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A worldwide analysis of the energy regulatory tasks and activities through the lenses of entropy and unsupervised statistical learning

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ABSTRACT

This paper provides an overview of tasks and activities of world energy regulatory authorities, through their regional associations. Regulatory practices are investigated when looking at federal, state and national authorities' replies to two surveys on electricity and gas markets. Empirical results show that the implementation of the energy regulation can be context-specific. Indeed, regulators' powers and tools show diversity, even among groups of regulators belonging to the same regional associations and then expected to act homogeneously. To inspect the similarity across regulators, a statistical index and an unsupervised statistical learning technique are proposed. The usage of these two methods is recommended to inspect the status of the regulatory harmonization, and to inspect if uniformed and coordinated energy policy actions are achieved in view of global resolutions towards a low carbon transition, and delineated environmental and sustainable goals.

1. Introduction and background

Over the last decades, important liberalization processes have taken place to open regulated markets to competition. Monopolies, firms and markets controlled by states have been abolished or reduced, and independent regulatory authorities have appeared in all continents. As far as the energy sector is concerned, most of research is focussed on market designs, market sessions and the mechanisms for the determination of prices, together with price modeling and forecasting; for extensive literature reviews see [1,2], for country specific analysis of price determinants and market interconnections see [3–9], and [10], among others.

However, little attention has been devoted to inspecting energy regulators' powers, tasks and activities, in both gas and electricity markets. A preliminary inspection was performed by Gianfreda and Vantaggiato [11] where the EU members' replies were studied only for electricity. Therefore, this paper aims at extending previous analysis to all worldwide regulators who responded to the electricity and gas surveys in 2011.

To understand and consequently learn from the information contained in these surveys, a worldwide data-driven analysis is conducted through two simple statistical methods to show the *status quo* observed when the information was collected.

Then, this paper provides empirical evidence about the energy regulatory practices and the degree of (dis)similarity of regulators' activities, when disentangling across *federal, state* or *national* jurisdictions. Similarities across regulators' replies are investigated through the Shannon's entropy index [12], whereas unsupervised statistical learning is used to unveil relationships and structures in the handled data by means of cluster analysis, since it naturally generates groups of regulators with similar profiles.

Results show that regulators' tasks and activities differed across jurisdictional levels in 2011; supporting the theory of polycentric systems [13]. Surprisingly, low similarity is found even among supposedly homogeneous groups of regulators, such as the European national regulatory authorities. These findings are important since they can be considered as an historical benchmark versus which testing any improvement towards more coordinated and globally convergent energy policies. Indeed, these two methods can be easily implemented in a process of continuous monitoring of the international cooperation among regulators, by simply measuring the degree of similarity of their answers to inquired topics, and this would promote more comparisons and enhance further discussions. Repeating this analysis regularly through years could help in understanding if a regulatory convergence is occurring. Moreover, depending on the formulation of the surveys, targets of inquiry could be policies and tools to support the transition to a low carbon future and a sustainable growth. In this regard, this analysis can be considered as a *starting point* for future investigations.

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The remainder of the paper is organized as follows: Section 2 provides a description of surveys and collected information, together with a taxonomy of worldwide energy regulators and their regional associations. The methodology is presented in Section 3. Empirical results are presented in Section 4. Section 5 provides discussion and conclusions with some policy implications and recommendations for the future.

2. Data on surveys and ERAs

2.1. IERN & its surveys

Data about the *energy regulatory authorities*' (ERAs) tasks and activities were collected by the *International Energy Regulation Network* (IERN) in 2011. IERN[1] was created on the energy regulators' initiative expressed during the World Forum on Energy Regulation (WFER) held in Rome in 2003 and implemented during the next WFER held in Washington in 2006. The main promoters of this initiative were European regulators, gathered around their voluntary regional association (the *Council of European Energy Regulators*, CEER) and in particular the Italian Regulatory Authority. Therefore, this initiative had undeniably a European characterization from its beginning, even if it was set up with the intent to serve as a repository of information on energy regulators' practices, for the benefit of all world energy regulators.

Initially, IERN collected online information about 310 energy regulatory authorities and thereafter it launched two surveys with the main objective of acquiring details about the regulatory practices: one focussing on standard information, and therefore simply called *basic*; and one with focus on the electricity sector, and so called *electricity*. In this way, all regulators had (and have) access to collected information, while looking for best practices or also practical arrangements.

The *basic* survey asked regulators about basic features as their 'age' since their creation, budgetary endowment, number of staff, number and type of sectors regulated, laws of establishment; and it consisted of just eight questions. Instead, the *electricity* survey was longer and inquired regulators about their specific activities in the electricity market. Unfortunately, the total rate of response to both surveys in 2009 and 2010 was only 20%. Later in 2011 there was a new launch of these surveys, after having modified some questions and added some new ones. In addition, a third survey covering 'gas' was also delivered.

In this latter experience, the rate of response to all three surveys was higher, indeed over a world total of 319 energy regulators, with 310 registered on the IERN website 85 answered to the surveys, with a rate of response of 27.4% within IERN, and covering more precisely the 26.6% of world energy regulators. Specifically, 81 regulators answered to the *electricity* and 77 answered to the *gas* surveys; hence, resulting in world response rates of 25.4% and 24.1% respectively. As expected, the lowest rate observed in gas can be related to the later liberalization of this market. Hence, this investigation considers only information retrieved from the last replies, given that the number of responding regulators grew in 2011.

It must be noticed that the surveys were formulated to gather a vast amount of information about energy regulators' powers, tasks and activities (as defined in [14]) and, more importantly, the formulation of questions reflected a European perspective, implicitly assuming and/or expecting competencies established by EU directives towards the creation of a liberalized, efficient, secure and common energy market; see [15].

However, later the intended audience of the surveys was enlarged from Europe to the entire world. Consequently, the surveys in their preliminary form were sent to all world regulators registered on the IERN website to collect comments and suggestions for improvements, and then received feedbacks were integrated before formal submission. According to this unique source of information about an intercontinental audience of world energy regulators, it is possible firstly to provide a taxonomy of world energy regulatory authorities (ERAs) and their regional 'associations', and, secondly, inspect their functions as inquired in 2011.

2.2. ERAs' powers, tasks and competencies in electricity and gas sectors

The first step in formulating a taxonomy of the *energy regulatory authorities* (ERAs) is to distinguish across jurisdictions, that is between *federal, state* and *national* ERAs.

Federal ERAs (FERAs) supervise interstate infrastructures in countries that are federations of states; as the USA, Canada, Australia, Russia, India, and Brazil. The counterparts of federal regulatory authorities are the *state-level* ERAs (SERAs) and they exist in each state of a federation of states; examples are the fifty US Public Utilities Commissions and the fourteen provincial regulators of Canada. Federal and state-level regulatory authorities usually have complementary competencies. The former ones regulate infrastructures extended across states, whereas the latter ones regulate utilities and infrastructures within the borders of their state. *National* ERAs (NERAs) are those existing in a national state, not constituted by a federation of states. They are usually unique within their jurisdiction and possess regulatory competencies over the whole sector within their own country. Clearly, this is not a sharp definition,[2] nevertheless federal and state-level authorities' competencies are expected to be relatively similar across jurisdictions.

To authors' best knowledge, the 319 world ERAs are organized in 180 SERAs, 8 FERAs (considering that both Brazil and India have separate agencies for the regulation of electricity, gas and oil) and 131 NERAs. However, it must be emphasized that the IERN website only listed 310 authorities[3] in 2011, hence the missing ones have not been considered in this analysis. More specifically, this analysis covers the replies provided by 52 NERAs, 6 FERAs (USA, Canada, Australia, Brazil, India and Russia) and 27 SERAs (6 from Australia, 16 from the USA, and 5 from Canada).

Considering that ERAs often belong to regional 'associations', we inspect also the *regional regulatory authorities* (RRAs), which are organized around the world to regulate infrastructures extended across countries with the goal of enabling cross-border trading. A taxonomy of these RRAs is provided in Appendix A, considering also that ERAs may be affiliated to several RRAs. Table 1 summarizes their names and

[1] Later, IERN became part of the *International Confederation of Energy Regulators* (ICER). More details are available on www.icer-regulators.net.

[2] For instance, the USA state-level regulators have competence over the placement of transmission lines (which typically extend across borders), whereas the Federal Energy Regulatory Commission (FERC) is in charge of the regulation of their tariffs.

[3] For instance, there are 13 regulatory authorities in Brazil, but only 10 are listed on the IERN website; similarly for India, where there are 26 ERAs but only 20 were included. Also, there are two separate agencies (one dealing with electricity and one with hydrocarbons) in Argentina, Bolivia, Kazakhstan and Pakistan (unfortunately no information were available about them). In the United Kingdom, there is a GB regulator (OFGEM) and a Northern Ireland regulator (NIAUR). In Romania, there are two regulatory bodies: one is the Romanian Energy Regulatory Authority (ANRE) and the other one is the National Regulatory Authority for Municipal Services (NRAMS). In Bosnia-Herzegovina, there are three energy regulatory authorities but only the national one, SERC, is on the database. The state of Alberta has two different regulators, one for oil & gas and one for utilities (with only the latter one included in this analysis). Additionally, there exists a regulator for a peculiar electricity interconnection system, acting among Guatemala, Panama, Honduras, El Salvador, Nicaragua, Costa Rica, and it is called SIEPAC, the Central American Electric Interconnection System; whereas, the regulator is the Regional Electric Interconnection Commission, CRIE. Set in Guatemala City, it serves as regulator for the new regional wholesale market and its board is formed by one representative from each country.

Table 1
Overview of the *Regional Regulatory Authorities*, with their Acronyms, full Names and Web-site.

ACRONYM	♯	RRAs NAME	WEBSITE
AFUR	5	African Forum for Utility Regulators	www.afurnet.org
ARIAE	8	Asociacíon Iberoamericana de Entidades Reguladoras de la Energía	www.ariae.org
CAMPUT	6	Canada's Energy and Utility Regulators	www.camput.org
CEER	26	Council of European Energy Regulators	www.ceer.eu
EAPIRF	1	*East Asia and Pacific Infrastructure Regulatory Forum*	www.eapirf.org
ERRA	20	*Energy Regulators Regional Association*	www.erranet.org
MEDREG	12	*Association of Mediterranean Regulators for Electricity and Gas*	www.medreg-regulators.org
NARUC	18	*National Association of Regulatory Utility Commissioners*	www.naruc.org
OOCUR	2	*Organization of Caribbean Utility Regulators*	www.oocur.org
RERA	3	*Regulators Association of Southern Africa*	not available
SAFIR	1	*South Asia Forum for Infrastructure Regulation*	www.safirasia.org
RAERESA	1	*Regional Association of Energy Regulators for Eastern and Southern Africa*	not available

Table 2
Response Rates within the *Regional Regulatory Authorities* for electricity and gas markets. Note first that EAPFIR, OOCUR, SAFIR and RAERESA have been omitted since only a few of respondents was covered. Secondly, to ease comparisons across similar ERAs, Russia and USA (both FERAs) have been excluded from ERRA in the computations for electricity, and Canada (FERA) from CAMPUT in the computations for gas.

	AFUR	ARIAE	CAMPUT	CEER	ERRA	MEDREG	NARUC	RERA
Electricity	16%	30%	43%	100%	55%	44%	28%	33%
Gas		15%	29%	100%	39%	26%	21%	

acronyms[4] providing in addition the number of members answering to IERN surveys; whereas, ERAs' details are reported in Tables A.8, A.9 and A.10, together with their country names (later used in the analysis for simplicity), their geographical location, affiliations to RRAs, and regulated sectors. Table 2 shows instead the rate of response within regional associations and across market sectors.

As far as respondents are concerned, we do not know their roles and we assume that they were in charge of undertaking this duty, hence representing our source of trustable information. As far as surveys are concerned, they were built considering generation/production, transmission, distribution and retail sectors in both the electricity and gas markets. Questions were addressing regulators' activities in eight fields: regulation, access rules, tariffs, unbundling, investment planning, quality standards, cross-border activities, and congestion & balancing; these are indicated with numbers and listed in the first column of Table 3. Then, the segments covered by the surveys are identified by capital letters and concur to form the macro-structure of the surveys. More precisely, the inquired segments were: regulation of generation (G.1), generation & wholesale tariffs (G.3); regulation of transmission (T.1), access rules for transmission (T.2), transmission tariffs (T.3), unbundling in transmission (T.4), investment planning in transmission (T.5), quality standards for transmission (T.6), cross-border disputes in transmission (T.7), congestion & balancing in transmission (T.8); regulation of distribution (D.1), access rules for distribution (D.2), distribution tariffs (D.3), unbundling in distribution (D.4), investment planning in distribution (D.5), quality standards for distribution (D.6); retail regulation (R.1) and retail tariffs (R.3). In addition, other issues concerning *consumers' protection*, *security of supply*, *environment issues*, and *energy efficiency* were considered.

Looking in details at the regulatory tasks investigated and so at the micro-structure of the survey, the five tasks inquired were: the ways of *regulation*, *making* and *enforcement powers*, as well as *powers to settle disputes*, and finally *monitoring activities*. These tasks are summarized in the first column of Table 4, where a sample of questions asked and possible answers have been included; whereas, the complete structure of the surveys is presented in Appendix B. Questions were of "check-all-that-apply" type, and each possible reply (which was a simple check) has been considered as a single "yes/no" answer. Therefore, regulators were allowed to provide multiple non-mutually-exclusive answers. Given the nature of these data, techniques of exploratory data analysis have been used to uncover hidden patterns. More specifically, the Shannon's entropy index and cluster analysis are considered.[5]

3. Methodology

As anticipated, in order to assess the similarity in ERAs' statutory activities, the Shannon's *entropy* (or *heterogeneity*) index and *cluster analysis* are implemented.

On one hand, the Shannon's index refers to a measure able to capture the diversity or the dissimilarities in replies while accounting for admissible answers and the real number of replies. It is a synthetic measure which indicates the extent to which regulators provided different answers implying dissimilar tasks (or the same answers, hence suggesting similar tasks). Other applications are in [16], who use this index to quantify the diversity in energy sources to assess the impact of RES penetration on energy security, and in [17] who instead use a modified version of the Shannon's index, including a correction factor, to measure the diversity in the fuel mix when assessing the energy security in Europe. On the other hand, cluster analysis is used to create groups in a way that regulators in the same cluster show similar profiles or, in other words, similar tasks. In what follows, the two techniques are described.

3.1. The Shannon's entropy index

This index was proposed by Shannon (1948) to quantify the qualitative diversity in text strings (often called uncertainty or "entropy") and it is used in this analysis to unveil the dissimilarity in energy regulators' replies.

Formally, let K be the number of categories (which are all the possible answers to one of the survey questions), n_i be the number of answers falling in the ith category (or the "checks" provided) with

[4] For further details as well as their geographical location, an interested reader can visit http://icer-regulators.net/icer-members/. Last accessed in May 2022.

[5] The ordinal approach has been discarded, since this would have implied establishing orders of importance in the replies according to a subjective judgement; and, regulators' replies were treated as nominal ones. Furthermore, the construction of an index has been avoided, since it would have been expressed in a numerical coded scale assigning arbitrarily ordinal numerical weights to variables that are not quantitative by nature. It is important to remind that the primary aim of these surveys was descriptive and they were not aimed at ranking regulators or assessing them in terms of their merits or demerits.

Table 3
Macro-structure of investigated activities across market sectors.

Fields of activities	Generation	Transmission	Distribution	Retail
1. Regulation	✓	✓	✓	✓
2. Access Rules		✓	✓	
3. Tariffs	✓	✓	✓	✓
4. Unbundling		✓	✓	
5. Investment Planning		✓	✓	
6. Quality Standards		✓	✓	
7. Cross-border activities		✓		
8. Congestion & Balancing		✓		

Table 4
Micro-Structure of investigated tasks, questions and possible answers.

Tasks with ID	Questions	Possible answers
A - Regulation	*How do you regulate?*	1. Authorization 2. Tendering 3. License 4. Any other authorization procedure 5. Other
	What type of entry point do you regulate? (only for Gas)	1. Storage terminals 2. LNG terminals 3. Interconnectors 4. Production terminals 5. Others
B - Powers	*What powers do you have?*	1. Setting of rule 2. Proposal of rule 3. Approval of rule 4. Other
C - Monitoring	*Do you monitor?*	Yes/No
D - Enforcement	*What enforcement powers do you have?*	1. Request of information 2. Publication of letters/reports 3. Issue of penalties 4. Issue of opinions 5. Imposition of your decision 6. Other
E - Dispute Settlement	*How do you settle disputes?*	1. Hearing 2. Arbitration 3. Actual Settlement 4. Other

$i = 1, 2, \dots, K$, and $n = \sum_i n_i$ be the total number of answers. Then, the proportion of cases falling into the ith category (i.e. the relative frequency) is given by $p_i = n_i/n$. The *Shannon's entropy* index is denoted by H and it is defined by

$$H = -\sum_{i=1}^{K} p_i \log(p_i), \tag{1}$$

where the convention $0 \log(0) = 0$ is used if one of the frequencies vanishes. When all categories are equally common (indicating diversity in the answers), all p_i values are equal to $1/K$, hence the index takes the value $\log(K)$. If all answers are concentrated in one category (and the others are rare), the Shannon entropy index approaches zero (that is there is no diversity). Therefore, these limits indicate the maximum and minimum possible dissimilarity or heterogeneity. Given that all regulators can "check all that apply", it is possible to observe more than one answer to each question. To accommodate this feature, all given answers have been taken into account in the computation of n. Missing values were treated in the following way: firstly only regulators who completed the whole survey were considered, and secondly, provided comments were used to fill the missing answers.

The *index of relative heterogeneity*, here indicated for simplicity by IRHE (or IRE in short), is obtained by normalizing this measure, that is by dividing H by its maximum value, formally

$$IRE = \frac{H}{\log(K)}. \tag{2}$$

This new index ranges between 0 and 1, indicating respectively minimum and maximum dissimilarity or heterogeneity. For convenience, its complement to one is often considered and it represents the *index for relative homogeneity*, indicated with IRHO (or IRO in short):

$$IRO = 1 - IRE. \tag{3}$$

Consequently, the latter index indicates the "similarity" which more intuitively associates higher similarity with higher values. To better explain its functioning, one computation is described in details. Consider the question *How do you regulate the construction of new generation plants?* in the electricity survey, and its four possible answers among "tendering, licence, any other authorization procedure, and other". The focus here is on replies provided by 25 EU members. In this example, the *field of activity* and the inquired *task* are both the 'regulation', that is field **1** and task **A** for generation (that is question **G.1.A** of the survey).

For this question, there are $K = 4$ categories of possible answers, that is $i = 1, 2, 3, 4$, with $i = 1$ for 'tendering', $i = 2$ for 'licence', $i = 3$ for 'any other authorization procedure' and $i = 4$ for 'other' (note that the ordering of categories is not important given that the index is based on frequencies). The following sequence of absolute frequencies is observed: $n_1 = 1$ answer for 'tendering', $n_2 = 12$ for 'licence', $n_3 = 4$ for 'any other authorization procedure' and $n_4 = 1$ for 'other'. Hence, the total checks were $n = n_1 + n_2 + n_3 + n_4 = 18$, meaning that some regulators did not provide any answer (indeed there are only 18 answers for 25 ERAs). Then, the corresponding proportions (or relative frequencies) are computed as $p_i = n_i/n$, and they are respectively $p_1 = 0.056$, $p_2 = 0.667$, $p_3 = 0.222$ and $p_4 = 0.056$. Taking their product with the logarithms, and adding them up across all 4 categories, H is obtained from Eq. (1). Dividing it by $log(4)$ as in Eq. (2), $IRE = 0.668$ and equivalently $IRO = 0.332$. This means that there is low homogeneity

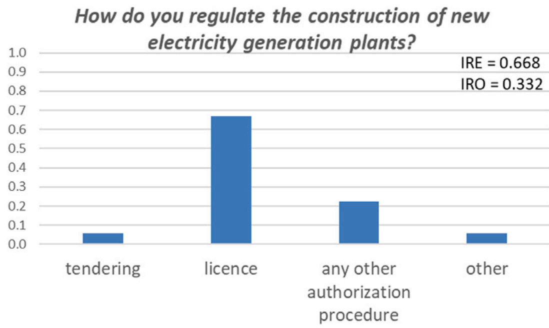

Fig. 1. Example of Heterogeneity among EU Regulators' Replies to the Question **G.1.A** in the Electricity Survey on *How the Construction of New Generation Plants is Regulated.*

or similarity in regulators' answers, and indeed the answers spread among all possible choices as graphically shown in Fig. 1. This is a clear indication that EU ERAs adopted dissimilar practices in the regulation for the construction of new generation plants.

Besides assessing the similarity (homogeneity) or the diversity (heterogeneity) in the answers *across* the regulatory authorities, discovering how far the regulatory authorities are 'from each other' with respect to their statutory activities was an additional intriguing question. Therefore, the diversity *between* regulatory authorities (as per the statutory activities investigated) has been assessed with cluster analysis.

3.2. Cluster analysis

Among tools of statistical learning, cluster analysis can provide a suitable solution for modeling and understanding complex data. Moreover, unsupervised statistical learning can build relationships in the data and we can learn from those resulting structures (i.e. distinct clusters), without the need of considering an output based on one or more inputs as it occurs for supervised statistical learning.

In this regulatory framework, we aim at understanding the (dis)similarity among regulators and cluster analysis, or clustering, can ascertain if regulators fall into relatively distinct groups, on the basis of the answers they provided. It is clear that identifying these groups is interesting since it can help regulators to monitor if an energy policy convergence has occurred.

As clustering is a method for discovering unknown subgroups in data, ERAs are classified into groups according to their replies. ERAs in the same cluster share similar profiles (that is they have similar tasks), whereas those belonging to different groups have dissimilar profiles. The aim is to understand how regulators are grouped together according to the similarity in their practices. Therefore, the point where ERAs (reported by the name of the country they belong to) entry the tree is considered without looking at the 'optimal number' of groups. When some countries appear detached from the rest of one tree, it is because the corresponding ERAs have provided different replies from the majority of ERAs, hence increasing the distance between themselves and the rest of the other ERAs. Indeed, the measure of "distance" used for these binary data is the key instrument to implement this analysis. It is worth emphasizing that here a low number of detected groups indicate that several regulators share the same practices, whereas as soon as the number of groups increases then more distinct practices are adopted and we are more far away from a global energy policy convergence. The methodology is briefly summarized below.

Among clustering techniques, the hierarchical agglomerative clustering has been adopted. This classifies ERAs into groups starting from fusing similar individual ERAs, and then fusing most similar groups into a final single group, called the "root" of the tree. The resulting graph, called *dendrogram*, summarizes graphically the clustering pattern showing the combination of progressive fusions as a result of the computed distance across groups. The ERAs' order appearing in the dendrogram is the order in which the groups enter the clustering without making any pre-determined and subjective assumptions. ERAs belonging to the same group differ from other groups, and different groups are identified any time that an increment in the distance is observed. The clustering strategy starts looking at similarity (or distance) of considered ERAs and fuses those with the highest similarity (or smallest distance). The two groups with the highest similarity are fused, and the relationship of the fused group to all other groups is recalculated using a combinatorial algorithm until only one group is left; see [18] for further details. To summarize, this technique has been implemented in the following way. Firstly, given the nature of the qualitative binary variables,[6] the *Jaccard's similarity coefficient* is computed as distance metric between ERAs' pairwise comparisons across all questions in the dataset, verifying when there are concordant answers. Indeed, it considers only those replies that are common to the respondents and this means, in our case, only the tasks that regulators have. Secondly, ERAs are grouped into a binary hierarchical cluster tree using the "complete" linkage function,[7] also known as the *furthest neighbor* since it uses the largest distance between objects in the two clusters, making groups appear more clear–cut. Thirdly, the *dendrograms* are plotted with ERAs on the x-axis and the Jaccard's similarity index on the y-axis, in a reverse order from higher to lower values, that is going from 1 in the origin (representing the maximum similarity) to zero in the upper bound (indicating the maximum dissimilarity). Therefore, the higher the tree, the higher is the distance among the clusters, and the lower is the similarity among ERAs.

Cluster analysis has been implemented using Stata considering different groups of ERAs to distinguish across jurisdictions (disentangling between federal, national and state or European ERAs), segments (generation/production, transmission, distribution, retail) and markets (electricity and gas).

4. Empirical results

4.1. Similarity across regulators

Results have been organized considering first ERAs jurisdictions, and then their regional associations. It is worth recalling that the computation of IROs has been implemented over the relevant *tasks* (A,B,C,D,E as listed in Table 4) for the considered *activities*. For instance, note that the IRO = 0.332, computed from the answers provided by the EU ERAs to question **G.1.A** and depicted in Fig. 1, is now reported in Fig. 2 for regulation together with the other tasks covered. The same representation is adopted in Figures C.12-19, where similar tasks over activities are considered for both markets and all segments while disentangling for jurisdictions.

The graphical representations with computed IROs show that regulators' replies are distributed rather equally across reply options. Overall, there are no remarkable similarities and it can be concluded that regulators' activities differed widely in 2011. It is interesting to observe that this analysis reveals diversity across activities and tasks even among supposedly homogeneous groups, as the European regulators.

[6] These variables have only two categories: checks are meant to represent competencies regulators' have, and 1 is used to code their 'presence'; whereas non-checks are competencies they do not have and zero is used to represent 'absence'. To this aim, the 'co-presences' are more important than the 'co-absences', thus this distance seems more appropriate because it is obtained by counting only the matches between two ERAs' replies.

[7] Other linkage functions are (i) the "average", which uses the average distance between all pairs of objects in any two clusters; and, (ii) the "single", called also the *nearest neighbor*, which uses the smallest distance between objects in the two clusters and then making groups appear closer than they actually are. Hence, the "complete" one is found to be the most suitable for this analysis.

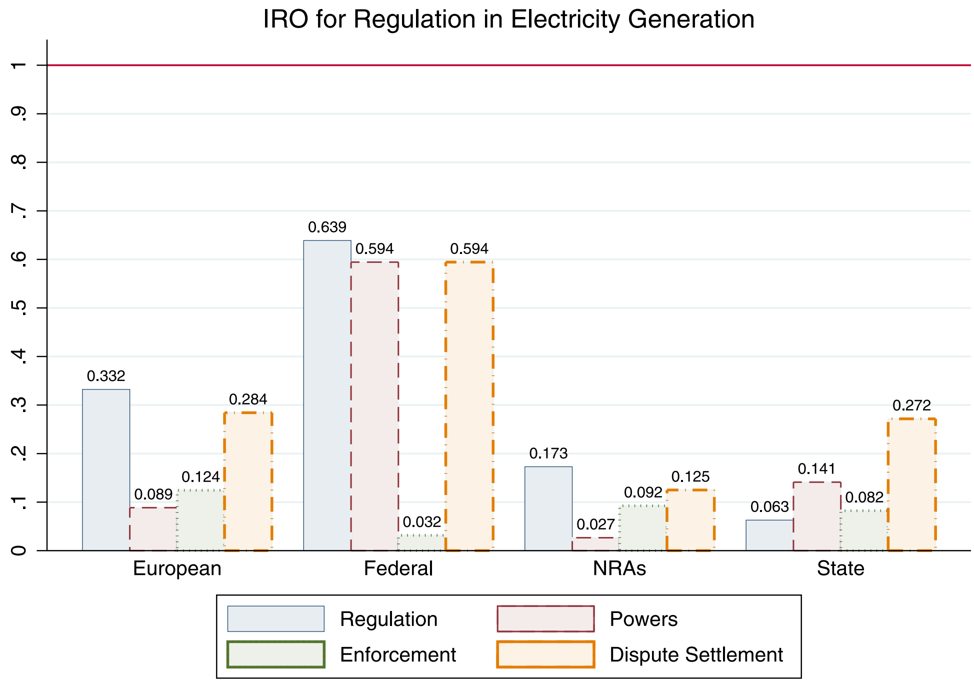

Fig. 2. IROs across tasks A (regulation), B (powers), D (enforcement powers) and E (Dispute Settlement) for the Field of Activity ♯ 1 *Regulation* in the Electricity Generation. This is part of Figure C.12. Note IRO = 0.332 for answers provided by EU ERAs to question **G.1.A**, as in Fig. 1.

However, it must be noticed that dissimilarity is least pronounced for federal authorities, which exhibit instead high values but usually they correspond to lack of powers, as for the first field of activity inspected, that is for the *Regulation* of transmission, distribution and retail tariffs (depicted in Figure C.12 for both electricity and gas markets). Indeed, IROs equal to one (implying perfect similarity or equivalently zero diversity) are obtained when all replies were concentrated in one answer or also when no checks/answers were provided. The replies of FERAs display lower dissimilarity compared to those of NERAs or SERAs, whereas slightly higher similarity is observed when European ERAs are considered. Energy regulators in federal countries show low dissimilarity due to the different competence over transmission that federal and state-level regulators' authorities have. It is worth mentioning that the American federal regulator *FERC* has exclusive competence over access rules to the transmission grid and transmission tariffs. Instead, the Australian federal regulation is handled by two entities: the *Australia Energy Market Commission* (AEMC) who 'writes the rules', and the *Australian Energy Regulator* (AER) who 'enforces the rules'. Both AEMC and AER coexist in the longest transmission network encompassing several territories and managed by the *Transmission System Operator* (AEMO). Thus, this results in Australian SERAs appearing to be less involved into the transmission sector. On the other hand, the Canadian federal regulator *National Energy Board* (NEB) has very different features from those of the US and Australian counterparts, in that it mainly deals with international issues and cross-border interconnections, while the regulation of transmission is left to provincial (state-level) authorities. An historical fact that may help the understanding is that the American and Canadian regulatory institutions were established as tribunals to deal with utility-related disputes and complaints. IROs are slightly higher across all gas segments, although we observe overall considerable variation.

Looking at market sectors, generation shows low similarity across jurisdictions (excluding FERAs in electricity). In details, regulators' replies show that most of them play no role in ex–ante regulation of construction of new generating plants; this is true also for EU ERAs and it is in line with the liberalization process undertaken at the EU level.[8] As far as transmission, distribution, and retail are considered, the former two segments are natural monopoly and naturally regulated; whereas, retail should be less regulated. In Europe we assisted to a progressive liberalization, however it appears more regulated than generation and transmission in both electricity and gas markets.

It is interesting to observe that regulators' comments clearly state that powers are conditioned on existing legislation; for instance, there are specific (regulatory) powers in generation when plants are essential to the security of supply. When moving vertically across sectors, the (low) similarity in regulation increases from generation to retail showing that regulators seem to answer slightly similarly: they opt for providing a licence or other authorization procedure instead of tendering. The IROs indexes for regulation from generation/production and transmission to distribution and retail respectively in electricity (in gas) range: from 0.332 (0.134) and 0.347 (0.388) to 0.572 (0.388) and 0.543 (0.547) for EU ERAs; the index goes from 0.173 (0.105) and 0.203 (0.301) to 0.307 (0.292) and 0.504 (0.458) for NERAs; from 0.063 (0.354) and 0.118 (0.135) to 0.109 (0.083) and 0.136 (0.154) for SERAs. It is remarkable that the index jumps to half point when electricity retail is considered, and this could be due to the liberalization of the sector undertaken in those years. Similar comments however apply to all other investigated fields as it can be easily detected in Figures C.13–C.19.

Overall, these results show that regulators' answers were distributed heterogeneously across all possible answers of the five questions on tasks (see Table 4). This is a clear indication that regulators follow different practices across activities and fields, as documented in 2011. Also Figs. 3, 4, 5 and 6 clearly show respectively that regulators undertake inhomogeneous regulatory practices to address the *security of supply*, the *energy efficiency*, *environmental issues* and the *consumers' protection*.

[8] Indeed, regulators' comments explain that generally (i) there are no powers, given that generation is fully liberalized (in Sweden); but in some cases (ii) regulator issues licences and licensing rules, and provisions are conditioned on existing legislation (in Poland) or are limited to environmental issues and to a positive socio–economic impact assessment (in Norway).

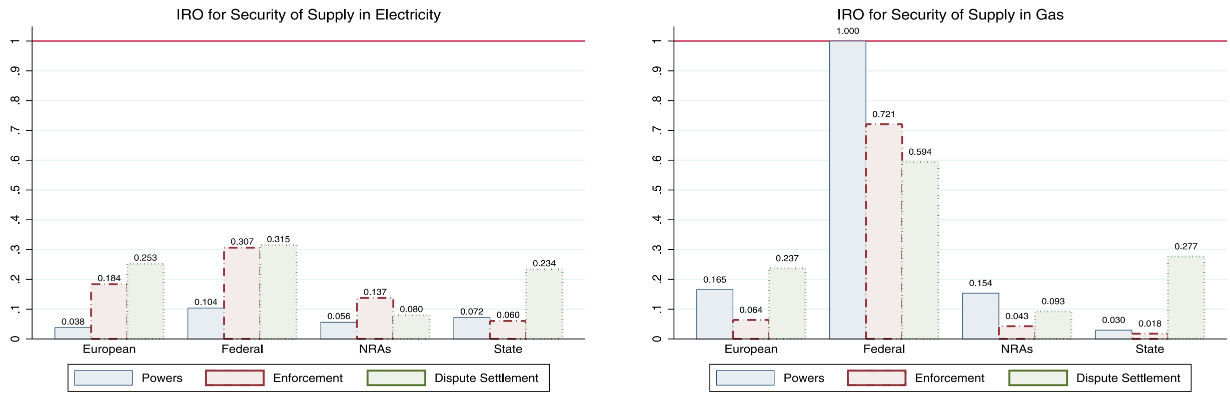

Fig. 3. IROs for *Security of Supply* in Electricity (on the left) and Gas (on the right) Sectors.

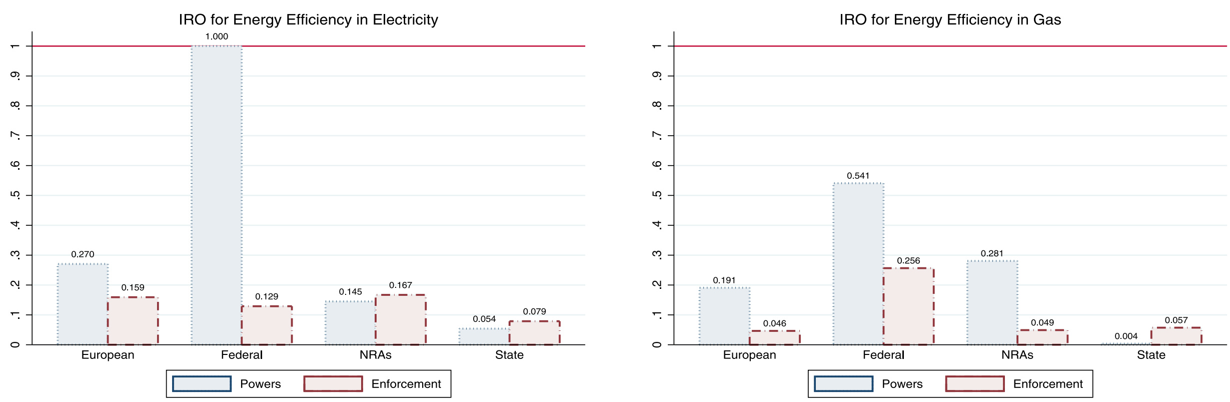

Fig. 4. IROs for *Energy Efficiency* in Electricity (on the left) and Gas (on the right) Sectors.

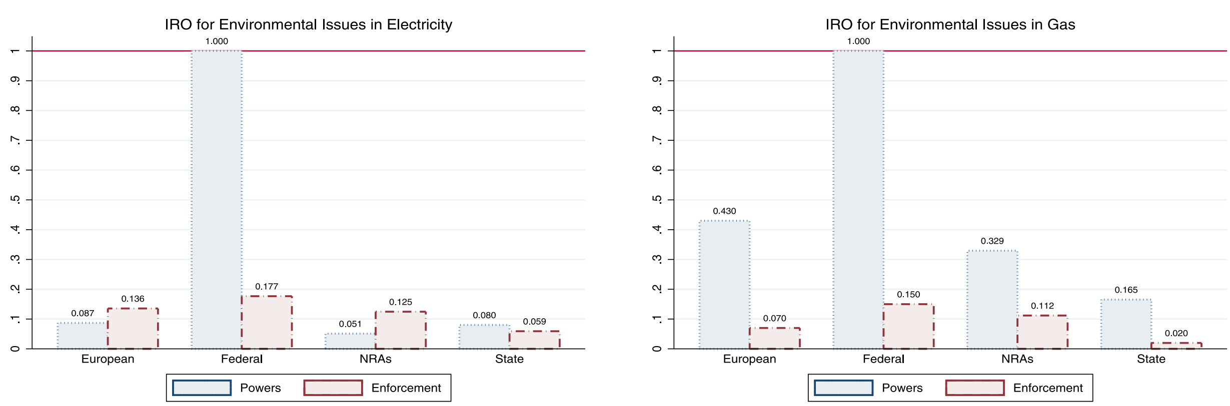

Fig. 5. IROs for *Environmental Issues* in Electricity (on the left) and Gas (on the right) Sectors.

4.2. Similarity between regulators

Moving to the analysis of similarities across *regional regulatory associations* (RRAs), IROs across associations are computed for electricity and gas, and results are presented in Tables 5 and 6 respectively. It must be emphasized that the analysis on RRAs has been conducted with some ad-hoc exclusions to account for jurisdictions. Hence, FERAs have been excluded from all RRAs, as well as associations with only one member or two members with few answers, whereas members included in the computations have been reported. Note that a color scale green-yellow-orange has been adopted for the highest, medium and lowest values of the index and that there are nine RRAs investigated for the electricity market, whereas only six for gas.

When electricity is considered, RRAs generally show from low to moderate similarity in both electricity and gas sectors. In the former case, only AEMC is characterized with high values, consistently across electricity segments and fields. Whereas, when gas in concerned, only CAMPUT regulators show high similarity. However, it must be emphasized that AEMC is not a proper RRA, the similarity index has been computed across its ERAs to understand the degree of similarity in electricity practices among its countries. Note that New South Wales, Tasmania, Western Australia and Australia Capital Territory have been considered, whereas the FERA for Australia has been excluded from the computations and, interestingly, full homogeneity is detected across all electricity segments apart from retail.

Going into further details, AFUR regulators are inspected only for electricity. They are generally characterized by heterogeneity in tasks and competencies among all segments. Indeed, IORs range between maximum diversity (with $IOR = 0$ in the settlement of disputes for investment planning in transmission) to maximum similarity (with

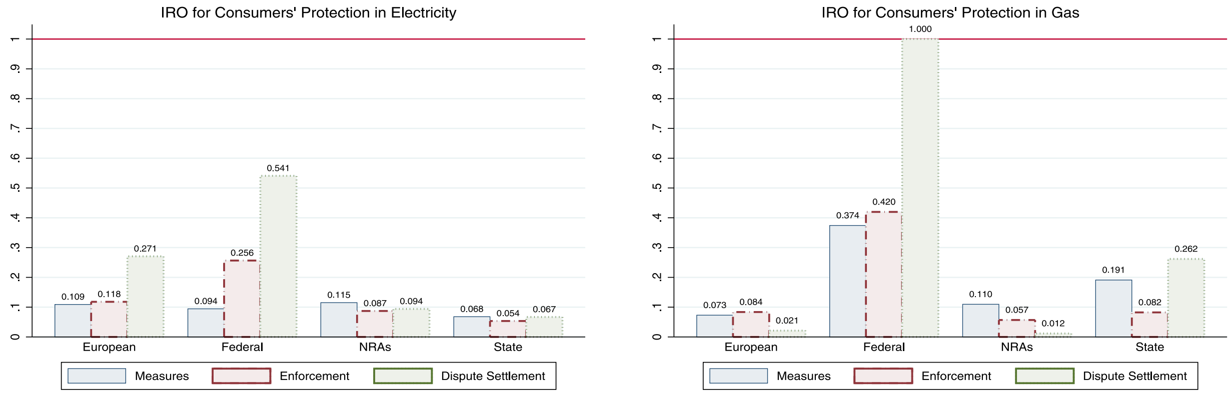

Fig. 6. IROs for *Consumer Protection* in Electricity (on the left) and Gas (on the right) Sectors.

$IRO = 1$ in powers concerning unbundling of distribution activities). This provides a picture in which (regulators in) Algeria, Cameroon, Tanzania, Togo and Zambia seem to adopt different practices. They show a moderate similarity, as for instance in powers for determining generation tariffs, in powers for unbundling transmission activities, or in regulating retail activities; with IROs constantly equal to 0.594.

ARIAE respondents are prevalently characterized by heterogeneity in tasks and competencies among all electricity and gas sectors, so implying that they adopt different practices. Moderate similarity is observed in the settlement of cross-border activities in electricity transmission ($IRO = 0.541$), in the regulation of the retail sector and in powers concerning the unbundling of transmission (both with $IRO = 0.5$). As far as gas is concerned, it must be clarified that perfect similarity is observed in the regulation of retail activities (with $IRO = 1$) only because there were no ARIAE members answering to that question; then we may assume that they have no competence in that task.

CAMPUT respondents are generally characterized by moderate or high similarity with regulators showing more homogeneous tasks and competencies in the gas market. It is interesting to observe that maximum similarity ($IROs = 1$) is observed for the settlement of disputes in electricity transmission, for cross border activities as well as in unbundling, with moderate similarity for the management of congestions and the system balancing, planning investments and retails. This is not surprising since the settlement of disputes between regulators and transmission system operators is a distinctive competence of North-American regulators; while is less common among EU regulators, since it is often delegated to other public bodies. Higher similarity is observed in gas, however, it must be emphasized that only few checks were identified hence resulting often in perfect similarity (even if regulators actually did not provided any answers). This occurs especially in production and cross-border activities in transmission, and it can be also due to the fact that the Canadian federal agency (the *National Energy Board*) has competencies almost exclusively over electricity and gas imports/exports at the international and inter-provincial levels.

CEER respondents are characterized by low and medium homogeneity in all sectors of both markets. Overall, IROs indicate moderate similarity across regulators, with maximum values observed in the regulation of electricity distribution ($IRO = 0.539$) and in the regulation of gas retail ($IRO = 0.504$). These results are surprising given the EU arrangements for the implementation of the *internal energy market* (IEM). However, note that the instruments used by the EU Commission to regulate the IEM are communications and directives which allow for national implementation considering local market structure and legislation, with suggested deadlines which are often not respected. Therefore, different speeds of implementation and market development are commonly observed, and this may explain the differences in regulators' practices.

ERRA respondents are generally characterized by heterogeneity in tasks and competencies among all electricity and gas markets. However, higher similarities are observed in regulating transmission, distribution and retail, with values 0.639, 0.705 and 0.680 in electricity and 0.814, 0.566 and 0.814 in gas. It must be noted that ERRA members do not aim at the creation of an internal energy market, as for CEER. ERRA's main purpose is to foster the development of competent and autonomous ERAs and promote exchange of experiences and information. To this end, ERRA has a wide annual program of training courses for members and non-members, and this could explain its high values indicating a shared practice among participants.

MEDREG countries are characterized by heterogeneity and moderate heterogeneity in tasks and competencies among all electricity and gas sectors. Full homogeneity in its members' replies is found only in regulating electricity transmission ($IRO = 1$) and in powers for the determination of tariffs for gas production and retail. Moderate similarity is observed in few cases in electricity as for the settlement of disputes in planning investments in transmission ($IROs = 0.515$) and in regulating distribution ($IRO = 0.594$), whereas it is more common to observe (medium) similar regulatory practices in gas as for instance for unbundling, investment planning and cross border activates in transmission. It should be recalled that MEDREG, like CEER, is a voluntary initiative involving regulators facing the Mediterranean thus including several, but not all, EU member states, Northern Africa and the Balkans, as well as Turkey. At the time of inquiry, MEDREG was young since it was created in 2007, and therefore it was reasonable to expect the heterogeneity characterizing its regulators' practice. However, more important than differences are aspects of similarities considering the variety of origins in its members: some regulatory convergence was already detected in 2011, and it would be interesting to observe if that process continued through more recent years.

NARUC respondents show homogeneity and moderate homogeneity in electricity and gas transmission, in the former case especially as far as tariffs, cross border, congestions and balancing activities are concerned; in the latter case, also for regulation of production and unbundling. These results are due to the fact that state-level regulators in the US only have competencies within their jurisdictions, and the federal agency (FERC) is the reference authority for interstate and cross-border transmission of electricity, oil and gas.

RERA respondents are Mozambique, South Africa and Tanzania. They only regulate electricity and are characterized by full homogeneity in powers concerning unbundling activities of electricity transmission and distribution, as well as in regulating distribution and retail activities, whereas in other competencies they show dissimilar practices.

Overall, based on the index for relative homogeneity, we can conclude that in 2011 regulatory practices differed widely across regulators' regional associations, even among groups expected to act more homogeneously because of historical relations or political influences. Therefore, the following analysis is implemented to unveil regulators' clusters of similar practices, this time not driven by their institutional membership but only considering their jurisdictions.

4.3. Regulators' clusters

Besides assessing the similarity across institutional memberships, we examine the similarity among regulators themselves leaving cluster analysis to discover regulators' groups with similar activities, tasks and practices. Let us recall that if common practices are spread across ERAs, then a limited number of groups is expected to emerge.

Dendrograms from cluster analysis for electricity and gas across jurisdictions and topics are presented in Figs. 7–11. However, an high-level summary is provided in Table 7, to summarize the number of groups over the total number of responding ERAs.

Given the high number of clusters compared to the number of countries, cluster analysis confirms the findings emerged with the IROs indexes, and the message is crystal clear: ERAs differ substantially in both markets according to energy regulatory tasks and activities put in place in 2011. From the resulting dendrograms, it can be observed that the trees split several times at low levels of similarity for all types (national, state, federal, or European) of ERAs, as indicated by the Jaccard index decreasing from 1 (maximum similarity at the bottom of the trees) to zero (maximum diversity at the root of the trees).

While SERAs cluster more coherently according to their geographical location, NERAs from extremely different countries (and RRAs) surprisingly cluster together. This finding could be due to the construction of the surveys and to the fact that regulators can have 'many' or 'few' powers with similarity detected also for no answers provided: this is a limitation of the analysis. However it is worth emphasizing that this study represents the first explorative attempt to understand if world energy regulators adopted similar tasks and activities as inquired in 2011; whereas, future qualitative analyses are recommended to investigate in more details the regulatory regimes across different countries. Even though, some patterns of geographical proximity emerged, as for the cluster of Austria, Denmark and Germany or for the one of Bulgaria, Poland, Czech Republic, and Hungary as far as NERAs in electricity are concerned. And surprisingly, low similarity was found for Scandinavian regulators despite their integration in NordPool: Denmark, Sweden, Norway and Finland expected to cluster together appear instead split and belonging to different clusters.

Because of the existence of a common legal framework for energy markets developed in EU legislative packages for the creation of the internal energy market, European NERAs were expected to show the most remarkable similarity. However, differences among EU regulators emerged and the observed low similarity could be due to the fact that each regulator tried to adapt the EU directions to its own internal legislation.

As SERAs are concerned, similarity is observed in activities of regulators from American states and Canadian provinces, given the long history of regulation in Canada and USA. Moreover, it is natural to observe Australian regulators behaving similarly to their Canadian and US counterparts because of their similar state-level jurisdiction.

Furthermore, NERAs from Latin America, the Caribbean, Eastern Europe, Asia and the Middle East are also expected to display similarity due to international influences. However, these countries were exposed to several influencers, as for instance the World Bank in Latin America and in the Caribbean, or also the USAID in Eastern Europe; and this could have contributed to generate further differentiations. Then, adaptations to the local context produced a high degree of dissimilarity and heterogeneity in tasks and activities, hence resulting in many small clusters rather than in few expected ones with a large number of regulators. Our results reveal that worldwide energy regulators adopted considerably different and context-specific practices in both electricity and gas markets in 2011. Despite formal and informal international cooperations, dissimilarities are generally observed also for *other issues* with few important exceptions. Indeed, for the first time we observe some clusters of perfect similarity in these topics, with countries grouping together at the root of the trees.

When *consumers' protection* is considered, it is interesting to observe that there are few occurrences in which ERAs show perfectly similar practices, examples are: Bosnia, Cameroon, Jamaica, Island and Mexico, as NERAs in electricity; Finland, Hungary and Luxembourg as NERAs and European ERAs in gas (see Fig. 8). When we move to *energy efficiency*, 4 clusters of 28, 4, and 2 NERAs are immediately determined in electricity; whereas, 5 clusters of 7, 2, 3, and 5 NERAs appear in gas. When we focus on EU ERAs, two clusters are immediately detected since 15 and 2 ERAs show perfect similarity in electricity. Whereas, 3 clusters of 5, 2, and 4 ERAs are found in gas (see Fig. 9). Practices for *environmental issues* identify 5 clusters of 5, 2, 3 and 17 NERAs immediately in electricity, and 4 clusters of 5, 2, 4 and 5 NERAs in gas. Surprisingly, only 3 clusters of 2, 3 and 5 European countries were identified in electricity, whereas 4 clusters of 3, 2 and 4 EU ERAs emerge in gas (see Fig. 10). As *security of supply* is concerned, again 5 clusters are immediately detected in electricity and only 2 in gas (although of 2 and 14 NERAs in the former case, and of 4 NERAs in the latter one). Disconcertingly, only two clusters of 2 and 6 EU countries were identified in electricity, and two clusters of 3 EU ERAs in gas (see Fig. 11).

Unfortunately, these topics show only limited patterns of perfect similarity. And even if this can be considered a good starting point, nowadays there is an extremely urgent need for a global energy policy convergence to reduce emissions and grant secure energy supply.

5. Discussion & conclusions

Nowadays, it is sad to observe low similarity for all tasks related to the *security of supply* (Fig. 3) and to the *energy efficiency* (Fig. 4), in both electricity and gas markets. In 2011, nobody was expecting what is currently occurring with the urgent need of granting the security of energy supply, trying to reduce, for instance, the EU dependence from (Russian) gas while improving energy efficiency; see [19,20]. Certainly, these fields need prompt and severe actions. At the same time, special attention should be paid to environmental issues, especially in these years in which we are assisting to a surge of coal generation replacing the reduced gas imports in some countries or the increased usage of gas generation in others. [21] describe the geopolitical implications of renewables, and how they can reshape the policies of energy security across countries, the cross-country collaborations and how renewables can induce conflicts for minerals required by these new renewable energy technologies.

Regulators should carefully consider that methane emissions are currently increasing, more than carbon emissions, and so feeding the worldwide environmental concerns. Ouellette et al. [22] and Leitch et al. [23] discuss how the reduction of emissions may be obtained

Table 5
IROs computed for Electricity Segments, Activities and Tasks within RRAs. Note that the color scale is green, yellow, orange for the highest, medium, lowest values. AFUR: Algeria, Cameroon, Tanzania, Togo and Zambia (all NERAs). ARIAE: Dominican Republic, Guatemala , Honduras, Mexico, Peru', Spain, Uruguay (all NERAs). CAMPUT: Alberta, British Columbia, Newfoundland & Labrador, Nova Scotia, Ontario (all SERAs). CEER: all 26 members (NERAs). ERRA: Bulgaria, Croatia, Estonia, Hungary, Latvia, Lithuania, Macedonia, Poland, Romania, Slovak Republic, Serbia, Turkey, United Kingdom, Albania, Bosnia-Herzegovina, Jordan, Saudi Arabia, and Montenegro (all NERAs). MEDREG: Algeria, Croatia, France, Italy, Slovenia, Spain, Turkey, Albania, Bosnia-Herzegovina, Jordan, Malta, and Montenegro (all NERAs). NARUC: Alabama, Arkansas, Illinois, Kentucky, Maryland, North Dakota, Oregon, Pennsylvania, South Carolina, South Dakota, Maine, Massachusetts, Minnesota, Nebraska, Vermont (all SERAs). RERA: Mozambique, South Africa, Tanzania and Zambia (all NERAs). AEMC: New south Wales, Tasmania, Western Australia and Australia Capital Territory (all SERAs).

Segments	Field of Activity	Tasks	AFUR	ARIAE	CAMPUT	CEER	ERRA	MEDREG	NARUC	RERA	AEMC
Generation	Regulation	Regulation	0.304	0.239	0.270	0.295	0.379	0.277	0.011	0.239	1.000
		Powers	0.041	0.054	0.270	0.120	0.235	0.041	0.061	0.000	1.000
		Enforcement	0.051	0.179	0.169	0.120	0.159	0.188	0.078	0.114	0.258
		Settlement	0.222	0.215	0.374	0.300	0.247	0.082	0.274	0.270	1.000
	Tariffs	Powers	0.594	0.047	0.594	0.337	0.139	0.077	0.079	0.250	0.541
		Enforcement	0.116	0.147	0.159	0.104	0.106	0.144	0.184	0.127	0.613
		Settlement	0.208	0.108	0.270	0.239	0.111	0.250	0.675	0.270	1.000
Transmission	Regulation	Regulation	0.250	0.087	0.500	0.489	0.639	1.000	0.047	0.315	1.000
		Powers	0.285	0.077	0.157	0.159	0.113	0.270	0.017	0.250	1.000
		Enforcement	0.064	0.191	0.125	0.073	0.118	0.114	0.058	0.121	0.613
	Access Rules	Powers	0.047	0.020	0.222	0.141	0.256	0.237	0.239	0.500	1.000
		Enforcement	0.152	0.142	0.178	0.125	0.146	0.139	0.256	0.121	
		Settlement	0.124	0.223	0.125	0.106	0.050	0.106	0.594	0.297	0.594
	Tariffs	Powers	0.270	0.208	0.374	0.190	0.351	0.282	0.500	0.041	0.500
		Enforcement	0.200	0.139	0.156	0.115	0.145	0.165	1.000	0.134	0.613
		Settlement	0.270	0.253	0.541	0.218	0.129	0.250	0.500	0.297	0.500
	Unbundling	Powers	0.594	0.500	0.208	0.095	0.017	0.222	0.222	1.000	1.000
		Enforcement	0.436	0.242	0.420	0.115	0.125	0.178	0.016	0.131	0.645
		Settlement	0.270	0.239	1.000	0.130	0.155	0.039	0.125	0.500	1.000
	Investment Planning	Powers	0.270	0.125	0.374	0.155	0.489	0.422	0.047	0.208	1.000
		Enforcement	0.145	0.351	0.158	0.192	0.169	0.241	0.090	0.144	0.226
		Settlement	0.000	0.239	0.515	0.162	0.183	0.515	0.351	0.009	0.541
	Quality Standards	Powers	0.047	0.219	0.270	0.062	0.311	0.270	0.039	0.208	
		Enforcement	0.138	0.098	0.148	0.196	0.157	0.146	0.084	0.114	0.226
		Settlement	0.082	0.214	0.270	0.229	0.064	0.195	0.315	0.297	0.500
	Cross-border Activities	Powers	0.239	0.039	1.000	0.354	0.215	0.124	1.000	0.222	1.000
		Enforcement	0.135	0.163	0.420	0.119	0.175	0.286	0.645	0.154	1.000
		Settlement	0.208	0.541	1.000	0.289	0.161	0.297	1.000	0.079	1.000
	Congestions & Balancing	Powers	0.219	0.041	0.315	0.337	0.476	0.257	0.208	0.223	1.000
		Enforcement	0.150	0.263	0.258	0.086	0.171	0.258	0.602	0.154	0.613
		Settlement	0.541	0.250	0.515	0.151	0.155	0.088	1.000	0.500	1.000
Distribution	Regulation	Regulation	0.079	0.250	0.541	0.539	0.705	0.594	0.034	1.000	1.000
		Powers	0.222	0.239	0.276	0.225	0.194	0.230	0.042	0.208	0.500
		Enforcement	0.127	0.138	0.207	0.123	0.139	0.183	0.034	0.114	0.066
	Access Rules	Powers	0.125	0.208	0.219	0.215	0.279	0.135	0.097	0.276	0.594
		Enforcement	0.145	0.136	0.160	0.126	0.146	0.151	0.065	0.114	0.258
		Settlement	0.041	0.054	0.276	0.103	0.100	0.048	0.100	0.297	0.250
	Tariffs	Powers	0.222	0.077	0.297	0.330	0.245	0.270	0.161	0.047	0.250
		Enforcement	0.138	0.150	0.159	0.123	0.157	0.146	0.061	0.127	0.440
		Settlement	0.124	0.077	0.500	0.117	0.157	0.193	0.133	0.297	0.594
	Unbundling	Powers	1.000	0.239	0.208	0.209	0.084	0.250	0.106	1.000	1.000
		Enforcement	0.130	0.256	0.135	0.118	0.154	0.161	0.106	0.110	0.387
		Settlement	0.500	0.208	0.500	0.223	0.130	0.388	0.308	0.500	1.000
	Investment Planning	Powers	0.250	0.270	0.311	0.138	0.271	0.469	0.048	0.250	1.000
		Enforcement	0.145	0.322	0.178	0.159	0.195	0.208	0.057	0.127	0.387
		Settlement	0.039	0.208	0.500	0.155	0.171	0.277	0.224	0.297	1.000
	Quality Standards	Powers	0.250	0.208	0.239	0.143	0.389	0.290	0.122	0.219	0.039
		Enforcement	0.127	0.117	0.178	0.127	0.148	0.142	0.063	0.114	
		Settlement	0.541	0.214	0.515	0.123	0.039	0.165	0.256	0.507	0.541
Retail	Regulation	Regulation	0.594	0.500	0.594	0.404	0.680	0.374	0.099	1.000	0.541
		Powers	0.500	0.222	0.270	0.058	0.118	0.541	0.091	0.515	0.041
		Enforcement	0.150	0.112	0.112	0.098	0.110	0.218	0.072	0.137	0.193
	Tariffs	Powers	0.250	0.270	0.270	0.191	0.165	0.079	0.105	0.025	0.515
		Enforcement	0.137	0.153	0.127	0.114	0.198	0.233	0.071	0.134	0.268
		Settlement	0.250	0.039	0.041	0.088	0.187	0.058	0.105	0.541	0.047

by potential complementarities between the oil-gas sector and the technologies for geothermal energy or oil sands cogeneration, making carbon-intensive regions and sectors less pollutant and active contributors to the development of low-carbon technologies. Case studies based on experiences in Canada (Alberta) and in France have shown that it is not possible to have unique policy prescriptions to the adoption of a new technology. In their experience, varied attempts to coordinate the achievement of a geothermal transition have resulted in opposite

Table 6
IROs computed for Gas Segments, Activities and Tasks within RRAs. ARIAE: Mexico, Peru', Spain and Uruguay (all NERAs) and Brazil (FERA). CAMPUT: Alberta, British Columbia, Nova Scotia and Ontario (SERAs). CEER: all 26 members (NERAs). ERRA: Bulgaria, Croatia, Estonia, Hungary, Latvia, Lithuania, Macedonia, Poland, Romania, Slovak Republic, Serbia, Turkey and United Kingdom (all NERAs). MEDREG: Algeria, Croatia, France, Italy, Slovenia, Spain, and Turkey (all NERAs). NARUC: Alabama, Arkansas, Illinois, Kentucky, Maryland, North Dakota, Oregon, Pennsylvania, South Carolina, South Dakota, New Hampshire (all SERAs).

Segments	Field of Activity	Tasks	ARIAE	CAMPUT	CEER	ERRA	MEDREG	NARUC
Production	Regulation	Regulation	0.005	0.208	0.122	0.127	0.223	1.000
		Powers	0.025	1.000	0.266	0.388	0.208	0.208
		Enforcement	0.121	1.000	0.101	0.363	0.156	0.102
		Settlement	0.270	1.000	0.253	0.222	0.208	0.208
	Tariffs	Powers	0.250	1.000	0.315	0.507	1.000	0.208
		Enforcement	0.032	1.000	0.245	0.140	0.351	0.102
		Settlement	0.239	1.000	0.250	0.250	0.500	0.354
Transmission	Regulation	Regulation	0.000	1.000	0.331	0.814	0.541	0.235
		Powers	0.219	0.208	0.153	0.136	0.237	0.214
		Enforcement	0.107	0.160	0.208	0.118	0.178	0.116
	Access Rules	Powers	0.041	0.500	0.161	0.111	0.124	0.500
		Enforcement	0.107	0.258	0.115	0.152	0.192	0.137
		Settlement	0.219	0.541	0.208	0.133	0.285	0.515
	Tariffs	Powers	0.270	0.500	0.240	0.236	0.125	0.066
		Enforcement	0.121	0.150	0.112	0.135	0.149	0.127
		Settlement	0.219	0.500	0.209	0.254	0.299	0.250
	Unbundling	Powers	0.250	0.500	0.195	0.675	0.250	1.000
		Enforcement	0.153	0.613	0.126	0.132	0.149	0.387
		Settlement	0.047	0.500	0.210	0.222	0.500	1.000
	Investment Planning	Powers	0.541	0.541	0.270	0.213	0.079	0.250
		Enforcement	0.263	0.258	0.192	0.208	0.190	0.066
		Settlement	0.208	0.500	0.214	0.515	0.500	0.270
	Quality Standards	Powers	0.079	0.515	0.235	0.220	0.062	0.052
		Enforcement	0.118	0.150	0.151	0.158	0.132	0.107
		Settlement	0.219	0.500	0.106	0.351	0.025	0.507
	Cross-border Activities	Powers	0.541	1.000	0.272	0.215	0.500	1.000
		Enforcement	0.153	1.000	0.203	0.182	0.205	1.000
		Settlement	0.208	1.000	0.326	0.594	0.208	1.000
	Congestions & Balancing	Powers	0.270	1.000	0.360	0.274	0.222	0.500
		Enforcement	0.149	0.613	0.117	0.149	0.198	0.246
		Settlement	0.208	0.500	0.213	0.282	0.290	1.000
Distribution	Regulation	Regulation	0.208	0.104	0.287	0.566	0.039	0.047
		Powers	0.222	0.276	0.140	0.090	0.219	0.122
		Enforcement	0.114	0.150	0.114	0.135	0.175	0.068
	Access Rules	Powers	0.250	0.515	0.164	0.161	0.226	0.209
		Enforcement	0.142	0.150	0.086	0.140	0.072	0.109
		Settlement	0.297	0.500	0.208	0.075	0.297	0.261
	Tariffs	Powers	0.104	0.500	0.306	0.143	0.311	0.236
		Enforcement	0.156	0.150	0.085	0.158	0.084	0.109
		Settlement	0.276	0.500	0.214	0.282	0.500	0.310
	Unbundling	Powers	0.250	0.500	0.252	0.324	0.315	0.064
		Enforcement	0.149	0.613	0.120	0.104	0.138	0.104
		Settlement	0.239	0.500	0.209	0.250	0.500	0.352
	Investment Planning	Powers	0.208	0.541	0.054	0.339	0.250	0.250
		Enforcement	0.236	0.258	0.181	0.128	0.251	0.056
		Settlement	0.500	0.500	0.223	0.523	0.208	0.561
	Quality Standards	Powers	0.079	0.515	0.433	0.430	0.311	0.095
		Enforcement	0.118	0.150	0.108	0.179	0.144	0.109
		Settlement	0.219	0.515	0.054	0.351	0.025	0.234
Retail	Regulation	Regulation	1.000	1.000	0.504	0.814	0.270	0.219
		Powers	0.041	0.239	0.076	0.081	0.039	0.115
		Enforcement	0.131	0.258	0.135	0.115	0.279	0.070
	Tariffs	Powers	0.208	0.500	0.155	0.194	0.239	0.238
		Enforcement	0.135	0.258	0.132	0.115	0.149	0.114
		Settlement	0.208	0.500	0.208	0.282	0.500	0.320

outcomes [24]. Hopefully more regulatory convergence can be advocated considering the status-quo documented in 2011. These issues are strongly interrelated with the issue of *consumers' protection*, which was a target of inhomogeneous regulatory practices (as depicted in Fig. 6). It is essential to defend vulnerable actors from indiscriminate price increases especially in times of wars and uncertainties. Therefore future inspections are extremely important and called for monitoring the convergence of all these regulatory practices.

Furthermore, debates on climate change have highlighted that efforts to solve the problem have not produced expected results. It has

Table 7
Number of groups identified over the total number of responding ERAs across fields and jurisdictions for both electricity and gas markets. Note: *n.a.* means that no ERAs provided answers.

	Electricity				Gas			
	NERAs	$_{EU}$ERAs	SERAs	FERAs	NERAs	$_{EU}$ERAs	SERAs	FERAs
All Fields	50/52	24/25	20/22	4/5	30/32	21/22	15/17	4/5
Consumers' Protection	43/52	23/26	19/21	3/5	27/32	18/22	15/20	n.a.
Energy Efficiency	22/52	11/26	14/22	4/5	21/32	15/22	12/20	n.a.
Environmental Issues	31/52	20/26	13/21	2/5	22/32	17/22	12/20	n.a.
Security of Supply	36/52	18/26	14/21	2/5	24/32	17/22	13/20	n.a.

been recalled how the conventional theory of collective-action advices that global environmental problems cannot be solved without an external authority that formulates appropriate actions to be taken, monitors behaviors, and imposes sanctions. On the other side, it is undoubtable that multiple actors at different scales can undertake many activities that cumulatively can result into several contributions to the reacting of the same common objective. Then, as [25,26] suggest it is important to encourage individual multiple efforts by actors and units working as a polycentric systems. At multiple scales, polycentrism may facilitate the achievement of common benefits and global goals, as well as fostering the learning from a variety of experiences emerging by the different policies adopted. On the long-run, global efforts should be put in place, but in the short- and medium term polycentric efforts may contribute to. This approach may produce interesting results in the reduction of emissions, because causes of climate change are actions undertaken by individual actors at smaller scales. Then, solving the global problem requires substantial changes at all levels, in the activities of individuals, families, firms, communities and governments; and this demands for a collective action, under the spirit of the familiar slogan "think globally but act locally".

Indeed, the conventional theory of collective action predicts that no one will voluntarily change his/her own behavior to reduce energy use and emissions, unless an external authority imposes enforceable rules able to change the incentives for those involved and then induce the expected modified behaviors [27]. At the same time, it may be argued that overlapping energy agencies and regulators may result in a chaotic inefficient system [28]. However, under polycentricity, the existence of multiple governmental units, agencies and regulators without a clear hierarchy and their activities at different scales may result in effective solutions. Studies on public goods have shown that large-scale units are part of the effective governance of metropolitan areas, and that small- and medium-scale units are also necessary components. Then, these teach the lesson that a single governance unit cannot solve global collective-action problems (because of global impacts) but efforts need to be performed, naturally, also at local- and state-levels ([13]; [29]; [30]; [25]; [26], and references therein).

Ostrom et al. [13] describes "polycentric systems" as connoted by many formally independent decision making centers interacting with competitive relationships, often entering into various contractual and cooperative actions or recurring to central mechanisms to resolve conflicts. Hence, they may function in a coherent manner in various political jurisdictions; also in the energy markets. As in energy, these polycentric systems are characterized by multiple governing authorities acting independently at different scales to make norms and rules within a specific domain, and then taking advantage of local knowledge. In this context, it may be easier to learn from others. In addition, a system organized polycentrically tends to enhance the innovation, adaptation, cooperation making the intended achievement more effectively and sustainingly obtainable. In this view, our results interestingly confirm polycentricity among energy regulators and their regional associations.

It is worth recalling that the polycentric approach has shown several advantages, as encouraging the experimentation by multiple actors, as the development of methods for assessing the benefits and costs of particular strategies adopted in one setting and comparing these with results obtained in other settings, as well as learning from diverse policies adopted.

At this point, however, it is also beneficial to give warning about the issue of inconsistent policies, which may represent an obstacle to the reaching of target policies (such as the reduction of emissions). As highlighted by Jennings et al. [31], a regulatory system may be subject to different political regimes which can vary across states and may discourage innovation, since industrial firms developing new technologies may find difficult to sell in areas characterized by different policies, and then taking the risk of not having sufficient returns of the initial investment. Also from this point of view, it is then important to have a co-existence of several energy regulatory authorities, helping in addressing the energy policy issues and then collaborating in solving problems ([32]; and references therein). At the same time, however, the creation or the existence of independent regulatory authorities may improve the regulatory stability and predictability, which also influence energy investors' decisions; see [19,20].

We do not study regulators' design options for assessing their independence since our surveys data do not provide indications about ERAs relationships with stakeholders. However, it has been observed that they can enrich the regulatory process, but, at the same time, regulators risk to identify themselves with industry they want to regulate. When parties have different resources and interests it may potentially occur that cooperation turn into cooptation (see [33]). Regulatory independence can also be enhanced by the existence of regulatory networks, but we have no way to test it empirically, and readers interested on regulators' independence are addressed to [14,34,35], and [36].

To summarize, this paper proposes a review of tasks, activities and practices adopted by energy regulatory authorities around the world to highlight the differences and commonalities on which attention should be paid. Reaching an harmonized view, practice and regulation, even if implemented differently cross world countries, would support indeed the argued transition to a low carbon future and will make the emissions targets closer and more easily achievable. Therefore, we proposes an innovative application of a statistical indicator and an unsupervised machine learning tool to inspect ERAs' practices, tasks and activities based on electricity and gas market segments, jurisdictions, and regional associations. In this way, we assess the degree of a global coordination among energy regulators characterized by frequent interactions within their regional networks. Our empirical results about dissimilar energy practices show the existence of energy polycentric systems, where national, state and federal regulators together with their regional associations can contribute at different scales and in several ways to the achievement of the global energy benefit by cumulating individual results.

Based on surveys submitted in 2011, our empirical results show that the implementation of the energy regulation and its practices were substantially different and adapted to various local contexts. These findings lead us to conclude that it has prevailed a process of adaptation to the specific institutional context in which they were performed. Indeed, regulators' powers and activities show diversity, even among groups of regulators belonging to the same regional associations and then expected to act homogeneously. This argument holds for developing countries, since they have adapted the design of regulatory institutions to their own needs, not necessarily emulating the practice of developed countries; or for the USA, notwithstanding over a century of history of public utility regulation; or also for the EU, where considerable efforts

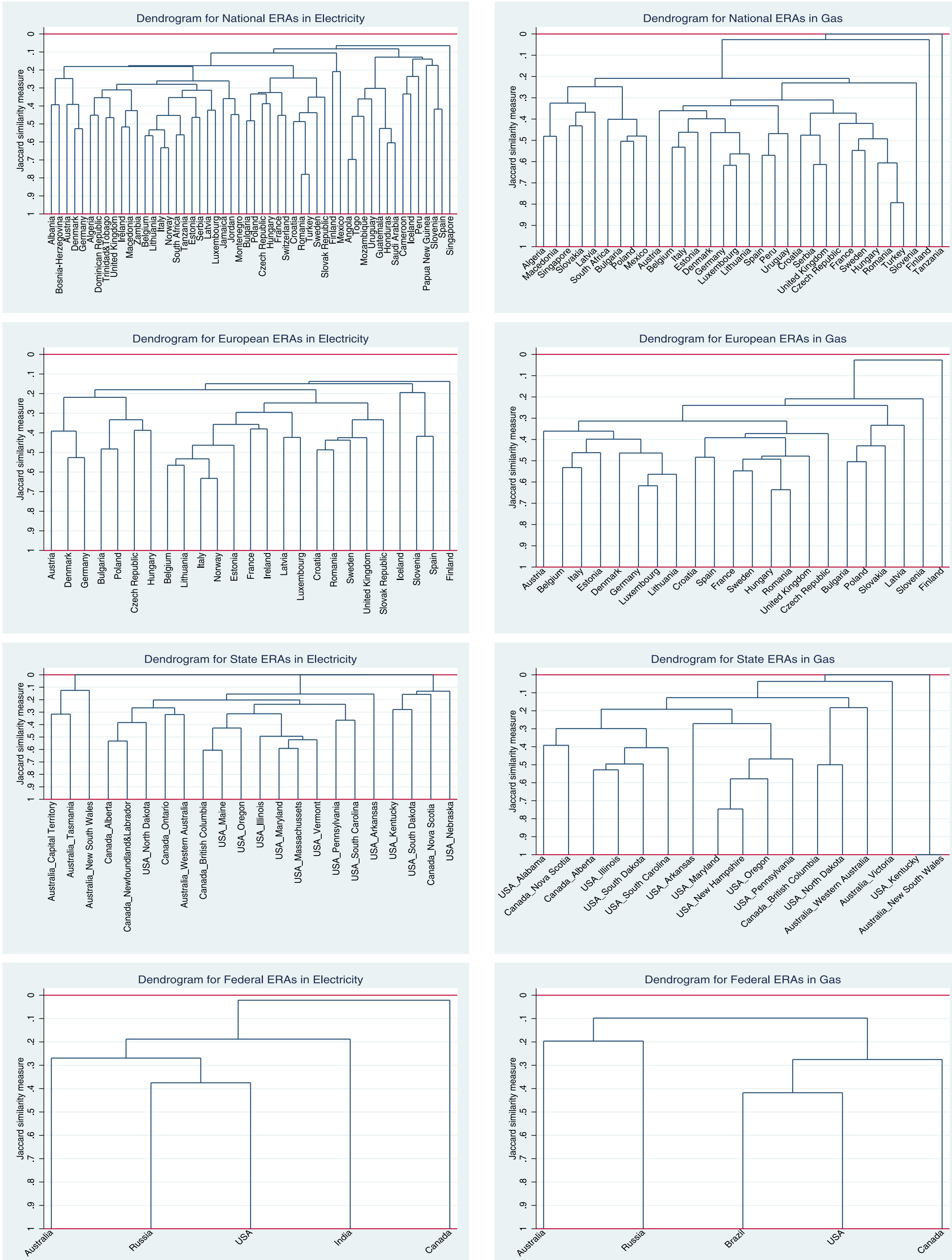

Fig. 7. ERAs' Clusters across Jurisdictions in Electricity (on the left) and in Gas (on the right) for *All Fields*.

of policy harmonization had taken place. However, it is plausible that European regulators' powers would show much higher levels of similarity, if these surveys were undertaken today and, indeed, monitoring the evolution of regulatory powers over time is a promising and worthwhile area for future research.

Even with a few limitations, as the exploratory nature of cluster analysis and the nature of the answers with their 'check to all that applies' that could mask different practices, this analysis is useful since it provides a first attempt to monitor the energy regulatory practices all around the world and it provides the first interesting empirical

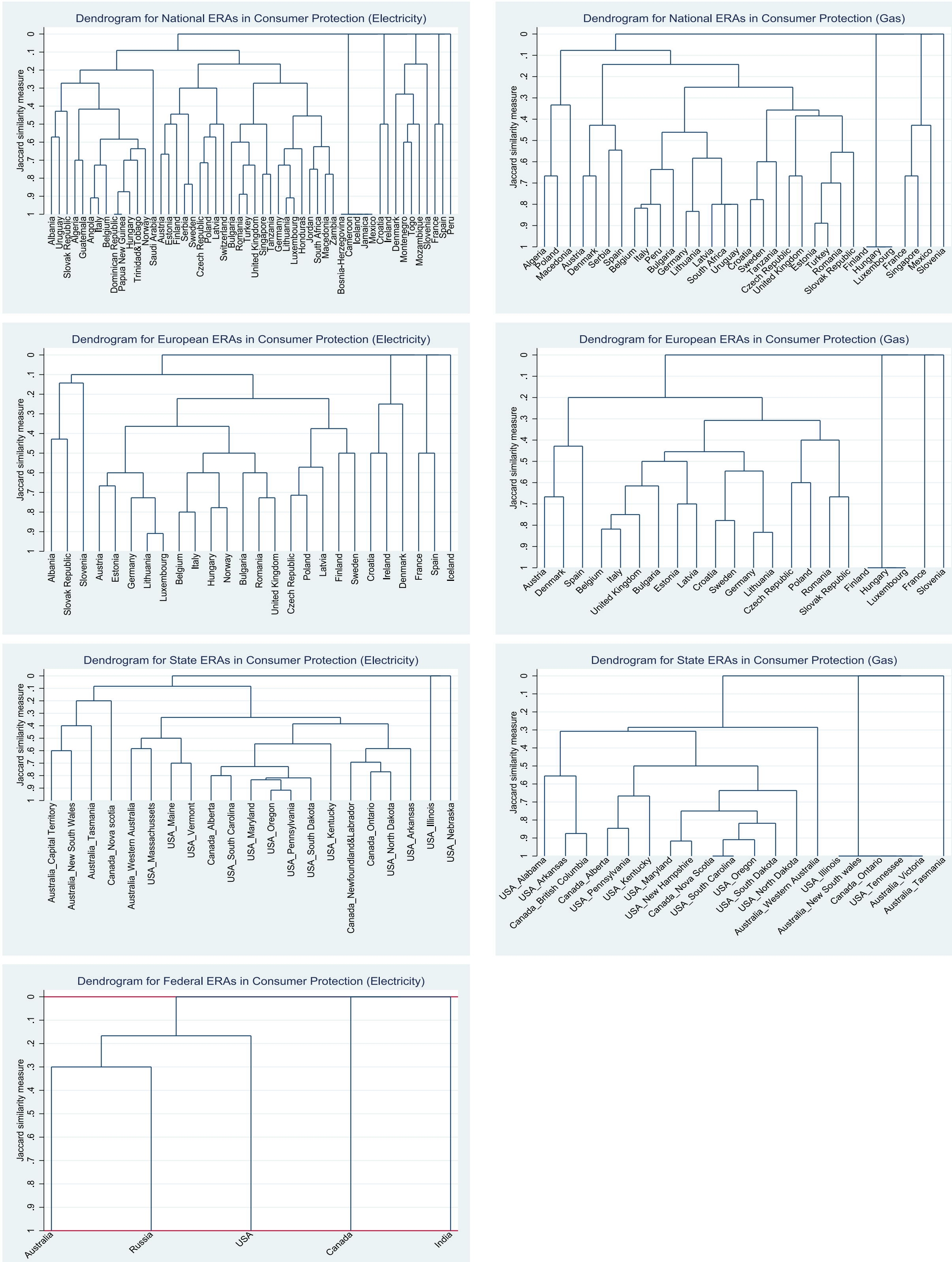

Fig. 8. ERAs' Clusters across Jurisdictions in Electricity (on the left) and in Gas (on the right) for *Consumers' Protection*.

evidence on differences of regulators' tasks and tools implemented or adopted, supporting the theory of polycentric systems. Then, the usage of the two proposed methods is recommended to inspect the status of energy policy harmonization and the regulatory coordination to verify if uniformed energy policy actions are progressively taking place and achieved in view of global resolutions towards a low carbon transition, and delineated environmental and sustainable goals. In this regard, our findings can be considered as an historical benchmark versus which

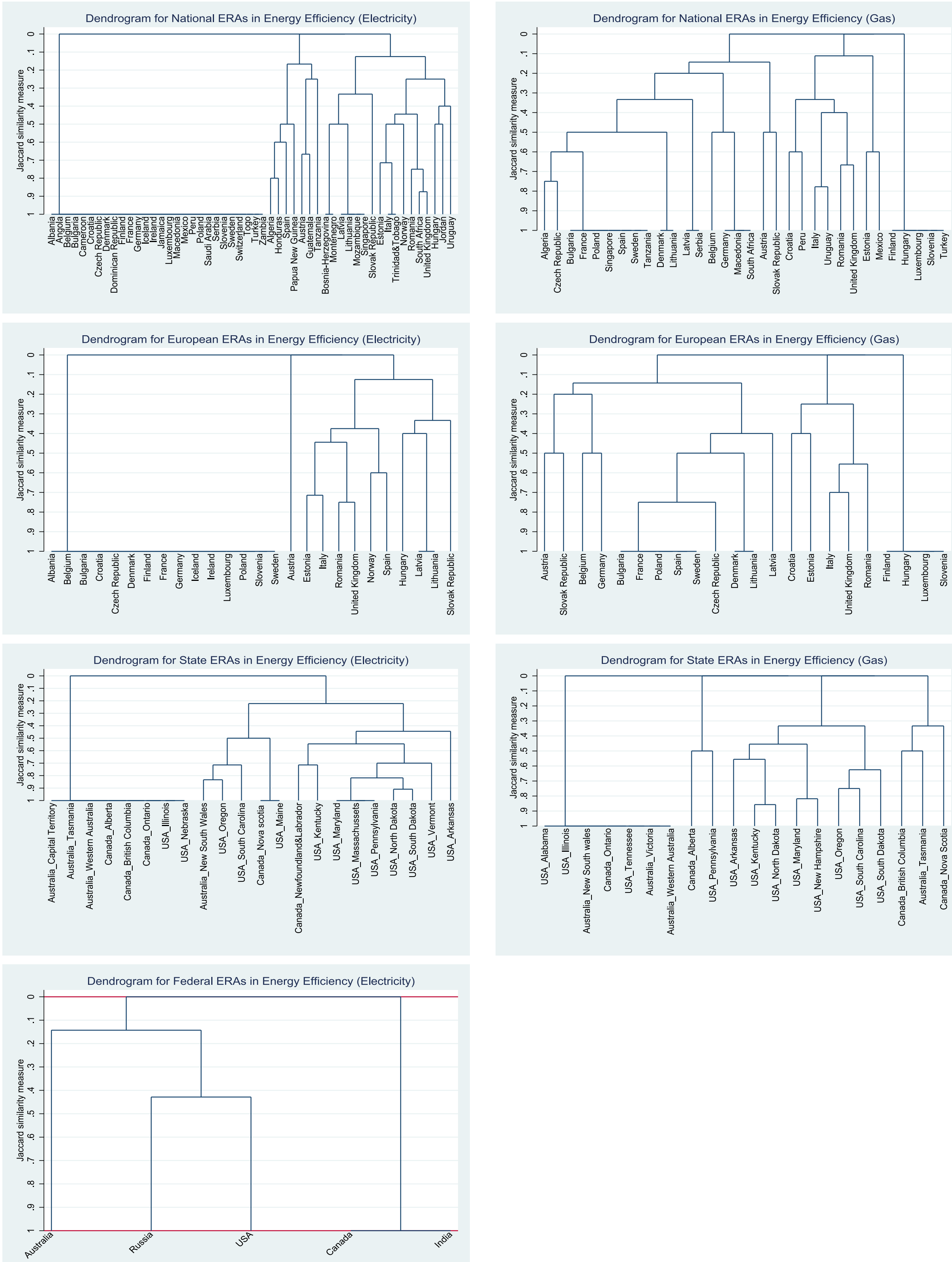

Fig. 9. ERAs' Clusters across Jurisdictions in Electricity (on the left) and in Gas (on the right) for *Energy Efficiency*.

testing any improvements towards a global energy policy to monitor the degree of polycentric international cooperation and to understand if a world energy regulatory convergence is occurring.

The major objective of this study is to make a comprehensive analysis of different ERAs' practices and tasks investigating the (dis)similarity patterns. Even if based on information dated back in 2011, our results may enhance further policy discussions and help policy-makers learn from each other's experiences by sharing the most effective practices adopted. All together this could generate a natural harmonization of regulatory activities, especially in contexts of environmental issues,

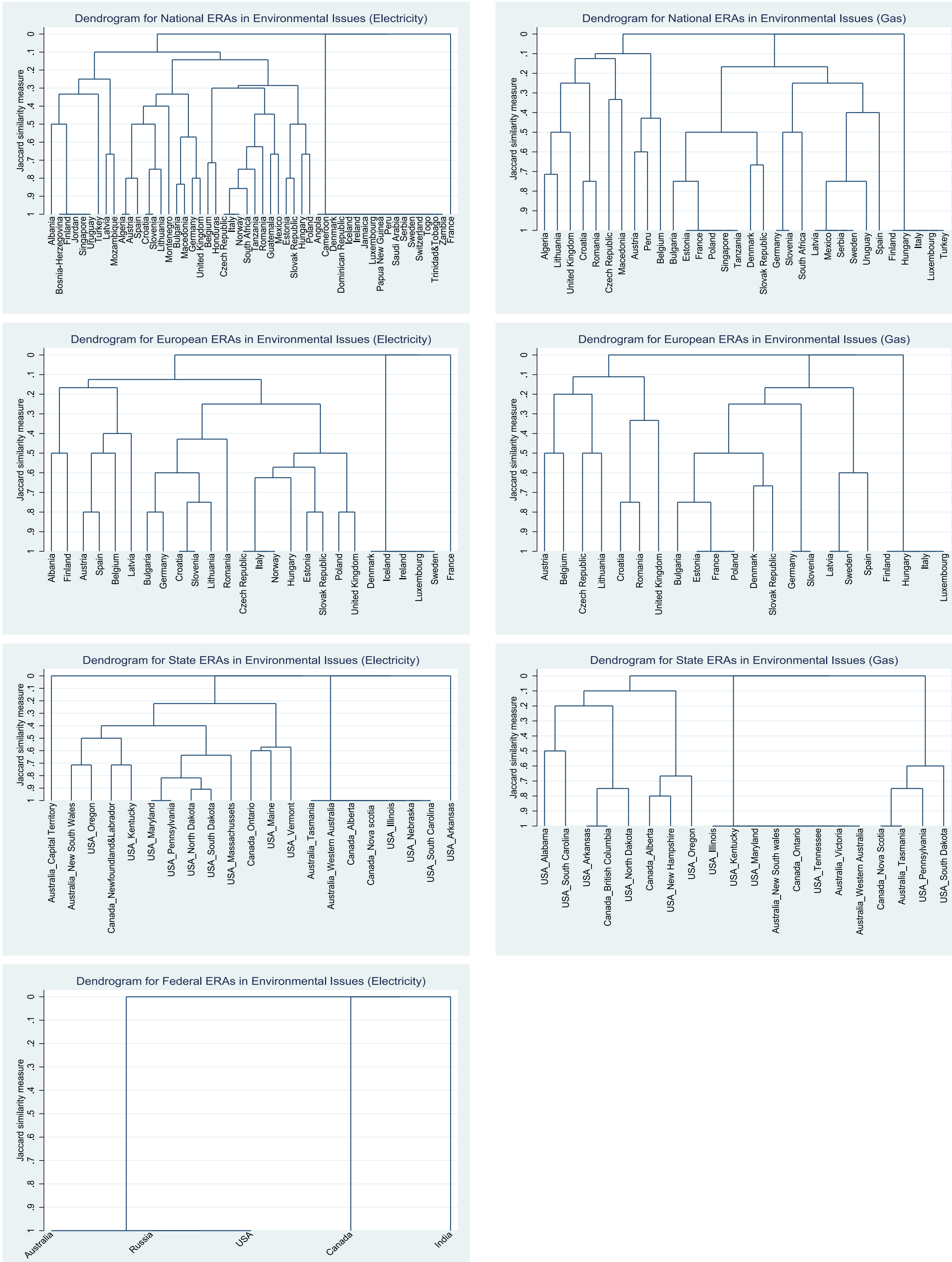

Fig. 10. ERAs' Clusters across Jurisdictions in Electricity (on the left) and in Gas (on the right) for *Environmental Issues*.

security of supply and consumers' protection. Adopting more efforts and implementing common appropriate actions at multi-scale levels may results in more coordinated actions and substantially reduce carbon (and methane) emissions, hence addressing more efficiently the global problem of climate change. Finally, we have adopted entropy and unsupervised statistical learning to depict the status of energy regulators' tasks and activities in a moment of time. However, different methodologies can be implemented to illustrate the dynamic (dis-)alignments in time and space among energy regulators. For instance, we believe that the socio-technical configuration analysis, effectively

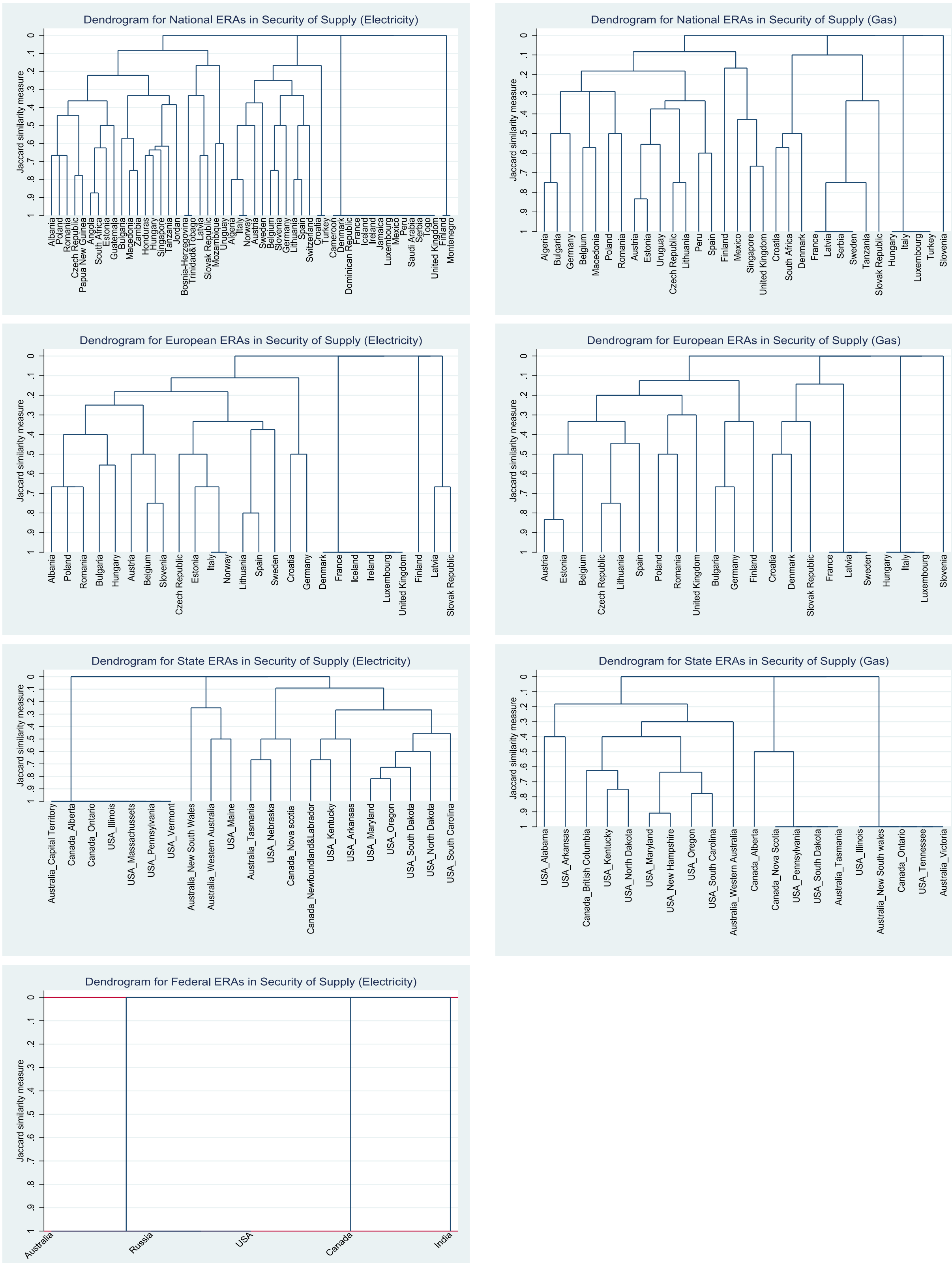

Fig. 11. ERAs' Clusters across Jurisdictions in Electricity (on the left) and in Gas (on the right) for *Security of Supply*.

implemented by Heiberg et al. [37] to detect and map shifts from centralized to more modular configurations of infrastructures, can be a promising line of future research.

CRediT authorship contribution statement

Angelica Gianfreda: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Giacomo Scandolo:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.energy.2023.126969.

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