Reliable Electricity: The Effects of System Integration and Cooperative Measures to Make it Work

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Reliable Electricity: The Effects of System Integration and Cooperative Measures to Make it Work

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Abstract

We investigate the effects of system integration for reliability of supply in regional electricity systems along with cooperative measures to support it. Specifically, we set up a model to contrast the benefits from integration through statistical balancing (i.e., a positive externality) with the risk of cascading outages (a negative externality). The model is calibrated with a comprehensive dataset comprising 28 European countries on a high spatial and temporal resolution. We find that positive externalities from system integration prevail, and that cooperation is key to meet reliability targets efficiently. To enable efficient solutions in a non-marketed environment, we formulate the problem as a cooperative game and study different rules to allocate the positive and negative effects to individual countries. Strikingly, we find that without a mechanism, the integrated solution is unstable. In contrast, proper transfer payments can be found to make all countries better off in full integration, and the Nucleolus is identified as a particularly promising candidate. The rule could be used as a basis for compensation payments to support the successful integration and cooperation of electricity systems.

Keywords: Electricity, Reliability of supply, Generation adequacy, System integration, Cooperative game

JEL classification: C63, C71, D47, Q42, Q48

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1. Introduction

To ensure reliability of supply, electricity systems need to comprise an adequate amount of reliably available generators. As systems are increasingly based upon large amounts of renewable energies, new challenges arise: many renewable resources, such as wind and solar, are variable in nature and incorporate the risk of recurring unavailability during times of stress. In this context, it is often argued that balancing effects should be lifted by means of system integration and additional interconnections, such that better levels of reliability may be reached.

Indeed, compared to isolation, system integration allows to deploy the clearly *positive* effect that if capacity is short in one part of the integrated system, there is a good chance that some spare generation can be made available from another part. Unsurprisingly, enhanced reliability of

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supply was therefore one of the main drivers to create extensive interconnected electricity systems, such as the European or the North-American one (e.g., Billinton and Allan (1996)).[1,2]

At the same time, however, system integration may also entail *negative* consequences: electricity systems carry the risk of "rolling blackouts", often affecting large parts or even the entire interconnected system. In consequence, system integration incurs a trade-off between positive and negative effects, thus calling for a careful reconsideration of the overall benefits. Moreover, the depicted trade-off may look very different for the individual systems involved, which may give rise to complex incentive structures to support (or even oppose) system integration and cooperation.

In the large body of literature on reliability in electricity systems, previous work was mostly focused on the *positive* effects of interconnection. For instance, the books by Billinton and Allan (1996) and Stoft (2002) comprise technical and economic analyses of the benefits from shared resources to balance capacity shortages via interconnections. Cepeda et al. (2009) study the positive implications from system integration for reliability and ways to internalize cross-border effects. Recently, Newbery et al. (2015) have highlighted the importance to consider the (positive) contribution from interconnections in reliability mechanisms, based on the case of the UK.

In contrast, this paper explicitly analyzes the trade-off between *positive and negative* effects of system integration. To this end, we introduce a straightforward probabilistic model for reliability of supply, and calibrate it with a comprehensive dataset for 28 European countries on a high spatial and temporal resolution. Europe is a particularly interesting case study as it consists of idiosyncratic but interdependent countries. While reliability of supply is often seen with a limited regional scope, bounded by political entities, legal jurisdictions, or historical borders[3], several blackouts have affected large parts of the interconnected system[4]. Moreover, Europe also appears to be a suitable case study due to its geographical size, high relevance of VRE penetration, as well as good data availability.

Based on this probabilistic model, our paper makes two important contributions: First, we contrast well-known benefits from system integration through statistical balancing (i.e., a purely positive externality) with unilateral or even mutually adverse effects (i.e., negative externalities) incurred by cascading outages on interconnections in a full-fledged empirical case study for Europe. We quantify our reliability metrics on different levels of system integration, finding that most Eu-

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[1] Note that in some references the term "reliability" encompasses two distinct time-scales: short-term issues are often referred to as "security", and long-term issues as "system adequacy". We only consider reliability as an issue of system adequacy in this paper, and will therefore use the two terms interchangeably.

[2] Even though we will restrict our focus on reliability of supply throughout this paper, note that interconnectors may also serve additional important purposes: they allow to reap gains from trade (e.g., Bessembinder and Lemmon (2006) or Mansur and White (2012)), and to reduce market power (Borenstein et al. (2000)).

[3] For instance, numerous countries have been implementing so-called capacity mechanisms, with the aim to reach a certain level of reliability within their own country borders, even though they form part of a larger interconnected system and share the risk of wide-area cascading blackouts. See, e.g., Joskow (2008), Cramton et al. (2013) or Joskow (2013) for a good overview of the general debate.

[4] For instance, in 2006 a cascading blackout affected over 15 million households in large parts of the European interconnected system.

ropean countries are self-sufficient with a substantial safety margin. However, we also find some countries that rely on imports to cover high demand levels. Overall, positive externalities from system integration prevail over the risk of detrimental outage imposition. However, several countries suffer from interconnection compared to an isolated state, mainly those with comparatively large reliability margins within their country boarders.

To investigate and cope with diverging incentives to support system integration (and as a second contribution), we build on well-known mechanisms from game theory to internalize systemic effects in a cooperative solution. The use of cooperative game-theoretical approaches is motivated by the observation that reliability is typically seen as a matter of national interest and not organized through integrated market-based solutions. Therefore, we explore measures to allocate individual contributions to security of supply in interconnected areas. These allocations could be used as a basis for (monetary) compensation payments, such that the positive and negative effects from system integration can be shared among all interconnected countries in a suitable way. We find that even though the problem is superadditive (indicating that integration increases total reliability, i.e., reduces the sum of expected electricity shortages for all interconnected countries), it is also non-convex (i.e., reliability of the system does not increase proportional to its size). These characteristics limit the number of stable rules for allocating externalities from system integration to individual countries. Nevertheless, testing several allocation rules, we identify the Nucleolus as a suitable candidate to deliver desirable properties, including stability as well as low (relative) variation among the countries. In contrast, the most appealing solution, namely to have *no* transfer payment (and thus, no need for a mechanism) fails to deliver a stable engagement. This clearly underlines the importance of our analysis.

Overall, our paper provides evidence that substantial benefits arise from system integration, and that suitable allocation rules can be found to distribute the overall benefits to make all countries better off. We thus conclude that well-designed compensation mechanisms for reliability could effectively support the successful integration and cooperation of electricity systems.

The rest of this paper is structured as follows: In Section 2 we present our model, and in Section 3 its calibration with European data. Results for reliability on different levels of system integration are reported in Section 4. Reliability as a cooperative problem is studied in Section 5. Section 6 concludes.

2. The Model

In order to ensure reliability of supply, electricity systems need to comprise a sufficiently large number of reliably available electricity generation units. Generation adequacy describes the ability of a electricity system to match expected levels of consumption. A well-established measure is the loss of load probability (LOLP), i.e., the probability of a system's available generation capacity C

being less than load L at a specific instant in time:

$$LOLP = P(C < L). \tag{1}$$

Note that the LOLP implicitly assumes an inelastic demand for situations where capacity is scarce, such that market clearing cannot be guaranteed. This is line with the observation that price responsiveness of electricity consumption is indeed fairly low, e.g., due to the lack of real time pricing (Lijesen (2007)).

From Equation (1), summing up the probabilities over time yields the Loss of Load Expectation (LOLE) during the considered number of hours. This is a measure often used to formulate or benchmark reliability levels, such as the 1-day-in-10-years criterion which has often been applied in the electricity sector, both in the academic literature (e.g., see Telson (1975)) as well as in practice (e.g., by the Midcontinent ISO or the ISO New England). Alternatively (or in addition), one may derive the expected energy unserved (EEU) by weighting the sum of LOLPs with the corresponding load levels. The advantage of the latter index stems from the fact that it measures actual quantities (e.g., GWh/year) instead of a frequency (e.g., hours/year).

In order to determine the effect of system integration on the risk of shortages, let us consider two systems A and B. Based on Equation (1), the LOLP metric may be determined for different system boundaries, i.e., for A and B isolated, as well as for A and B integrated. These cases are listed in the following table.

	Risk of shortage in A	Risk of shortage in B
A isolated	$LOLP^A = P(C^A < L^A)$	
B isolated		$LOLP^B = P(C^B < L^B)$
A & B integrated	$LOLP^{AB} = P(C^A + C^B < L^A + L^B)$	

Table 1: Loss of load probability in two systems, isolated and integrated

Note that the above definition of $LOLP^{AB}$ implies two important suppositions: First, that loss of load is cascading, i.e., that capacity shortages affect all load within the considered system boundaries. Depending on the context, this may be overly pessimistic. However, it is in line with the observation that large parts of the consumption side cannot be controlled by the system operator (e.g., Lijesen (2007)). Moreover, empirical evidence shows that blackouts may indeed affect large parts of interconnected systems without being hindered by virtual borders. Second, we suppose that no bottlenecks between A and B limit the exchange of capacity in case of scarcities. Of course, this is untrue for real world electricity systems. However, the setting may be seen as an important benchmark regarding the possibility to integrate systems. Moreover, if generation scarcities in electricity systems are small (as often observed in reality due to stakeholders leaning towards rather high levels of risk aversion), even small transfer capacities may suffice without causing bottlenecks.[5]

Let us now take a look at the various events that may occur for the case of A and B being integrated (small letters denote realizations of the corresponding random variables):

Case 1. Both countries short: $c^A < l^A \cup c^B < l^B \Longrightarrow c^A + c^B < l^A + l^B$

Case 2. Both countries long: $c^A \geq l^A \cup c^B \geq l^B \Longrightarrow c^A + c^B \geq l^A + l^B$

Case 3. A short, B long, AB long: $c^A < l^A \cup c^B \geq l^B \cup c^A + c^B \geq l^A + l^B$

Case 4. A short, B long, AB short: $c^A < l^A \cup c^B \geq l^B \cup c^A + c^B < l^A + l^B$

Case 5. A long, B short, AB long: $c^A \geq l^A \cup c^B < l^B \cup c^A + c^B \geq l^A + l^B$

Case 6. A long, B short, AB short: $c^A \geq l^A \cup c^B < l^B \cup c^A + c^B < l^A + l^B$

Comparing the above (joint) events to their corresponding outcomes in isolated systems, at each instant the integration of A and B may yield different effects: No changes in cases 1 and 2; A gains from interconnection in case 3; B loses in case 4; B gains in case 5; and A loses in case 6.

The loss of load probability for the case of A and B being integrated can be depicted by the law of total probability, summing up the probabilities of all (mutually exclusive) cases where AB is short (i.e., the probabilities of cases 2, 4 and 6 occurring):

$$\begin{aligned} LOLP^{AB} = {} & P(C^A < L^A \cup C^B < L^B \\ & + P(C^A < L^A \cup C^B \geq L^B \cup C^A + C^B < L^A + L^B) \\ & + P(C^A \geq L^A \cup C^B < L^B \cup C^A + C^B < L^A + L^B). \end{aligned} \tag{2}$$

Comparing $LOLP^{AB}$ with isolated systems allows to disentangle the various effects of system integration:

- The first term of Equation (2) is weakly smaller than the LOLP in isolated systems. This is due to the fact that shortages unlikely affect both systems at the same time (as long as outages are not perfectly dependent). This balancing support is a *positive* externality in integrated systems.

- The second and third term add probabilities for shortages to the integrated system, imposed by the risk of imbalances in one of the subsystems. This is a *negative* externality in integrated systems.

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[5] Note that the model could be extended to include limited transmission capacities such as in Cepeda et al. (2009), for instance. However, we stick to the unrestricted formulation for the sake of simplicity and analytical and numerical tractability.

While both externalities may generally be present in integrated systems, their size and overall direction depends on the specific statistical characteristics. Indeed, from a general viewpoint, integration may be mutually beneficial, unilaterally beneficial for one and adverse for the other, or even mutually adverse for the two systems concerned. Due to this theoretical ambiguity, and in order to derive further practice-oriented insights, we will calibrate our statistical model in a relevant empirical case study. This step will also allow to naturally extend our analysis to $N > 2$ interconnected systems.

3. Model Calibration

For our research subject, the interconnected European electricity system appears to be a suitable case study due to several reasons: Europe comprises a large number of idiosyncratic countries while their electricity systems are highly interconnected. Reliability is generally a key concern, and the large scale integration of variable renewable energies renders the issue even more important (e.g., CEER (2014b)). At the same time, reliability is mainly considered as an issue of national interest for which national transmission system operators (TSOs) are responsible. Moreover, there is a large variety of targets and approaches relating to reliability (CEER (2014a)). Meanwhile, the role of interdependencies with physically interconnected countries appears to be largely unspecified (e.g., Newbery et al. (2015)). Last but not least, several sources are available to calibrate our statistical model with a sufficient amount of data.

Recall Equation (1) that needs to be solved to obtain the level of system reliability. For the purpose of calibrating our model, we use three types of data: First, detailed information about dispatchable power plants. By assuming that outages of conventional power plants are independent, the distribution of random variable C can then be determined through convolution of the individual plants' outage probability (e.g., Billinton and Allan (1996)).[6] Second, data on system load. We will estimate the (multivariate) distribution of load levels L from simultaneous historical observations. As we only have one observation per instant in time t, we need to extend our model to multiple time periods. Random variable L may then be replaced by corresponding observations l_t.[7] And third, renewable infeed data. As wind power has become a relevant source of undispatchable electricity generation in Europe, we will subtract it from system load (and thus use residual load levels to be covered by dispatchable generation units).[8]

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[6] A more elaborated approach could in addition consider dependencies among power plant outages due to weather events affecting multiple power plants in a similar way, e.g., due to a lack of cooling water in heat waves, or equipment breakdowns in storms. However, this would entail the need to derive the joint outage probability by means of much more sophisticated multivariate statistical model (e.g., copula techniques) which are difficult to implement for extensive datasets such as ours.

[7] This is the so-called hindcast approach described, e.g., in Zachary and Dent (2011).

[8] Note that we disregard the impact of solar power due to the lack of appropriate data on the relevant geographical scale.

The common characteristic of all these data will be their regional coverage including the following European countries: AT, BE, BG, CH, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IT, LT, LU, LV, NL, NO, PL, PT, RO, SE, SI, and SK. Further specifications are discussed in the following.

3.1. Dispatchable Power Plants

For installed electricity generation capacities of different types, we were able to get an extract from the power plant database developed and maintained at the Institute of Energy Economics at the University of Cologne (ewi). This database aims at incorporating detailed information about all power plants in Europe at a unit level. For every power plant, a large number of technological and economic characteristics is listed, including its year of commissioning, net capacity, generation efficiency, etc. The database is continuously maintained to include the latest information available, e.g., by including specific information from newsletters and industry contacts. The data used in this study reflects the status at the end of 2016, and contains more than 15000 generators. To ensure an appropriate quality of the database, we benchmarked aggregated capacity levels with other publicly available sources. No major deviations were found.[9] Details on the benchmark may be found in Appendix A.

In addition to the units' net generating capacities, our model also requires information regarding their availability. These are mainly influenced by planned and unplanned power plant outages. We assume different availability factors for the different fuel types, extracted from historical availability reports. Details are reported in Appendix B.

Based on installed capacities and their availabilities, we need an efficient routine to calculate generation probability functions for systems as large as the European one. We implement and use the same algorithm as in Hasche et al. (2011) which proved to be fast enough to derive the probability function for systems consisting of more than 15000 power units in about 12 hours on a standard laptop.

3.2. Load

Vertical net load levels are reported on an hourly basis for each European country on the transparency website of ENTSO-E (ENTSO-E (2016a)). We consider all data available, i.e., six consecutive years (2010-2015). According to ENTSO-E (2016a), vertical net load on a electricity system is referred to as the hourly average active power absorbed by all installations connected to the transmission or distribution network.

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[9] Note that the benchmark may only be conducted on an aggregated capacity level as detailed information on individual power plants is not publicly available from other sources.

3.3. Wind

We use the dataset developed in Henckes et al. (2016) for 20 years of hourly electricity generation profiles of wind turbines throughout Europe. This data, in turn, is derived from two sets of data: First, hourly wind speeds for 20 years (1995-2014), generated by the numerical weather prediction model COSMO-REA6. This model takes measurements as well as reanalysis data as an input and generates hourly profiles for wind speed on a 6x6 km grid covering the entire European continent. As a second input, the model builds on unit-level information for wind power throughout Europe (status December 2014) taken from The Wind Power. Specifically, installed capacities along with turbine characteristics are used to determine what these capacities would have produced given the wind speeds from the COSMO-REA6 model. For further information, the interested reader is referred to Henckes et al. (2016).

3.4. Data Construction

We will assume that there is no causal relationship between the availability of yearly wind and load profiles. This allows us to combine historical observations in order to enhance the joint probability space. Specifically, we can combine 20 wind years with 6 load years, yielding a total of 120 sample years and 120 distinct joint observations for each instant in time t. Each year is assumed to occur with the same probability. Note that by combining yearly profiles, interannual patterns and interrelations are preserved. For instance, wind may exhibit a similar yearly pattern as load, with higher values in winter and lower values in summer. Meanwhile, the simultaneity of the data among the various countries needs to be maintained for every instant in order to capture spatial interdependencies. For instance, mild winters or deep depressions typically affect large geographical areas.

4. Reliability on Different Levels of System Integration

In the following, we will report the results of our reliability measures for different levels of system integration: national, regional and European. While the national and European levels are self-explanatory, our approach for integrating countries into regions should be clarified. We use the regional initiatives for electricity in Europe which were launched in spring 2006 by the European Regulators Group for Electricity and Gas to speed up the integration of Europe's national electricity markets via an interim step to creating a single-EU electricity market ERGEG (2006). There are seven regional initiatives:

1. Baltic: LV, LT, EE
2. Central South: AT, FR, DE, GR, IT, SI
3. Central East: AT, CZ, DE, HU, PL, SK, SI

4. Central West: BE, NL, LU, DE, FR

5. France-UK-Ireland

6. Northern: DK, FI, DE, NO, PL, SE

7. South West: FR, ES, PT

Results are depicted in Figure 1 by means of boxplots representing distributions of (120) yearly LOLEs. We find that most countries are able to fully cover their load levels with generators located within their own national borders, i.e., their are self-sufficient with respect to generation capacity with a substantial safety margin and LOLEs well below 1 hour per year. There are, however, a few noticeably exceptions (such as HR, LV, SI) which depend on imports to cover high load levels. Isolated, loss-of-load-expectations would be as high as 400 hours per year in those countries.

Integration yields high levels of reliability in all seven regions considered ($LOLE$ <1h/y), and a loss-of-load-expectation of zero in all 120 sample years on a European level.

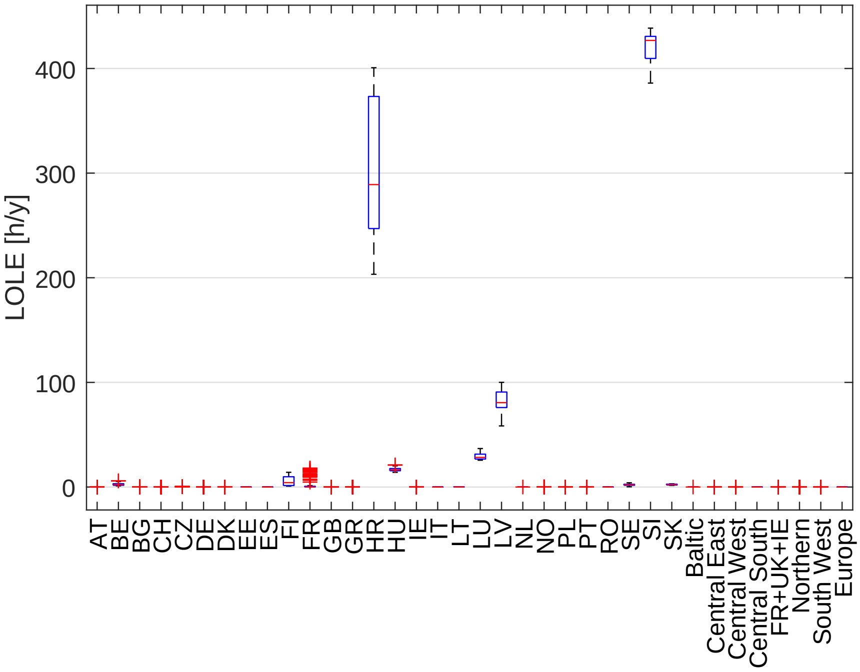

Figure 1: Distribution of yearly Loss of Load Expectation for isolated and integrated countries

While Figure 1 has shown reliability levels for current (exogenous) system states, we are also able to depict endogenous load adjustments. Especially, targeting at a certain level of reliability, we may analyze the possible upwards or necessary downwards adjustments in load. Using the well-known 1-day-in-10-years criterion, the relative scaling factors depicted in Figure 2 generally reflect those of Figure 1, but allow for more detailed insights. On a country level, factors range from -44.4% for Luxembourg up to 119% for Romania, and are mostly positive (again reflecting self-sufficiency of most countries). Regional initiatives could sustain a load increase of 13.2-42.1%, and Europe as a whole 45.2% before reaching the threshold. Noticeably, the load-weighted average increase in national load levels amounts to 24.7%, clearly indicating that the integrated figures cannot be derived from the national ones. Or, in other words, national figures are non-additive, due to statistical interdependencies in supply and load.

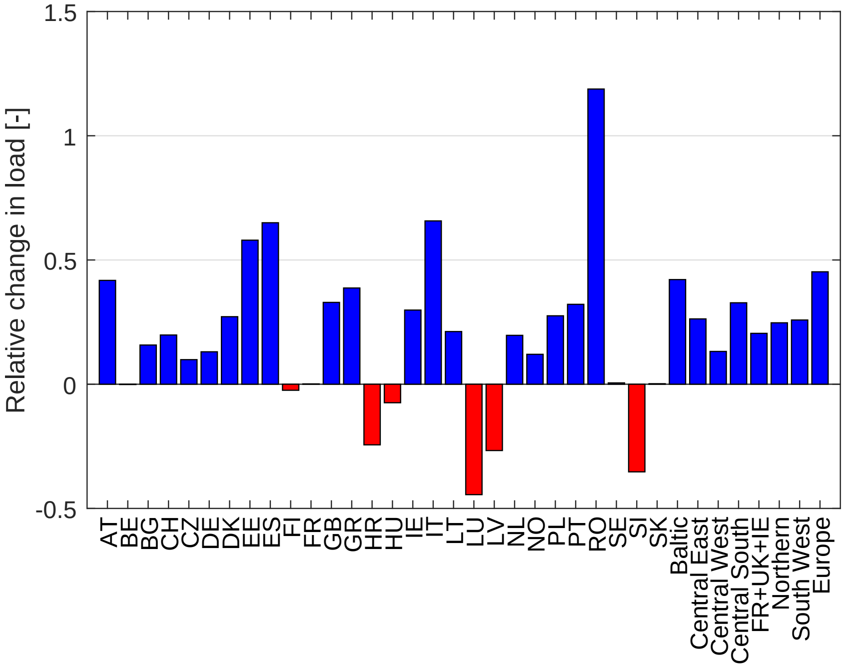

Figure 2: Scaling factor to reach a threshold of 1-day-in-10-years in isolated and integrated countries

5. Reliability as a Cooperative Problem

As we have argued during the course of the paper, countries may share benefits from statistical balancing, but also the risk of cascading outages when being interconnected. These counteracting forces impact the incentives for countries to cooperate with respect to reliability. This can easily be verified in the previously presented reliability figures: we note that compared to an isolated state, some countries take advantage of improved reliability levels when being integrated in a larger system. For instance, Latvia has an isolated LOLE of 29.52 h/y, while it reduces to $3.7e^{-5}$ h/y as part of the Baltic regional initiative and to zero when considering Europe as a whole. For those countries, the positive effects from system integration – as discussed in Section 2 – clearly prevail. In contrast, however, there are also examples showing the opposite: Great Britain has a very high level of reliability in an isolated state (i.e., $1.3e^{-10}$ h/y), but is worse off as part of the FR-UK-IE region. This effect can also be seen in the load scaling factors in Figure 2, and equally applies to the expected energy unserved (EEU) metric. For instance, Spain alone could sustain a load scaling of 65%, but only 26% as part of the South West region. Overall, our results demonstrate that high and low reliability levels typically average out when being interconnected, i.e., the country with low (high) reliability looses (gains) reliability. This effect is caused by positive interdependencies between load and wind generation levels in European countries, such that (unilateral) benefits in one direction often come along with (unilateral) adverse effects in the other direction. This in turn is important for cooperation: if utility from system reliability was completely non-transferable from one country to another, it would often hold true that countries with comparatively low (high) reliability levels support (oppose) system integration with respect to reliability.

At the same time, however, we observe that from an overall system perspective, the beneficial effects from system integration prevail. Specifically, the joint overall risk for unserved energy is by far the lowest within the interconnected European system (recall that even though this result may look evident, cascading blackouts could have caused a different behavior, as shown in our conceptual analysis in Section 2). Therefore, if countries accept compensation mechanisms, i.e., if the utility from reliability is transferable (e.g., by means of monetary payments), full system integration is efficient. An allocation rule can thus be found that leaves all participating countries better off in an integrated system. Notwithstanding, the challenge remains to coordinate the participating countries, such that they are indeed willing to engage in this integrated approach.

To tackle this challenge, a straightforward option would approach the coordination problem by means of integrated markets, where users express their willingness to pay for reliability across borders. However, we observe that reliability is often seen as a matter of national interest which shall not be exposed to market forces. Therefore, to enable cooperative solutions in a non-marketed environment, we formulate the problem as a cooperative game and study different rules to allocate the positive and negative effects to individual countries. Weighted with estimates of the value of unserved energy[10], these allocations could be used as a basis for (monetary) transfer payments to compensate for different levels of contribution to overall system reliability with a shared risk of cascading blackouts.

In the following, in order to reduce complexity and to ensure analytical tractability, we will restrict our focus to a reduced set of countries, namely the ones contained in the Central Western European (CWE) regional initiative (i.e., BE, DE, FR, LU, and NL). To be in line with the typical reliability benchmark of 1-day-in-10-years, we scale the countries' load by 1.13 (recall the results presented in Figure 2). Note that the CWE region is indeed an interesting case study as they are known to be a forerunner with respect to cooperative measures in the design of electricity systems.[11]

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[10] Also known as Value of Lost Load (VoLL).

[11] For instance, they were the first region to implement a novel congestion management design in their market clearing, i.e., the so-called flow-based market coupling.

5.1. Problem Definition

To depict incentives and bargaining positions in the cooperation of reliability in electricity systems, we define the situation as a cooperative cost game (N, v), where $N = \{BE, DE, FR, LU, NL\}$ is the set of countries, and $v(S)$ the characteristic function measuring the value of a nonempty coalition of countries $S \subseteq N$. The coalitional value at stake is the level of expected energy unserved. Instead of the actual values, however, we normalize with the individual expected energy unserved of each country in the grand coalition. This allows us to isolate the externalities from system integration which shall be shared among the participating countries. Moreover, we thus achieve a zero payoff for the grand coalition which ensures that wealth is redistributed but not generated or lost. The characteristic function is thus defined as

$$v(S) = EEU^S - \sum_{i \in S} EEU_i^N = \sum_{i \in S, t \in T} l_{i,t}(LOLP_t^S - LOLP_t^N). \tag{3}$$

Note that the joint values defined in the previous equation can only be realized if the countries contained in the coalition are physically connected by interconnectors. Therefore, we need to define the physical connection matrix, from which we can derive the matrix of possible coalitions, as depicted in the following two tables.

	BE	DE	FR	LU	NL
BE			1		1
DE			1	1	1
FR	1	1			
LU		1			
NL	1	1			

(a) Physical connection matrix

#	BE	DE	FR	LU	NL
1	1				
2		1			
...				...	
6	1		1		
7	1				1
...				...	
21	1	1	1	1	1

(b) Possible coalitions

Table 2: Definition of the coalition structure

The number of physically feasible coalitions is thus reduced from $2^5 - 1 = 31$ to 21, due to missing interconnections between several countries. For the 10 remaining coalitions, we define the joint value to be additive, i.e., they may engage in contractual, but no physical cooperation.

Figure 3 shows the resulting LOLE distributions for all possible coalitions, together with the number of coalition members. Visually, we observe a general tendency towards higher levels of reliability when increasing the number of integrated countries, which is in line with the results presented in Section 4. However, a more detailed analysis will be necessary to grasp the problem characteristics.

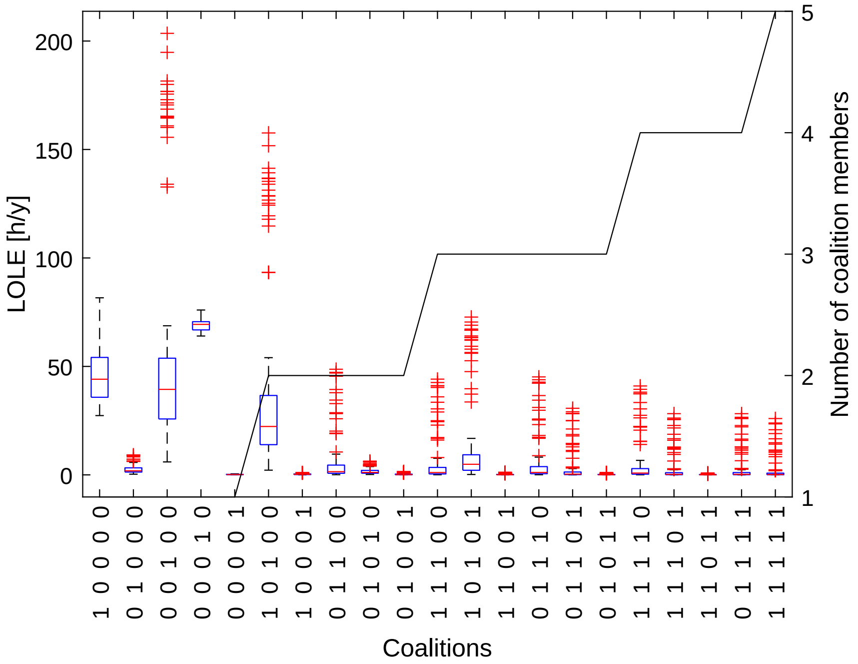

Figure 3: Distribution of coalitions' yearly Loss of Load Expectation

5.2. Problem Characteristics

In a formal analysis of our game, we find the following characteristics (see, e.g., Shapley (1971) for a detailed and more technical reference):

- The game is **weakly sub-additive**, i.e., the joint value of any subset $S \subseteq N$ defined by the joint amount of EEU is equal or smaller than the sum of the values of any partition of S. Therefore – overall – the positive effects from system integration prevail. The EEU of the grand coalition amounts to 549 GWh/y.

- Despite its sub-additivity, the game is found to be **non-convex**. Therefore, there are no clearly increasing incentives for joining a coalition as the coalition grows. Loosely speaking, the level of generation adequacy of the system does not increase proportional with its size. Therefore, it does not hold that the incentives for joining a system strictly increase as the system grows (i.e., no critical mass or snowballing effect).

- The game has a **non-empty core**, i.e., there is a non-empty set of payoff imputations for the grand coalition under which no subset (i.e., smaller coalition) of countries has a value greater than the sum of these countries' payoffs. In other words, there are stable allocations that incentivize all countries to engage in full system integration.

5.3. Problem Solution

In order to make countries engage in a cooperative approach to ensure generation adequacy, we will now look for a suitable solution concept $\Phi \in \mathbb{R}^N$ that incentivizes countries to form and stay within the grand coalition. More practically, we aim at monetary payments as a means to share the realized benefits within the grand coalition by transferring utility from one country to another.

In principle, there would be an infinite number of rules, e.g., Belgium could transfer $1, 2, 3, ...$ monetary units to Germany, etc. However, each rule naturally implies certain properties and should ideally entail desirable outcomes: First, the rule should result in a *stable* coalition, such that no subcoalition has an incentive to deviate. Formally, it should thus lie within the core of the problem. Recalling that the core of the problem was found to be non-empty, we know that such rules must exist. Second, the allocation should also be perceived by the coalition members as *"fair"*. Intuitively, this means that the allocation should respect that countries are different with respect to their contribution to supply adequacy. A more precise definition will be given hereafter.

We will in the following investigate a range of different allocation rules to solve our problem with respect to these properties. For the sake of applicability, we limit our attention to rules that are unique and efficient, i.e., the sum of the individual allocations must add up to the joint value of the grand coalition. As we have normalized our game, this requires that $\sum_i \Phi_i(v) = v(N) = 0$, and thus ensures that transfer payments redistribute wealth among the five countries.[12]

As a natural first solution, we will investigate the *No transfer* rule. Clearly, this solution would be particularly appealing as it circumvents the need to establish any (potentially costly) transfer payments. In other words, the grand coalition could emerge without any intervention.

Besides the *No transfer* rule, we will assess the *Shapley value*, the *Demand-weighted Shapley value*, the *τ-value*, the *Nucleolus*, and the *Solidarity value* which are all well-established in the context of cooperative games. We skip the technical details about these rules and refer the interested reader to Peleg and Sudhölter (2007) or Driessen (2013), for instance.

Table 3 lists the country-specific payoffs for each of the six allocation rules. We report both, absolute and relative values, i.e., the transfer paid (if negative) or received (if positive) by each country as well as (in brackets) the allocated value relative to the country-specific yearly demand (in thousandth). Note again that each rule is efficient with the sum of all country payoffs adding up to zero. Also note that the numbers in Table 3 are given in GWh/y and are thus not per se suitable for monetary transfer payments. However, as the issue at stake is unserved energy, the numbers could easily be weighted with estimates of the VoLL to define actual monetary transfers. Empirical estimates are typically in a range from a few €/kWh to more than 250 €/kWh.[13]

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[12] We also omit the analysis of values that build upon à priori defined unions, such as the Aumann-Drèze or the Owen value as we believe they are inapplicable to our problem.

[13] See, e.g., Serra and Fierro (1997) for the case of Chile, De Nooij et al. (2007) for the Netherlands, Leahy and Tol (2011) for Ireland, or Reichl et al. (2013) for Austria. For a comprehensive recent overview of VoLL estimates, the reader is referred to Schröder and Kuckshinrichs (2015).

In addition to the actual payoffs, Table 3 also reports for each rule the number of coalitions with incentives to deviate from the grand coalition coalition under the suggested payoff. Moreover, the individual countries' EEUs are listed for the isolated and fully integrated state.[14] Note that the sum of the EEU isolated values (-6410.3 GWh/y) is by far worse than the sum of the EEU in the grand coalition (-549 GWh/y), once more indicating the benefits of an integrated system.

	Allocation					**Blocking**
	BE	**DE**	**FR**	**LU**	**NL**	**coalitions**
No transfer	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	8
Shapley value	238.7 (2.8)	1532.1 (3.0)	-2324.3 (-4.9)	8.5 (1.5)	545.0 (4.8)	6
Weighted Shapley value	-91.9 (-1.1)	1160.3 (2.3)	-1551.5 (-3.3)	-54.5 (-9.8)	537.6 (4.7)	1
Tau value	-141.5 (-1.7)	891.3 (1.8)	-1065.2 (-2.3)	15.8 (2.8)	299.6 (2.6)	0
Nucleolus	-92.0 (-1.1)	786.5 (1.6)	-1032.2 (-2.2)	7.4 (1.3)	330.2 (2.9)	0
Solidarity Value	107.6 (1.3)	478.0 (0.9)	-887.6 (-1.9)	80.0 (14.4)	222.0 (2.0)	3
EEU isolated	-640.8 (-7.5)	-224.5 (-0.4)	-5483.6 (-11.6)	-57.9 (-10.4)	-3.5 (0.0)	
EEU in grand coalition	-36.3 (-0.4)	-211.1 (-0.4)	-251.6 (-0.5)	-2.2 (-0.4)	-48.0 (-0.4)	

Table 3: Results for different allocation rules. Absolute values are EEU, in GWh/y; Relative values (in brackets) are EEU / Yearly demand, in thousandth

For illustration, let us discuss Table 3 based on the example of Belgium, while assuming for simplicity that the VoLL is 1 €/kWh: In isolation, the expected loss from blackouts in Belgium is -640.8 Mio.€/y, while it can be reduced to -36.3 Mio.€/y if engaging in the grand coalition of 5 integrated countries. At the same time, all five rules within the grand coalition allocate payoffs to Belgium which clearly leave the country better off compared to isolation (the minimum is -141.5 Mio.€/y (i.e., a payment) which still results in a net benefit compared to the delta of +604.5 Mio.€/y in expected losses from blackouts).

Despite these benefits, Belgium may find it even more attractive to form subcoalitions providing a better payoff compared to the grand coalition under certain allocation rules. This is indicated by the positive numbers of blocking coalitions. Indeed, under the *No transfer* rule, Belgium could team-up in a two-country coalition with the Netherlands to reduce their expected loss from (-36.3) + (-48.0) = -84.3 in the grand coalition to only -10.7 Mio.€/y[15]. If the *No transfer* rule applies, this two-country coalition would therefore have a clear incentive to leave the grand coalition. Due to this reasoning which holds true for 7 further subcoalitions[16], the *No transfer* rule is unstable. In comparison, other allocation rules are (partially) able to compensate Belgium and the Netherlands by means of transfer payments, such that their incentive to leave the grand coalition is mitigated.

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[14] Largest relative EEU isolated numbers are observed for the countries with lowest reliability, in line with the findings presented previously in Section 4, Figure 1. The absolute EEU isolated naturally depends on the size of the country. For instance, Germany and France have a similar yearly consumption of 504 and 471 GWh/h, but very different levels of reliability. In contrast, France and Luxembourg (the latter having a yearly consumption of 5.6 GWh/y) have similar levels of reliability, but very different system sizes.

[15] Note that this latter value is not contained in the table.

[16] E.g., another obvious example are the Netherlands which are better off isolated than under *No transfer*.

For instance, the *Shapley value* allocates to BE and NL 238.7 + 545.0 = 783.7 which – together with their expected loss of (-36.3) + (-48.0) = -84.3 in the grand coalition – leaves them better off with a sum of +699.4 compared to -10.7 in a two-country coalition.

The *Shapley value* is a particularly important solution concept in cooperative game theory, representing the marginal individual contributions to the grand coalition. Moreover, it is normatively fair in the sense that it is the only rule fulfilling the efficiency, additivity, linearity and dummy axioms. Despite these desirable characteristics, however, we find that the Shapley value does not lie in the core, but has 6 blocking coalitions (all comprising France which is given an extremely adverse payoff of -2324.3).[17] The *Weighted Shapley value* considers the countries' demand levels and therefore yields a more balanced result, but still represents a solution with one coalition blocking (namely $S = \{BE, DE, FR, LU\}$ which has an incentive to oppose the relatively large payoff of 537.6 GWh/y to the Netherlands). Similarly, the *Solidarity value*, even though revealing a more egalitarian distribution of the benefit, faces opposition of three subcoalitions.

In contrast to the previous solutions, all two remaining allocation rules imply no blocking coalitions, and can therefore be considered as stable and more appropriate for real-world application. The *τ-value* is a unique allocation for games with a non-empty core, based on the concept of introducing an upper and a lower bound for each country.[18] In contrast, the *Nucleolus* is the (unique) outcome that lexicographically minimizes the list of excesses, i.e., the difference between what the members of the coalition could get by themselves and what they are actually getting if they accept the allocations suggested by a solution. The nucleolus is always located inside the core (if it is non-empty, just as in our case), and thus assures the stability of the grand coalition.

All of the above allocation rules affect the countries' payoffs, and no clear statement can be made which rule is "best". Nevertheless, two conclusions can be made: First, the most appealing solution, namely *No transfer*, results in an unstable payoff structure and therefore seems to be impractical. Second, the *Nucleolus* might be the most suitable allocation rule: No coalition is blocking it, and it shows the lowest variation in relative values (apart from the *No transfer* rule). We argue that a reduced level of heterogeneity in the relative values may substantially facilitate the rule's practical implementation, due to the fact that payoffs will typically be allocated on the demand-side.

5.4. Sensitivity Analysis: The Effect of Additional Interconnectors

As depicted in Section 5.1, our cooperative game's definition is based upon the physical connection matrix which we have so far assumed to be in line with currently existing interconnections.

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[17] Technically, this result stems from the fact that the game is non-convex. If the problem was convex, the Shapley value would necessarily be comprised in the core of the problem.

[18] The bounds are defined by a so-called utopia payoff beyond which the player would be excluded from the grand coalition, and a minimal right payoff which is guaranteed to each player when they offer the utopia payoff to the other players.

Our results depend upon this matrix as physically impossible coalitions can only realize an additive value when jointly being engaged in a coalition.

To investigate the effect of the interconnection infrastructure, we recalculate our results with an alternative physical connection matrix. It comprises all additional interconnections that could eventually be built between the five countries, as shown in Table 4.[19]

	BE	DE	FR	LU	NL
BE		1	1	1	1
DE	1		1	1	1
FR	1	1		1	
LU	1	1	1		
NL	1	1			

Table 4: Physical connection matrix with additional interconnectors

Noticeably, the EEU within the grand coalition (-549 GWh/y in total) will equally emerge from the new setting as countries will again all be interconnected. However, additional interconnections will allow for additional (sub)coalitions, thus potentially leading to a reallocation of payoffs. If so, some countries might be better off, while the payoff for other countries will then necessarily be reduced.[20]

In our calculations we find that the general characteristics of the game are not changed, i.e., it is again (super-)additive, non-convex and has a non-empty core. In contrast, however, the problem solution shows some interesting deviations as can be seen from the allocations and blocking coalitions in Table 5.

	Allocation					**Blocking coalitions**
	BE	**DE**	**FR**	**LU**	**NL**	
No transfer	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	10
Shapley value	293.3 (3.4)	1424.8 (2.8)	-2304.7 (-4.9)	128.4 (23.1)	458.2 (4.0)	7
Weighted Shapley value	119.9 (1.4)	987.5 (2.0)	-1418.4 (-3.0)	-36.9 (-6.6)	347.8 (3.1)	1
Tau value	-81.2 (-1.0)	754.0 (1.5)	-990.6 (-2.1)	16.3 (2.9)	301.4 (2.7)	0
Nucleolus	-74.9 (-0.9)	759.3 (1.5)	-1014.1 (-2.2)	7.4 (1.3)	322.3 (2.8)	0
Solidarity Value	123.4 (1.4)	453.8 (0.9)	-883.5 (-1.9)	112.2 (20.2)	194.2 (1.7)	3
EEU isolated	-640.8 (-7.5)	-224.5 (-0.4)	-5483.6 (-11.6)	-57.9 (-10.4)	-3.5 (0.0)	
EEU in grand coalition	-36.3 (-0.4)	-211.1 (-0.4)	-251.6 (-0.5)	-2.2 (-0.4)	-48.0 (-0.4)	

Table 5: Results for different allocation rules with additional interconnectors. Absolute values are EEU, in GWh/y; Relative values (in brackets) are EEU / Yearly demand, in thousandth

Despite the payoffs (naturally) remaining unchanged in the *No transfer* rule, two additional

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[19] Note that France and the Netherlands as well as Luxembourg and the Netherlands do not share a joint border and can therefore not be interconnected.

[20] Note that it will therefore be difficult to find consensus about additional interconnections within the grand coalition. Nevertheless, it may well be the case that two countries find it *individual* rational and mutually beneficial to build an interconnector at their border.

subcoalitions now exist that oppose this payoff in the grand coalition, i.e., $S = \{BE, DE\}$ and $S = \{BE, DE, LU\}$. Those countries can now realize an improved payoff due to their physical interconnection, while their values were only additive in the original state.

In a similar vein, the *Shapley value* now faces opposition from a different set of subcoalitions. $S = \{BE, DE, FR, LU\}$ is no longer blocking due to increased payoffs (jointly they now get -458.2 GWh/y instead of -545.0 GWh/y). In turn, however, two additional subcoalitions gain power and oppose (namely, $S = \{BE, DE, FR, NL\}$ and $S = \{BE, FR, LU, NL\}$), thus leading to 7 instead of 6 blocking coalitions for the Shapley value. For the *Weighted Shapley value*, the blocking coalition $S = \{BE, DE, FR, LU\}$ is replaced by $S = \{DE, FR, LU, NL\}$ due to the massive payoff reduction for the Netherlands and payoff increase for Belgium. The set of opposing coalitions under the *Solidarity value* remains unchanged.

It is remarkable that Belgium, France and Luxembourg are all better off in all allocation rules. These countries' interconnections were not fully developed in the original state, and the additional lines allow them to build beneficial (sub-)coalitions. Noticeably, these countries would thus have strong incentives to support these new interconnections. The picture is reversed for Germany and The Netherlands which are worse off with additional interconnections.

Overall, applying the same criteria to select a most suitable allocation rule as before (based on stability and low heterogeneity in the relative allocated values), we conclude that the *Nucleolus* delivers promising features which are insusceptible to deviations in the interconnection levels.

6. Conclusions

This paper has investigated the effects from system integration for reliability of supply in electricity systems. We have presented a model to analyze the trade-off between benefits from statistical balancing on the one hand, and the shared risk of cascading outages on the other. In our empirical case study for the European interconnected system, we found that beneficial effects prevail. We have then applied cooperative game-theory to coordinate reliability among integrated countries, finding that without intervention, cooperation would be hindered by systems that are highly reliable by themselves and worse off in an integrated state. In contrast, however, if utility from reliability was transferable, e.g., by means of monetary compensation payments, solutions can be found to incentivize a coordinated approach, due to the subadditivity of the problem. However, non-convexity of the problem limits the number of suitable allocation rules. For instance, several well-established approaches, such as the (weighted) Shapley value, fail to deliver a stable outcome. In contrast, the Nucleolus and τ-value were identified as suitable candidates for the current system state defined by expected load levels, generation and interconnection: no (sub)coalition has an incentive to oppose it. Meanwhile, the Nucleolus shows lower heterogeneity in the relative values which may facilitate practical implementation. In a sensitivity analysis for enhanced interconnections, payoffs are reallocated, but the general picture remains. We concluded that the Nucleolus appears to be the most interesting allocation rule overall to make all countries better off. In practice, it could be used as a basis to share the joint benefit from system integration among individual countries by means of compensation payments, thus supporting their successful integration and cooperation. Yet, in order to bring the concepts presented in this paper closer to application, future work needs to address the effect of limited interconnection capacities, as well as a more detailed analysis of demand-side management.

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Appendix A. Database benchmark

In order to benchmark the power plant database used in this paper, we compare it to three other publicly available sources of information, namely Eurostat, Eurelectric and ENTSO-E (Eurostat (2016), Eurelectric (2014) and ENTSO-E (2016b)). Figure A.4 shows the aggregated net installed capacities for each country for three technological classes each (i.e., nuclear, combustibles and water). Note that in comparison with the much more detailed representation of technological classes in the ewi ER&S database, the other sources aggregate on a much higher level, such that three classes is the best possible resolution for the comparison. As can be seen, overall capacity levels match well. Deviations may be due to different times of accounting, availability of information (e.g., small-scale units), or difficult classification issues (e.g., hydro power).

Appendix B. Availability factors

We assume fuel-type specific factors according to historical observations as reported in VGB and Eurelectric (2012) and dena (2010) and shown in the following Table B.6.

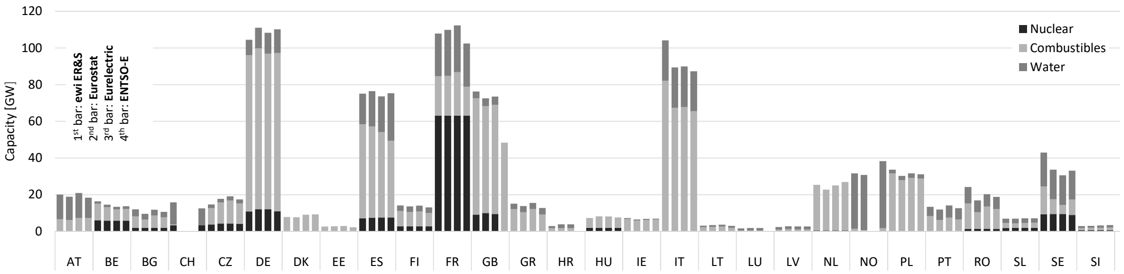

Figure A.4: Comparison of net generating capacity as listed in different sources

Fuel type	**Availability**	**Capacity [GW]**
Biomass	88.0%	6.38
Coal	83.9%	27.73
Gas	88.3%	25.42
Geothermal	90.0%	0.03
Hydro (pump) storage	90.0%	10.63
Hydro run-of-river	40.0%	3.92
Lignite	85.3%	20.95
Nuclear	83.3%	12.07
Oil	89.2%	4.14
Others (Waste, Landfill gas, etc.)	90.0%	5.32

Table B.6: Availability factors and installed capacities per fuel type