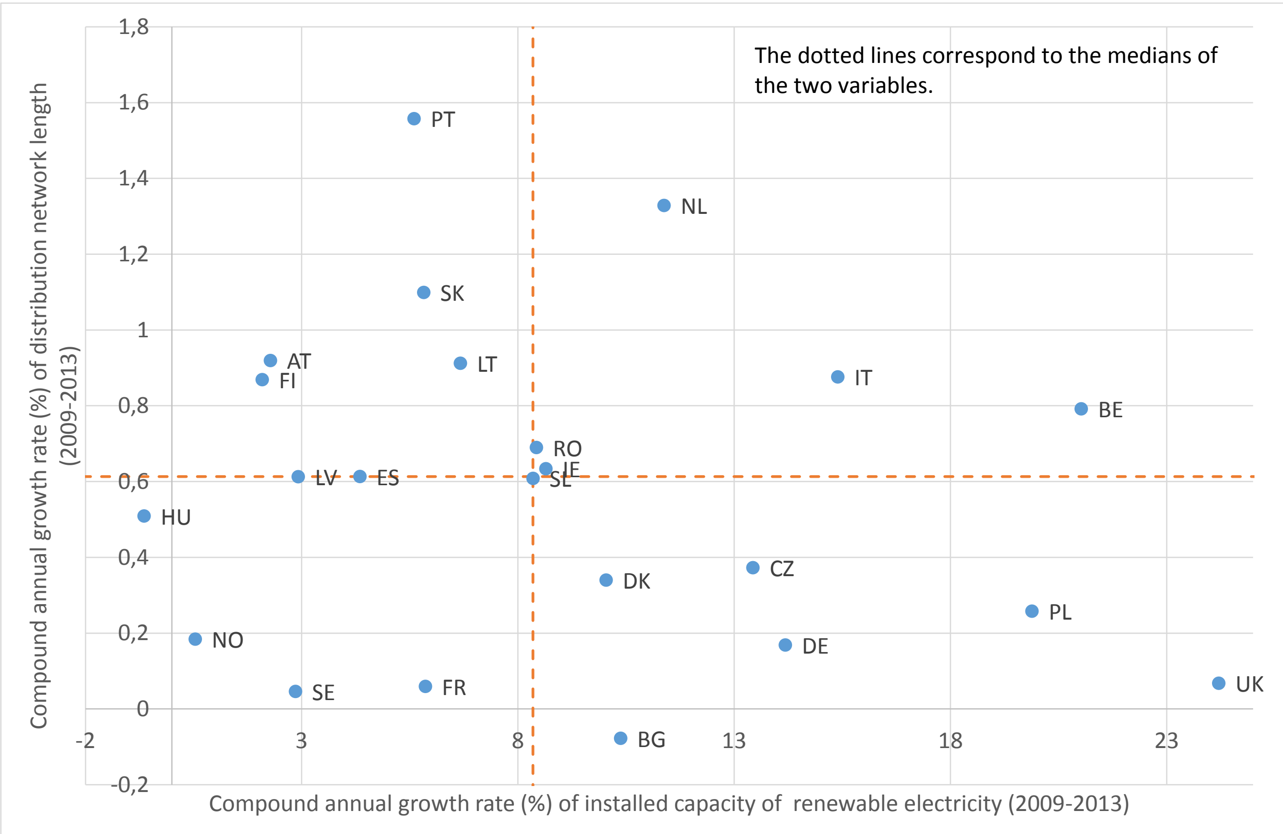


Figure 5. Change in distribution losses and electricity generation from renewables

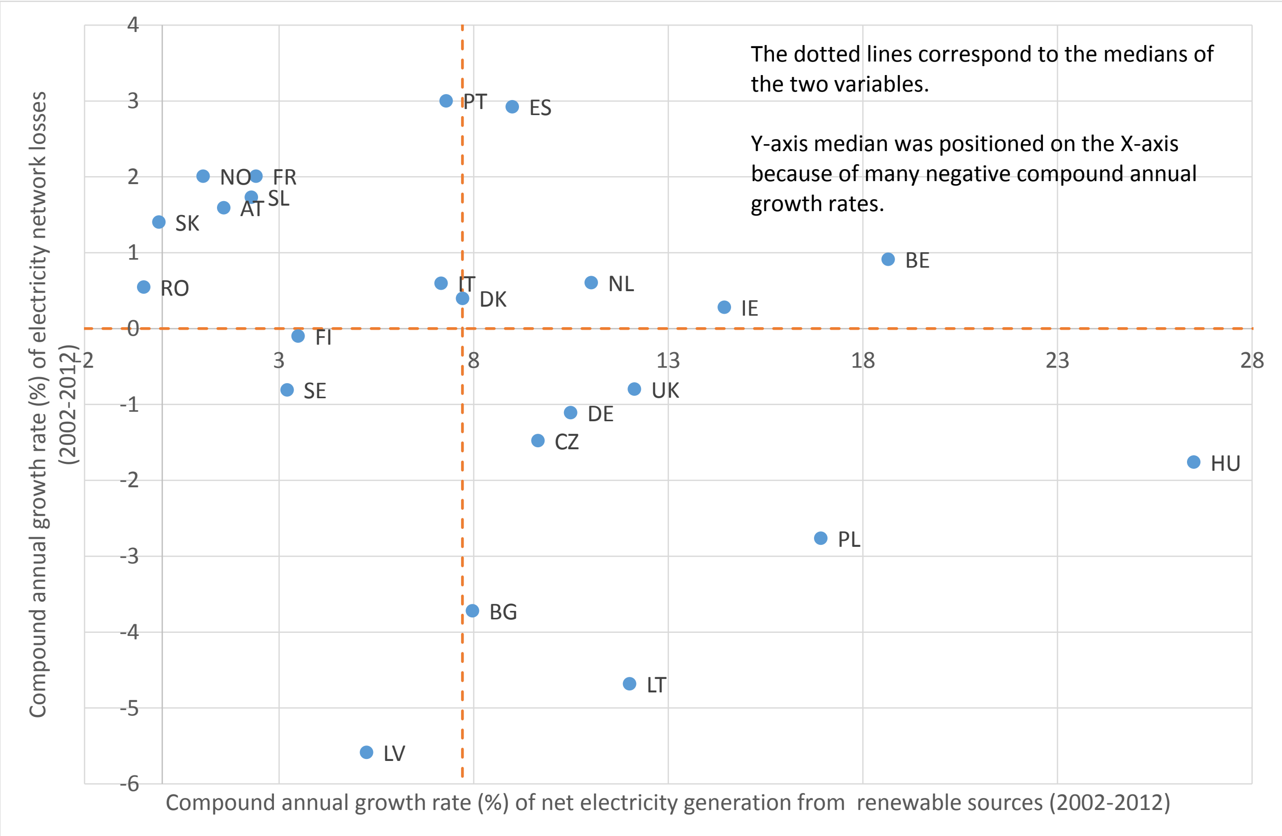


Figure 6. Smart grids Investments and Renewables

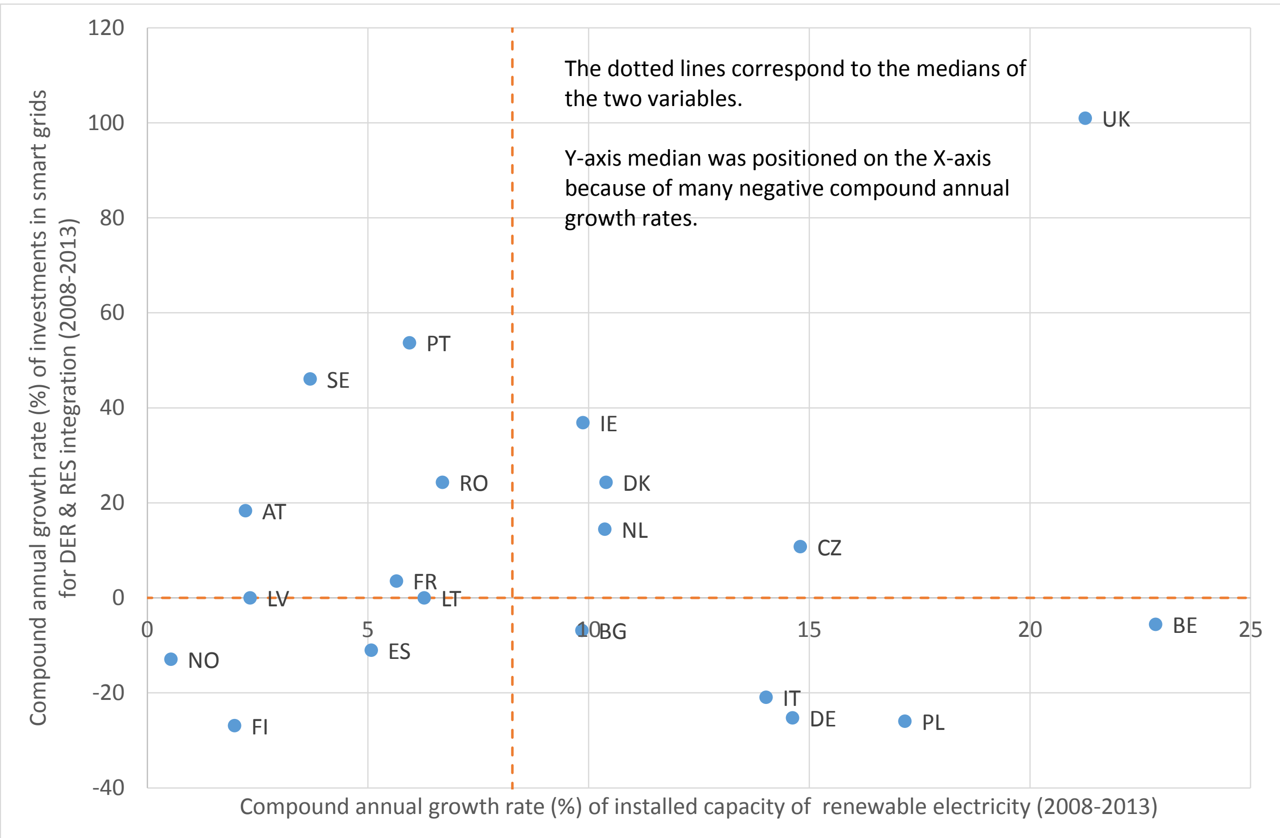


Figure 7. CAPEX and Renewable energy sources

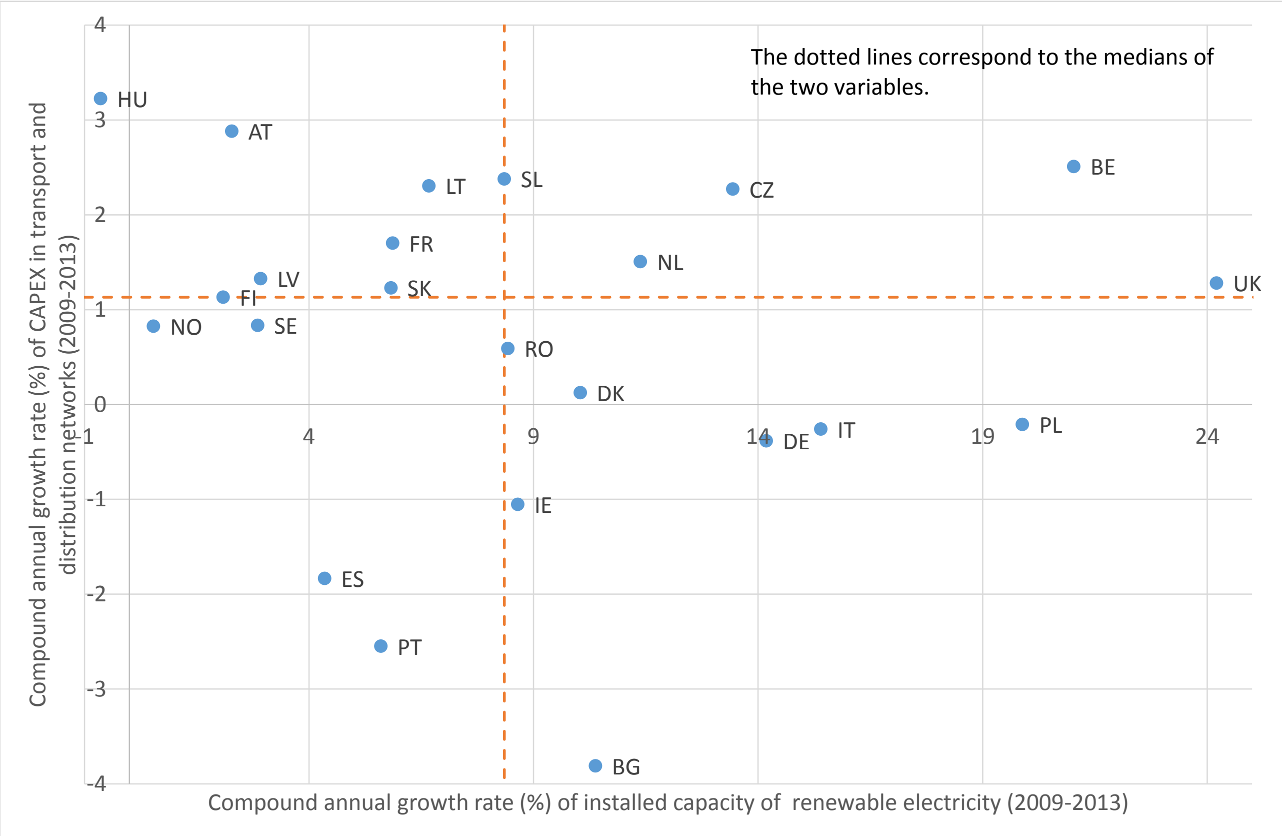


Figure 8. Overall network costs paid by households and Renewable energy sources

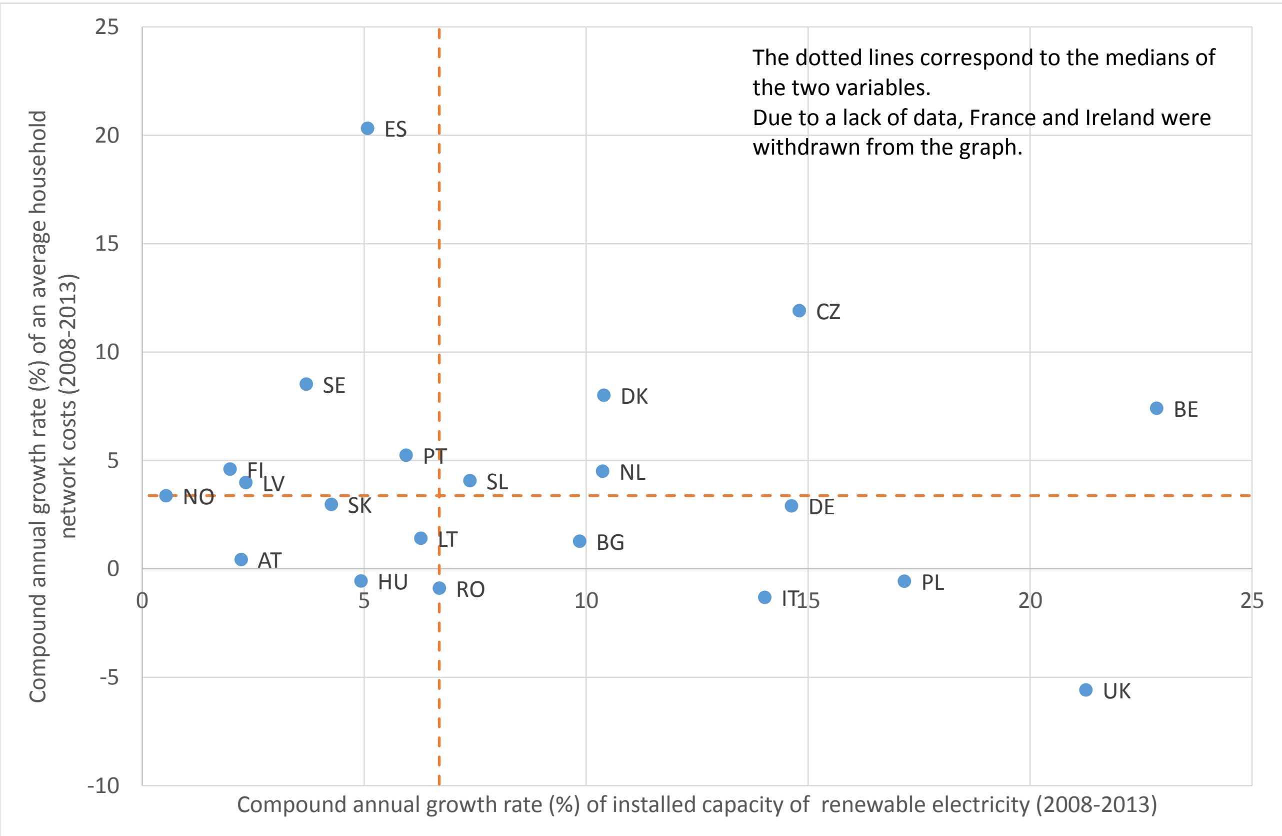
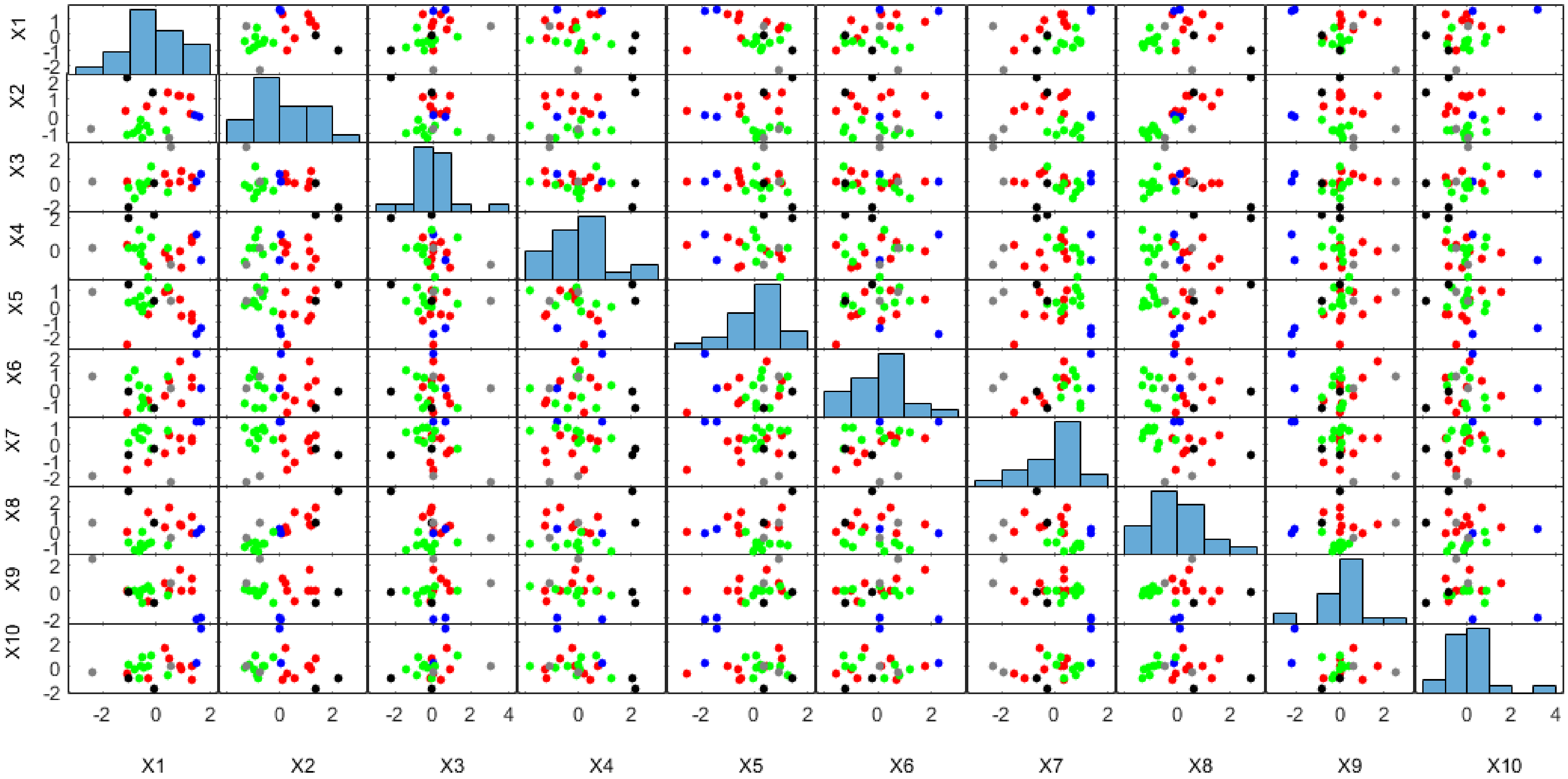


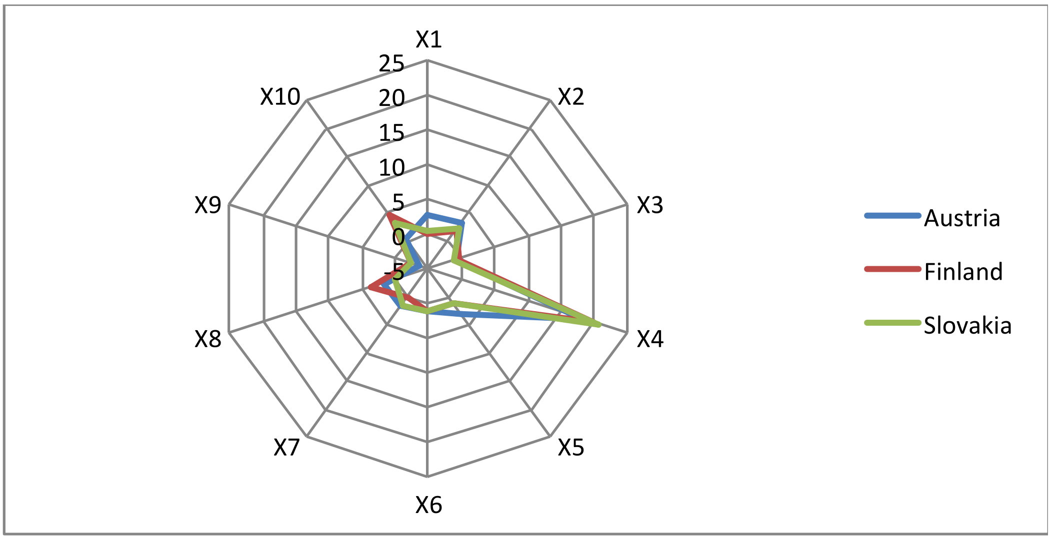
Figure 9. Results of the cluster analysis on the whole set of variables



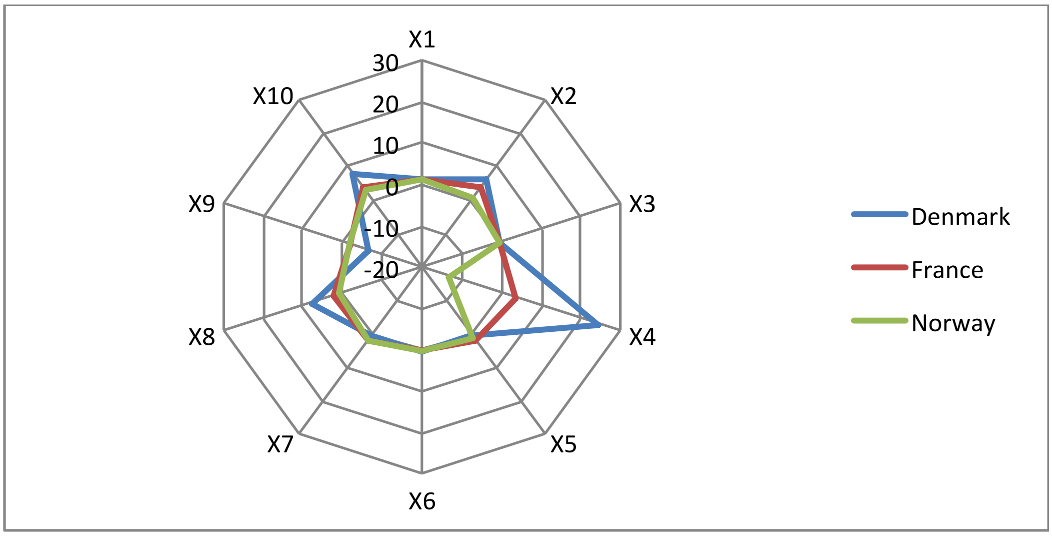
Notes: The codes X1…X10 refer to Table 1. This figure describes the results of the cluster analysis with the k-mean algorithm applied to the whole set of variables. The figure displays all the pairwise scatter plots of the variables 1 to 10. For instance, the graph in column 1 and line 2 reports each country i according to its coordinates $\{x_i, y_i\}$ with x the variable 1 and y the variable 2. Each cluster appears in different color. The countries in cluster 1 are represented in red, in cluster 2 in blue, in cluster 3 in green, in cluster 4 in black and in cluster 5 in grey. Histogram plots of each variable are displayed along the diagonal.

Figure 10. Radar charts

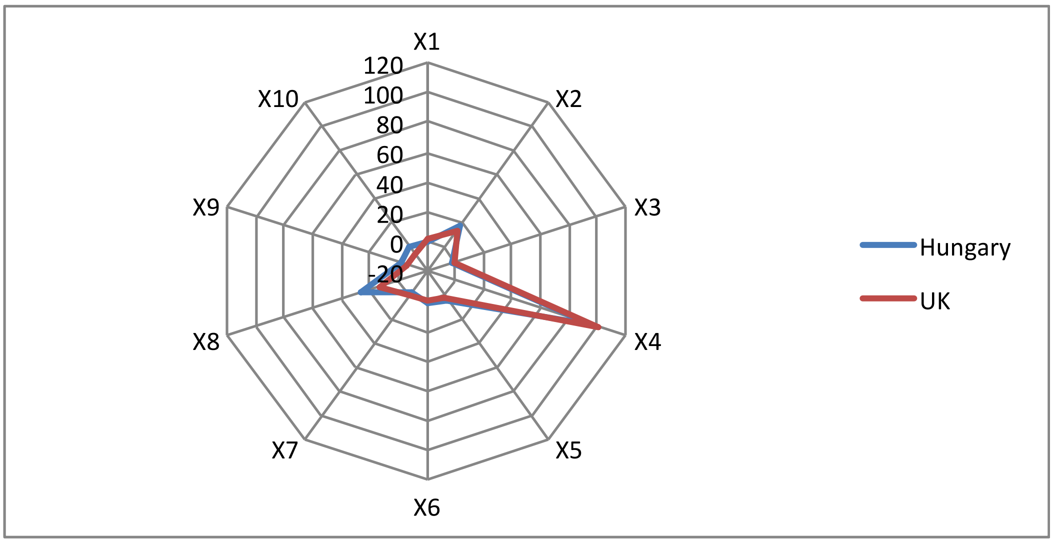
Group 1: Austria, Finland, Slovakia



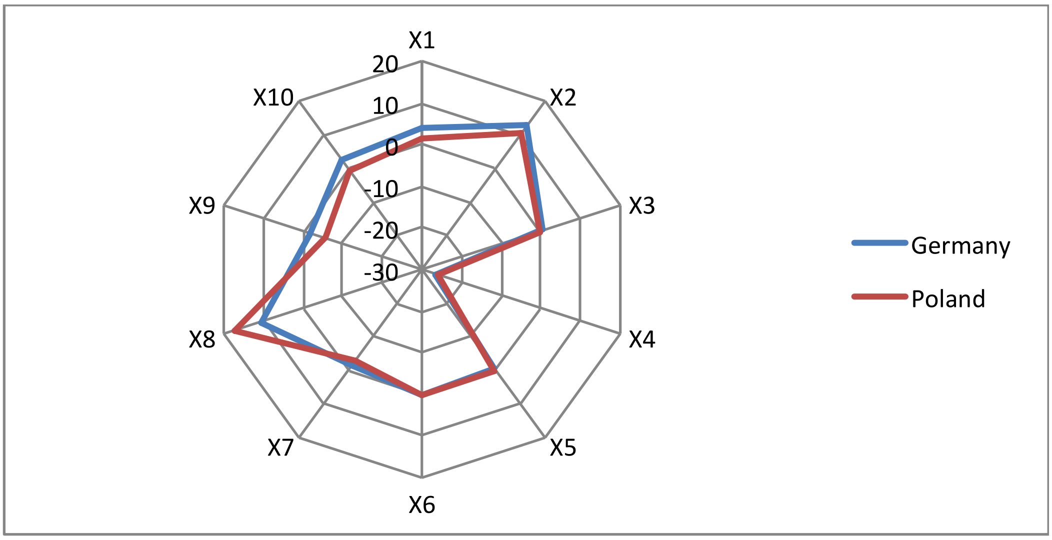
Group 2: Denmark, France, Norway



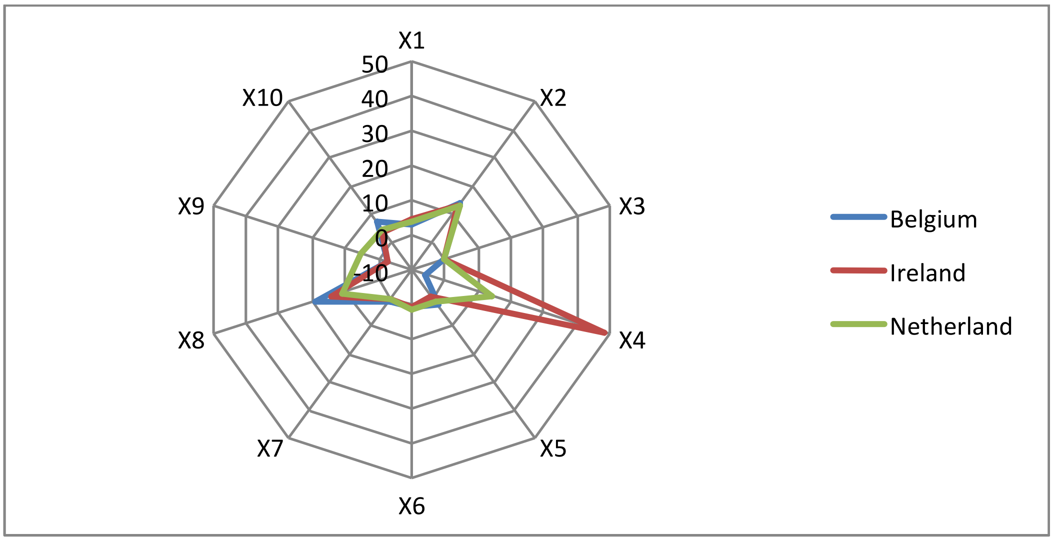
Group 3: United Kingdom, Hungary



Group 4: Germany, Poland



Group 5: Belgium, Ireland, Netherlands



Notes: The code of the indicators X1,…,X10 can be found in Table 1. These figures display the values of the 10 indicators for countries with homogenous characteristics as identified by the k-means algorithm.

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