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Reliability in Multi-regional Power Systems – Capacity Adequacy and the Role of Interconnectors

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Abstract

Based upon probabilistic reliability metrics, we develop an optimization model to determine the efficient amount and location of firm generation capacity to achieve reliability targets in multi-regional electricity systems. A particular focus lies on the representation and contribution of transmission capacities as well as variable renewable resources. Calibrating our model with a comprehensive dataset for Europe, we find that there are substantial benefits from regional cooperation. The amount of firm generation capacity to meet a perfectly reliably system could be reduced by 36.2 GW (i.e., 6.4 %) compared to an isolated regional approach, which translates to savings of 14.5 bn Euro. Interconnectors contribute in both directions, with capacity values up to their technical maximum of close to 200 %, while wind power contributions are in the range of 3.8 - 29.5 %. Furthermore, we find that specific reliability targets heavily impact the efficient amount and distribution of reliable capacity as well as the contribution of individual technologies.

Keywords: Reliability of supply, Capacity adequacy, Multi-regional power system, Interconnector, Variable renewable energy

JEL classification: C61, C63, D47, L50, Q42, Q48

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1. Introduction

Due to its high economic value, reliability of supply has always been a major concern in electricity systems. The topic has been subject to extensive scientific research effort, both

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from a technical as well as an economic perspective (see, e.g., Billinton (1970) or Telson (1975) for early contributions in the two fields). However, new challenges are currently arising due to the large-scale deployment of renewable energies to avoid greenhouse gas emissions and combat climate change. The reason lies in the variable nature of many renewable energy resources, such as wind and solar, and the possible risk of recurring unavailability during times of stress (e.g., Cramton et al. (2013)).

In order to foster reliability of supply in power systems, interconnections with neighboring regions have proven an effective means. As such, balancing effects in supply and demand may be lifted, and better overall reliability levels be reached (e.g., Cepeda et al. (2009) or Hagspiel (2017)). In fact, enhanced reliability of supply was the main reason to create large interconnected electricity systems, such as the European or the North-American one. In the context of renewable energy integration, large-scale systems gain further importance due to the fact that renewable energy resources are typically more diverse on a wide geographical scope. Hence, cooperative actions with respect to reliability gain further importance to account for balancing effects (both in load and generation) and to reach envisaged reliability levels at lower costs compared to an isolated approach.

From a political perspective, however, reliability of supply is often considered an issue of national interest. As a consequence, assessments and measures to ensure reliability often have a narrow spatial scope, e.g., bounded by national borders.[1] For instance, capacity mechanisms have been put into place in many power systems worldwide, with the aim to reach a certain level of reliability within national borders (e.g., Joskow (2008)). In this context, interconnectors with neighboring countries are often included in a very simplified manner, or even excluded explicitly. This inevitably results in market distortions and economic inefficiencies (e.g. Newbery (2015)). As a countermeasure, the European Union has recently required member states to account for cross-border trade within capacity mechanisms (EU Commission (2016)). Benefits shall thus be lifted by means of cooperative considerations and actions. However, it so far lacks stringent approaches to investigate reliability in multi-regional power systems with capacity-constrained interconnectors to ensure security of supply in highly meshed and interdependent electricity systems (Newbery (2015)). At the same time – as we will show in this paper – cross-regional effects and

[1]This is particularly relevant for the European context where energy policy is largely driven by idiosyncratic yet interconnected and interdependent nation states. Note that this is in contrast to other more integrated systems, such as – for instance – the multi-state approach of the PJM independent system operator in the Eastern interconnection (U.Ss) controlled by the Federal Energy Regulatory Commission (a single policy maker).

interconnectors have a major impact on reliability assessments. Especially, they largely drive the overall amount and distribution of generation capacity needed to ensure reliability. Therefore, misspecifications may entail substantial economic inefficiencies and distributive effects.

As a simple intuitive example, consider two systems A and B: In an isolated system-state, A and B both require 5 units of reliable capacity to achieve a certain reliability target. It is clear that the overall amount of reliable capacity might be decreased to less than 10 units when these systems interconnect, for instance due to statistical balancing in load. However, determining the optimal overall amount of reliable capacity Z and its best locational shares Z_A, Z_B for reliable capacities requires a consistent analysis of the entire system, including the joint probability distribution of load and generation as well as limited interconnection capacities. Naturally, the extension to $N > 2$ interconnected systems further complicates the problem and constitutes a complex multivariate probabilistic optimization problem.

Against this background, this paper provides a comprehensive framework to investigate reliability in power systems consisting of multiple technologies and multiple interconnected regions. We first review well-known probabilistic metrics to determine the level of reliability in isolated one-regional power systems as well as the contribution of individual generators (known as capacity value[2]). Subsequently, we extend this literature which typically neglects capacity-constrained transmission infrastructure. In contrast to (stochastic) simulation techniques, we propose a novel approach based on a comprehensive optimization model that flexibly accounts for multi-regional settings and multiple generation technologies, including dispatchable power plants and variable renewable energies, as well as capacity-constrained transmission lines. The main innovative strength of this model lies in its ability to quantify the economically efficient amount and distribution of reliable capacity in each region within a consistent optimization framework. Furthermore, it may also be used to determine the capacity value of individual technologies in a system context. Our paper therefore incurs some noticeable difference compared to papers or reports that assess adequacy for a given or assumed system state, such as the report of the PLEF on system adequacy (Pentalateral Energy Forum (2018)) or ENTSO-E's Seasonal Outlook (ENTSO-E (2017)). While these latter assessments take generation capacities as exogenous input to derive reliability metrics, our approach tackles the issue from the opposite side: we take reliability metrics as given and endogenously optimize the firm capacity levels across interconnected regions to achieve

[2]Capacity value is also often referred to as capacity credit. Throughout this paper we will, however, stick to the term capacity value.

these targets.

After a general description of our methodology, we introduce the comprehensive numerical dataset used to calibrate our model for different European case studies. The focus of the data lies on system properties incorporating large-scale variations – such as infeed from wind and solar power – to replicate the (joint) probability of various possible system outcomes. As direct observations are missing (due to a rapid system development with respect to the deployment of variable renewable energies), we build our optimization on a synthetic dataset created from 20 years of hourly reanalysis data with a high level of spatial resolution. In contrast, we abstract from a full representation of other existing generators in the system to be in line with our objective to endogenously determine the amount of equivalent firm capacity needed to serve load at some level of reliability.

In a first step, we illustrate our approach based on two two-regional systems (namely France - Germany and France - Great Britain). Specifically, we depict how an interconnector can contribute to reliability, dependent on its size as well as the joint probability of load levels and capacity availability. Second, we apply the model to the entire European electricity system in order to quantify the efficient amount and location of firm generation capacity to achieve reliability targets as well as the contribution of wind power and interconnectors in a realistic case study. Compared to an isolated region-by-region approach, cooperation by means of an efficient usage of interconnectors would allow to reduce the overall necessary amount of reliable generation capacity by 32.4 GW (i.e., 6.1 %) on a European level to ensure perfect reliability, also impacting the distribution of capacities. In this cooperative solution, several interconnectors contribute in both directions, with up to their technical maximum of close to 200 % of their nominal capacity.[3] In contrast, due to its variability, the contribution of wind power is only in the range of 3.8 - 29.5 %. These results provide empirical evidence that a consistent analysis of multi-regional systems with restricted interconnector capacities is crucial for reliability of supply analyses. In practice, our approach could thus be used for the improved design of capacity mechanisms by providing an approach to consider interdependencies with physically connected neighbors. Moreover, the large differences between the first-best and isolated results provide strong arguments to achieve reliability targets efficiently in a cooperative manner, e.g., by means of joint capacity mechanisms.

As an additional insight, we find that specific reliability targets heavily impact the efficient amount and distribution of reliable capacity as well as the contribution of individual

[3] In our calibration, we will assume a directional transmission efficiency $<100\,\%$, such that the capacity value is slightly reduced.

technologies. In practice, policymakers and system engineers should therefore choose reliability targets for power systems with care to avoid inefficiencies from excessively high (or low) capacity levels.

The rest of this paper is structured as follows: In Section 2, we introduce our methodology. The data are discussed in Section 3, while our results are comprised in Section 4. Section 5 concludes.

2. Methodology

Different methodologies have been proposed to determine generation adequacy and the capacity value of individual technologies in settings with one region only (i.e., without considering grid restrictions). The Loss-of-Load-Expectation (LOLE) and the Expected-Energy-Unserved (EEU) are two well established measures to depict the ability of a system to cover expected load levels (e.g., Billinton and Allan (1996)). After having determined the total system's adequacy, one may derive the contribution of individual technologies – typically referred to as capacity value or capacity credit (e.g., Keane et al. (2011), Madaeni et al. (2013)). Different approaches exist, but the equivalent firm capacity (EFC) is often recommended due to its ability to provide consistent results (Amelin (2009)).

In the following, we will first revise the well-known LOLE, EEU and EFC measures, valid for a one-region one-technology setting. We will then present an alternative formulation based on an optimization problem, before we extend our analysis to generation adequacy and the capacity value in a multi-region multi-technology context.

2.1. Notation

We will use the notation as listed in Table 1. Unless noted differently, we will use capital letters for random variables, bold capital letters for sets, and lower case letters for parameters, and bold lower case letters for nominal optimization variables.

2.2. Reliability metrics for one region only

In a self-contained system without transmission constraints, we follow Billinton and Allan (1996) and define the loss-of-load probability at a specific instant in time t as

$$LOLP_t = P(X_t^e < L_t), \tag{1}$$

i.e., as the probability that the available existing capacity X^e is smaller than load L_t. X_t^e will typically represent the availability of multiple power generators in the system, each

Sets	
$i \in \mathbf{I}$	Existing generators
$m, n \in \mathbf{M}$	Regions
$t \in \mathbf{T}$	Time slices
Random variables	
L	Load
X^e	Availability of existing capacity
Y	Availability of extra capacity
K	Availability of import capacity
Parameters	
$LOLP$	Loss of load probability
$LOLE$	Loss of load expectation
EEU	Expected energy unserved
$\bar{x}^e$	Nominal capacity of existing generator
x^e	Availability of existing generator
$\bar{y}$	Nominal capacity of extra generator
v	Capacity value of extra capacity $\bar{y}$
l	Load
$\bar{k}$	Transmission capacity
η	Transmission efficiency
Optimization variables	
$\mathbf{z}$	Overall equivalent firm capacity needed
$\mathbf{z}^y$	Equivalent firm capacity of extra capacity $\bar{y}$
$\mathbf{u}$	Load curtailment
$\mathbf{k}$	Capacity exchange

Table 1: Model sets, parameters and variables

characterized by its nominal capacity $\bar{x}_i^e$ and its capacity availability $X_{i,t}^e \in [0,1]$, such that $X_t^e = \sum_{i \in \mathbf{I}} \bar{x}_i^e X_{i,t}^e$. Note that in the above equation, we implicitly assume that load is inelastic with no adjustment when capacity is scarce, e.g., due to the lack of real time pricing. Consequently, in a market environment, there may be situations where all capacities are running at maximum availability without being able to serve the level of load, i.e., market clearing cannot be guaranteed even if there are high price levels.

Summing up probabilities over some time-period T yields the well-known reliability level measure Loss-of-Load-Expectation

$$LOLE = \sum_{t \in \mathbf{T}} LOLP_t. \tag{2}$$

A straightforward extension of the LOLE is the reliability measure EEU, weighting the LOLPs with the expected load level that cannot be served (therefore indicating the severity of these situations):

$$EEU = \sum_{t \in \mathbf{T}} E(L_t - X_t^e) * LOLP_t. \tag{3}$$

To determine the contribution of individual technologies, we determine their equivalent firm capacity. I.e., we derive the amount of equivalent firm capacity $\mathbf{z}^y$ by which X_t^e can be reduced when installing some new capacity $\bar{y}$ with availability $Y_t \in [0, 1]$ whose capacity value shall be determined, such that the initial (target) reliability level EEU is achieved. To this end, the modified equation that needs to be solved for $\mathbf{z}^y$ writes as

$$EEU = \sum_{t \in \mathbf{T}} E(L_t - (X_t^e + \bar{y}Y_t - \mathbf{z}^y)) * P(X_t^e + \bar{y}Y_t - \mathbf{z}^y < L_t). \tag{4}$$

Due to the fact that $\bar{y} > 0$ and $0 \leq Y_t \leq 1$, it must hold that $\mathbf{z}^y \geq 0$. The capacity value of a technology with capacity $\bar{y}$ is then defined as

$$v = \frac{\mathbf{z}^y}{\bar{y}}, \tag{5}$$

with $0 \leq v \leq 1$.

Note that the above equations for the capacity value are typically solved by means of numerical iteration. Loosely speaking, after $\bar{y}$ has been added to the system, in each step $\mathbf{z}^y$ is increased by some small amount until the target EEU is reached. Due to the convexity of the problem, this approach is guaranteed to yield the desired result.

2.3. The effect of interconnections

In contrast to the self-contained system considered before (say, system m), let us now study the effect of system interconnections. For illustration, assume m is interconnected with system n by means of a line with maximum transfer capacity $\bar{k}$. In this case, the $LOLP$ of m needs to be extended by several terms:[4]

$$\begin{aligned}
LOLP_{m \leftarrow n} = P(&X_m < L_m \text{ and} && \text{(6a)}\\
&[X_n < L_n \text{ or} && \text{(6b)}\\
&(X_n > L_n \text{ and } L_m - X_m > X_n - L_n) \text{ or} && \text{(6c)}\\
&(X_n > L_n \text{ and } L_m - X_m < X_n - L_n \text{ and } L_m - X_m > \bar{k})]). && \text{(6d)}
\end{aligned}$$

[4]For better readability, we skip the subscript t and superscript e here.

The above equations state that a capacity shortage $X_m < L_m$ in system m may be relieved by means of an interconnection with system n. However, this does not hold if there is no spare capacity in n (Equation (6b)), if the spare capacity is not large enough to cover the shortage in m (Equation (6c)), or if the transfer capacity is not sufficient to cover the shortage in m (Equation (6d)). We will illustrate the meaning of these four terms for a numerical example in Section 4.

Note that comparing Equation (6) with Equation (1) reveals that it must hold that $LOLP_{m \leftarrow n} \leq LOLP_m$, i.e., that an interconnected system m is at least as reliable as if it was isolated. Consequently, interconnections will have a neutral or a lowering effect on the level of equivalent firm capacity needed to serve load at some predefined level of reliability in the respective systems.

This beneficial effect may also be seen in an alternative formulation for the LOLP of m being interconnected with n, where capacity imports are contained in a lump-sum variable $K_{m \leftarrow n}$:

$$LOLP_{m \leftarrow n} = P(X_m + K_{m \leftarrow n} < L_m) \tag{7}$$

Due to the fact that only imports are considered, K is positive. From above, K is bounded by the import capacity $\bar{k}$, such that the support of $K_{m \leftarrow n}$ is $[0, \bar{k}]$. Of course – as stated above – if K is positive, it must be that $LOLP_{m \leftarrow n} \leq LOLP_m$. Or, conversely, that the amount of equivalent firm capacity needed may be smaller in an interconnected system to reach a fixed target reliability.

Unfortunately, beyond the statement that interconnections must yield positive effects, this theoretical analysis does not allow to derive further details regarding the size of the effect. This is due to the fact that the specific system's $LOLP$ (and thus, its $LOLE$, too) depends on the specific statistical characteristics of the random variables involved, i.e., their joint distributions. In fact, even if assuming independent variables in the above equations, the joint distributions and inequalities can – if at all – analytically only be tackled by means of upper and lower bounds (e.g., by applying Hoeffding's or Bennett's inequality). The case is further complicated when considering dependent variables which naturally occur in our area of application, such as load and wind profiles in neighboring countries.

Because of these inherent analytical complexities, we will continue our analysis by presenting a framework to endogenously determine the level of equivalent firm capacity which we can calibrate with numerical data to derive further insights into the generation adequacy of multi-regional interconnected systems.

2.4. A framework for endogenous equivalent firm capacity

The above introduced reliability metrics typically build upon *exogenous* systems, characterized by the availability of existing capacities X_t^e and (expected future) demand levels L_t. In contrast, we suggest an approach to *endogenize* the level of equivalent firm capacity. Similar to the concept of equivalent firm capacity described in Equation (4), we strive for a probabilistic optimization program minimizing the equivalent firm capacity $\mathbf{z}$ that needs to be added to (or removed from) the system to achieve the target reliability level EEU. For notational simplicity, let us drop the capacity additions $\bar{y}$ and aggregate all capacities exogenously given to the system by their nominal capacities $\bar{x}_i^e$ and their capacity availabilities $X_{i,t}^e$. The program to solve for one region can be written as follows (8):

$$\min \mathbf{z} \tag{8a}$$

$$\text{s.t.} \quad \sum_{t \in \mathbf{T}} E(L_t - (\sum_{i \in \mathbf{I}} \bar{x}_i^e X_{i,t}^e + \mathbf{z})) * P(\sum_{i \in \mathbf{I}} \bar{x}_i^e X_{i,t}^e + \mathbf{z} < L_t) \leq EEU \tag{8b}$$

Due to the fact that the above probabilistic problem is hardly solvable for the general case, we formulate its deterministic equivalent which is a linear program. The idea is to replace probabilities and random variables by their deterministic counterpart, which may then be calibrated based on data covering a large range of possible outcomes. The validity and consistency of the result obtained may then be justified by the central limit theorem (Zachary and Dent (2011)).

For one single region (or market), the objective function (9a) minimizes the equivalent firm capacity $\mathbf{z}$ in this region subject to two constraints: First, the adequacy constraint (9b) states that the equivalent firm capacity should be greater or equal to the region-specific and time-varying demand l_t minus the load curtailment variable $\mathbf{u}_t$ minus the sum of the exogenously given technologies' available capacity at every instant in time t. And second, the reliability constraint (9c) requires the sum of load curtailment activities $\mathbf{u}_t$ not to exceed a certain reliability target, specified as expected energy unserved EEU within the considered period of time T.[5]

$$\min \mathbf{z} \tag{9a}$$

$$\text{s.t.} \qquad \mathbf{z} \geq l_t - \mathbf{u}_t - \sum_{i \in \mathbf{I}} \bar{x}_i^e x_{i,t}^e \qquad \forall t \tag{9b}$$

$$\sum_{t \in \mathbf{T}} \mathbf{u}_t \leq EEU \tag{9c}$$

Note that the load curtailment variable $\mathbf{u}_t$ allows for a relaxation of the load serving requirement in Equation (9b). If EEU is set to zero, only one of the hourly constraints (9b) is binding, namely the hour of peak residual demand (given that all residual demand levels are distinct).[6] With EEU increasing, the peaks are increasingly shaved off by the load curtailment variable $\mathbf{u}_t$.

Solving roblem (9) yields $\mathbf{z}^*$, i.e., the equivalent firm capacity required to obtain the requested level of reliability in one region. In order to determine the capacity value of technology $i = i'$, we simply need to set $\bar{x}_{i'}$ to zero and resolve the model, thus yielding $\mathbf{z}^+$. Equivalent to the difference in equivalent firm capacity depicted in Equation (5), the technology and region-specific capacity value can then be calculated by Equation (10).

$$v = \frac{\mathbf{z}^+ - \mathbf{z}^*}{\bar{x}_{i'}} \tag{10}$$

2.5. Extension to interconnected regions

Extending Problem (9) to multiple interconnected regions while assuming cooperation with respect to reliability, the planning problem becomes an integrated optimization. The objective function (11a) aims at minimizing the sum of required equivalent firm capacity $\mathbf{z}_m$ over all regions, subject to four constraints: First, the adequacy constraint (11b) states

[5]Note that it is straightforward to reformulate the problem when reliability targets are based on the *LOLE* measure. Specifically, Equations (9b) and (9c) need to be modified using $\mathbf{s}_t$ as the load shedding (binary) variable:

$$\mathbf{z} \geq l_t \mathbf{s}_t - \sum_i \bar{x}_i^e x_{i,t}^e \quad \forall t$$

$$\sum_t (1 - \mathbf{s}_t) \leq LOLE$$

Note that for the case of LOLE, the problem becomes a mixed integer optimization.

[6]Residual demand $= l_t - \sum_i \bar{x}_i^e x_{i,t}^e$.

that the required equivalent firm capacity should be greater or equal to the region-specific and time-varying load $l_{m,t}$ minus the load curtailment variable $\mathbf{u}_{m,t}$, minus the sum of the additional technologies' available capacity, and plus electricity exchanges $\mathbf{k}_{m,n,t}$ from region m to region n at every instant in time t. We charge electricity imports with an efficiency loss $\eta_{m,n}$ in order to account for transmission losses. The reliability constraint (11c) remains unchanged compared to the one-region optimization above. Note that by Equation (11c), a specific target reliability shall be reached within each region. Additionally, however, we now need an electricity exchange constraint (11d) limiting $\mathbf{k}_{m,n,t}$ to the installed transmission capacity $\bar{\mathbf{k}}_{m,n}$.[7]

$$\min \sum_{m\in\mathbf{M}} \mathbf{z}_m \tag{11a}$$

$$\begin{aligned}\text{s.t.} \quad \mathbf{z}_m \geq\ & l_{m,t} - \mathbf{u}_{m,t} - \sum_{i\in\mathbf{I}} \bar{x}^e_{i,m} x^e_{i,m,t} \\ & + \sum_{n\in\mathbf{M}} \mathbf{k}_{m,n,t} - \sum_{n\in\mathbf{M}} \eta_{m,n}\mathbf{k}_{n,m,t} \qquad \forall m,t,m\neq n \end{aligned} \tag{11b}$$

$$\sum_{t\in\mathbf{T}} \mathbf{u}_{m,t} \leq EEU_m \qquad \forall m \tag{11c}$$

$$\mathbf{k}_{m,n,t} \leq \bar{k}_{m,n} \qquad \forall m,n,t,m\neq n \tag{11d}$$

Solving Problem (11) yields $\mathbf{z}^*_m$. In order to determine the capacity value of technology $i = i'$ in region $m = m'$ with respect to the entire system, we set the corresponding capacity $\bar{x}^e_{i',m'}$ to zero and resolve the model, which yields $\mathbf{z}^+_m$. Based on the result we can calculate $v_{m',i'} = \frac{\sum_{m\in\mathbf{M}} \mathbf{z}^+_m - \mathbf{z}^*_m}{\bar{x}^e_{i',m'}}$. In contrast, if we aim at the capacity value of technology $i = i'$ in region $m = m'$ with respect to its own isolated region m', we solve the problem for isolated systems and calculate $v_{m',i'} = \frac{\mathbf{z}^+_{m'} - \mathbf{z}^*_{m'}}{\bar{x}^e_{i',m'}}$. Analogously, we can determine the capacity value of a specific transmission capacity $\bar{k}_{m',n'}$ between region $m = m'$ and $n = n'$ by setting the capacity to zero and solving for capacity levels $\mathbf{z}^+_m$.

3. Data

The data required to calibrate our model can be classified into three areas: First, we need region- and time-specific load levels ($l_{m,t}$). Second, information is required for capacity

[7] Again, reformulation to represent the $LOLE$ measure is straightforward.

availabilities of existing generators, i.e., installed nominal capacity levels $\bar{x}^e_{i,m}$ as well as their corresponding availabilities $x^e_{i,m,t}$. Third, we need data on the transmission capacities $\bar{k}_{m,n}$.

Common to all data will be the regional coverage: We aggregate data on a national level, and cover the following European regions: Austria (AT), Belgium (BE), Bulgaria (BG), Switzerland (CH), Czech Republic (CZ), Germany (DE), Denmark (DK), Estonia (EE), Spain (ES), Finland (FI), France (FR), Great Britain (GB), Greece (GR), Croatia (HR), Hungary (HU), Ireland (IE), Italy (IT), Lithuania (LT), Luxembourg (LU), Latvia (LV), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Sweden (SE), Slovenia (SI), Slovakia (SK).

Recall that load $l_{m,t}$ and generation availability $x^e_{i,m,t}$ need to be calibrated with a large amount of possible outcomes to replicate the characteristics of the corresponding random variables L_t, X^e_t. To this end, we will deploy the so-called hindcast approach, i.e., we calibrate the model using a large number of historical joint observations (for details, the reader is referred to Zachary and Dent (2011) and Keane et al. (2011)). Furthermore, we combine historical observations in order to better represent the joint probability space. Specifically, we focus our attention on load and wind capacity availability, which are the system properties with the largest variation.

Load data are taken from ENTSO-E (ENTSO-E (2016a)) for the years 2010 - 2015. They depict the national vertical load, i.e., the amount of electricity consumed, on an hourly basis. It should be noticed that these historical measurements were a result of a functioning electricity system and may include some price responsiveness of consumers or load shedding. To calibrate our model, however, we need to assume that the observed load data is price inelastic. Meanwhile, historical load data is the best proxy available for the fluctuating electricity demand over time, and price responsiveness during times of scarcity was indeed found to be fairly low (Lijesen, 2007).

Our hourly wind generation profiles are based on wind speeds from reanalysis data in COSMO-REA6 provided by the Hans Ertel Centre for Weather Research (HErZ) (Bollmeyer et al., 2015). Energy output has been calculated for the existing wind parks in 2014 using data from *The Wind Power*[8] with the methodology explained in Henckes et al. (2018). The total dataset consists of 20 years with hourly wind production levels from 1995 - 2014. In contrast to wind power, solar power could not be included due to the lack of sufficiently disaggregated data with respect to installed capacities.

We combine each load year with each wind year available in order to get a good repre-

[8] `www.thewindpower.net`

sentation of the joint probability space. Noticeably, we implicitly assume there is no causal relationship between wind and load. [9] This leads us to a total of 120 years with hourly load and wind data. Note that the amount of data used in our analysis is well beyond the requirements identified by Hasche et al. (2011), and can hence be expected to yield consistent results. In order to reduce the computational burden, we focus our analysis on the relevant, most extreme conditions. This was done by sorting and filtering the data at a threshold of 0.1 % of the highest residual load cases being relevant for system adequacy.[10]

In contrast to the detailed representation of load and wind, we abstract from a full representation of other existing generators in the system. This is mainly due to three reasons: First, detailed information about installed capacities of individual generators and their capacity availabilities is difficult to obtain (i.e., for thermal and hydro power plants, but also for other renewable technologies, such as PV). Second, abstraction allows to circumvent the need to derive a probability function for the availability of capacity X, usually depicted via a Capacity Outage Probability Table (COPT) and calculated via convolution.[11] Third, and most importantly, abstraction is in line with our objective to determine the amount of equivalent firm capacity needed to serve load at some level of reliability. Therefore, our model can be seen as a way to endogenously determine the amount of equivalent firm capacity that needs to enter the system while other system characteristics are fixed. For instance, the expansion of renewable energies is typically driven by support schemes and hence largely exogenous.

Data on transmission capacities are based on publications by ENTSO-E in the Ten Year Network Development Plan (ENTSO-E, 2016c). We make use of Net Transfer Capacity (NTC) values to represent average transmission capacities between countries in 2016. NTC is the maximum exchange program between two areas compatible with security standards applicable in both areas and taking into account the technical uncertainties on future network conditions ETSO (2001).

[9] The average correlation over all countries between wind and load is 0.08 with a median of 0.06. Therefore we assume no causal relation between both.

[10] We tested up to which point the filtering had an effect on the results and found that while increasing the threshold from 0.1 % to 0.2 % had no effect, a further reduction to 0.07 % indeed influenced the results.

[11] Note that implicitly, we thus also circumvent the need to further reflect on fundamental policy differences between countries that might affect the entire argument of a more efficient Europe, such as substantial differences in nuclear or renewable policies, for instance.

4. Results

We present our results in two main steps: first, we consider the illustrative case of two-regional systems to gain insights into the general problem characteristics and model outcomes. Second, we deploy our complete dataset for the entire European continent for more comprehensive and realistic results.

4.1. Two-regional system

4.1.1. Isolated regions

For illustration, we parametrise our isolated region model (i.e., Problem (9)) with one year of data from France, Germany and Great Britain. Figure 1 shows scatter plots of residual load (i.e., load - wind power) for the region combinations Great Britain - France (left) and Germany - France (right).

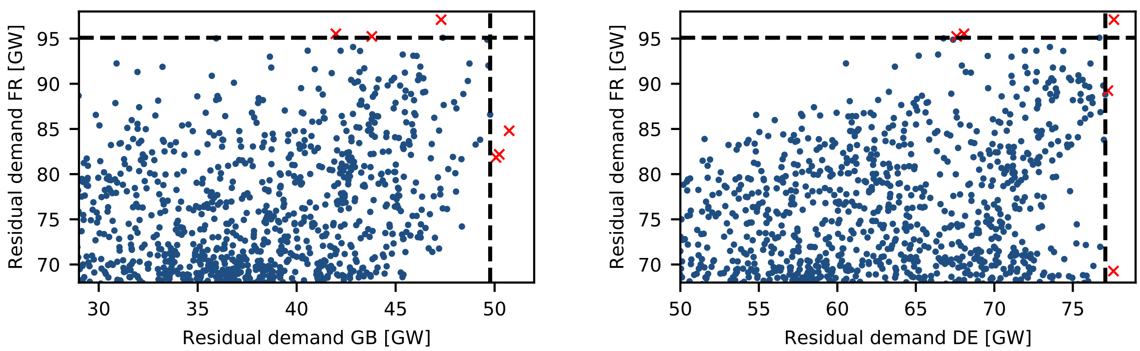


Figure 1: Critical residual demand in the isolated two-regional systems Great Britain (GB) - France (FR) (left) and Germany (DE) - France (FR) (right) for LOLE = 3 h/y

The dashed lines represent the level of equivalent firm capacity ($\mathbf{z_m}$) required in the respective region when they strive for reliability in an isolated approach.[12] We apply here a typical reliability benchmark of 3 hours per year which is often used in theory (e.g., Keane et al. (2011)) as well as in practice (e.g., in the capacity markets in Great Britain or by the ISO New England). Therefore, the scatter plots depict residual load levels exceeding the necessary level of equivalent firm capacity during 3 hours in each region. In our methodology section, this would have been depicted by an expected value of 3 in Equation (2). Naturally,

[12]Recall from the previous sections that this level of equivalent firm capacity relates to the overall system needs and does not distinguish existing power generation units, except for wind power. Nevertheless, for deriving further practical implications, one may compare these figures with (derated) existing capacities present in today's power system. We will do so in Section 4.2.

tightening the reliability target shifts the required equivalent firm capacity lines outwards, up to a perfectly reliable system (LOLE = 0) where the dotted lines cover all residual load levels and no load shedding is allowed to occur.

Note that in the right hand side figure, there is one situation where residual load cannot be met in both regions at the same time (indicated by the dot in the rectangle in the upper right corner). In contrast, the data in the left hand side figure show no coincidental load shedding. This is crucial for benefits from cooperation, as demonstrated in Equation (6) and discussed in the subsequent section.

4.1.2. Cooperating regions

In case of cooperation, regions take into account interconnections with neighbors to reach their envisaged reliability target while solving the integrated problem (11). Therefore, they take full advantage of balancing effects on the supply as well as on the demand side.

Requirements for equivalent firm capacity. For illustration, in Figure 2 we recapture the region combinations Great Britain - France and Germany - France. Again, the thicker dashed lines depict the necessary equivalent firm capacity level per region which can now be reduced due to gains from cooperation (corresponds to term (6a) in Equation (6)). The thinner dotted lines represent the sum of equivalent firm capacity plus transmission capacity (2 GW for GB - FR and 1.2 GW for FR - DE), derated by a transfer efficiency of 0.95.[13] Thus, all points in between the dashed and dotted lines – indicated by green triangles – can be covered by capacity exchange between the two regions.

Noticeably, interconnectors can only contribute to system adequacy if there is sufficient generation in the adjacent region to be exported. This is the case as long as the point of interest does not lie above the sloped dotted line in the top right corner which limits the interconnector's contribution to system adequacy (depicted by terms (6b)-(6d) in Equation (6)). Interestingly, as the critical situations change due to the interconnection, there are now two situations in the right hand side figure where residual load cannot be met in both regions simultaneously (indicated by the two crosses in the upper right corner). Also in the left hand side figure, there is now one simultaneous load curtailment situation. This explains the reduced number of crosses compared to Figure 1.

[13]The directional efficiency factors of transmission capacities are hard to quantify and break down to one single number. In reality they depend on line length and the topology of the grid. As our model is focused on gaining first insights based on the methodology proposed we use a value of 0.95 as an estimate.

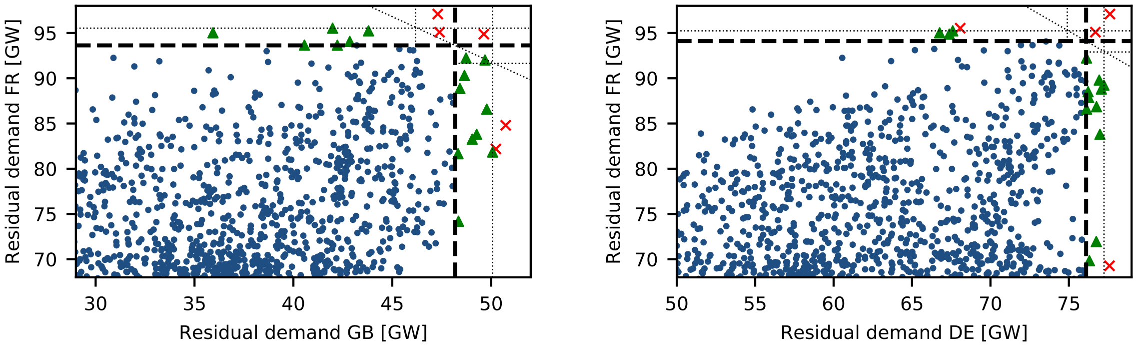


Figure 2: Critical residual demand in the cooperating two-regional systems Great Britain (GB) - France (FR) (left) and Germany (DE) - France (FR) (right) for LOLE = 3 h/y

The capacity value of wind power. Figure 3 shows the capacity value of wind power derived from Equation (10)) and the full dataset for isolated and cooperating two-regional systems. The graph depicts the capacity value of increasing wind capacities ranging from 0 - 80 GW in the respective region, while in the cooperation case the installed wind capacity in the interconnected region is held constant at its installed capacity in 2014, as listed in Table 3 in the Appendix. In general, our results confirm that the capacity value decreases with increasing capacity installations due to decreasing returns to scale (e.g., see numerical evidence by Hasche et al. (2011) or Keane et al. (2011), or theoretical analyses by Zachary and Dent (2011) or Hagspiel (2018)). For perfectly reliable systems (LOLE = 0), the problem reduces to the analysis of the hour with peak residual load. Due to the stochastic nature and at times low output of wind power, this approach yields low and rather flat capacity values in a perfectly reliable system (Figures 3a, 3b). Flat capacity values arise when peak residual load is reduced at a constant rate with increasing wind capacity. Relaxing the reliability constraint to LOLE = 3 (Figures 3c, 3d) and the corresponding EEU (Figures 3e, 3f) increases the capacity value of wind, due to the fact that wind is then allowed to deliver its contribution within a longer (i.e., relaxed) period.[14] Note that this results from the shaved off peaks due to load curtailment. Thus we observe that setting a low reliability level EEU results in flat capacity values for wind power which in turn increases equivalent firm capacity requirements and thereby total system costs.

Figure 3 also shows how the capacity value of wind is affected by cooperation, i.e., a change in the reference system the wind may contribute to. For LOLE = 0, wind in Great

[14]The EEU has been derived from Equation (3) with a LOLE = 3 in isolated regions, resulting in EEU values amounting to GB 3.72 GWh, FR 6.17 GWh, and DE 2.43 GWh.

Britain and France does not benefit from cooperation, as the interconnector is used to its full capacity during peak load, irrespective of the installed wind capacity in the two regions (Figures 3a, 3b). In contrast, the usage of German interconnectors during peak load increases with increasing wind capacity, thus reducing the equivalent firm capacity requirements of the interconnected system, and resulting in improved wind capacity values (Figure 3b).

Interestingly, at relaxed reliability levels and wind capacities >10 GW in Great Britain, the capacity value of wind for cooperating regions is (slightly) lower than for isolated regions. This at first counter-intuitive result can be explained by the observation that, in contrast to wind capacities <10 GW, the critical residual load situations switch to hours where the interconnectors with France and Great Britain are congested, resulting in higher equivalent firm capacity requirement.

Even though the EEU reliability target is directly derived from LOLE = 3, capacity values are different (Figures 3e, 3f). Especially, the capacity value of wind in France for capacities <10 GW is not constant as for LOLE = 3, but decreases starting from a higher value. This is due to the fact that the EEU target allows to distribute the energy unserved to an arbitrary amount instead of only a restricted amount of hours.

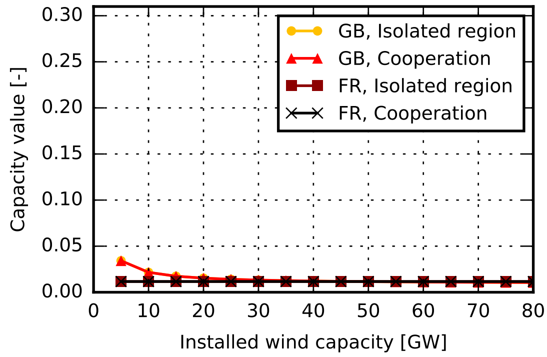
The capacity value of interconnectors. Figure 4 shows the capacity value of the interconnectors for cooperating two-regional systems. Noticeably, values can exceed 100 % due to its utilisation in two directions. Thus, they are limited by 200 % in a world without transmission losses, and by 190 % when taking into account directional efficiency factors of $\eta = 0.95$.

The interconnector between Great Britain and France is found to be highly beneficial, contributing its technical maximum to both regions at low capacity levels. This implies that peak load hours are mutually exclusive. Capacity values begin to drop slightly after 4.3 GW for LOLE = 0, and after 2 GW for relaxed reliability targets.

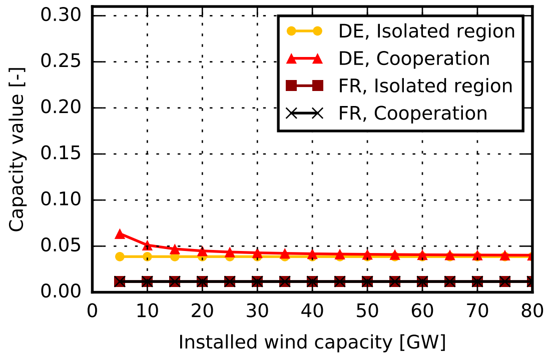
Looking at the two-region system Germany - France with LOLE = 0, the interconnector capacity value is at its maximum up to an interconnector capacity of 1.3 GW, followed by a sharp decrease. Relaxing the reliability level to LOLE = 3 or EEU leads to new peak residual demand situations where the interconnector capacity is not fully utilized anymore. This results in lower values for small capacities, but also much slower decrease (such that the curves intersect with the one for LOLE = 0). Essentially, this is due to the shape of the residual demand curve as compared to the peak residual load.

4.2. European system

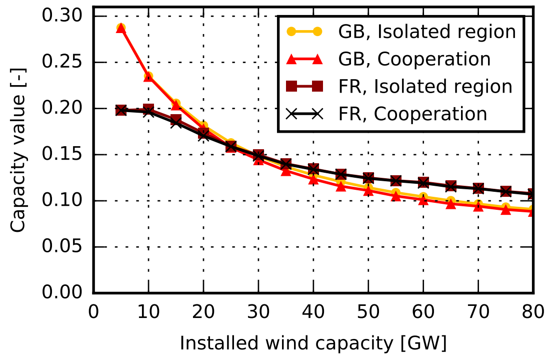
We will now investigate efficiency gains through cooperation on a European level. More specifically, we look at minimum required equivalent firm capacity in each region consid-



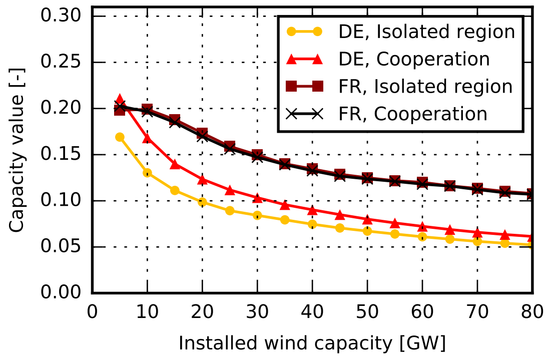
(a) Wind power in GB and FR, respectively, for two-region system GB - FR | LOLE = 0



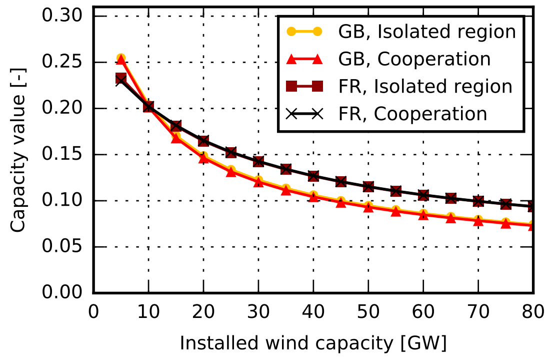
(b) Wind power in DE and FR, respectively, for two-region system DE - FR | LOLE = 0



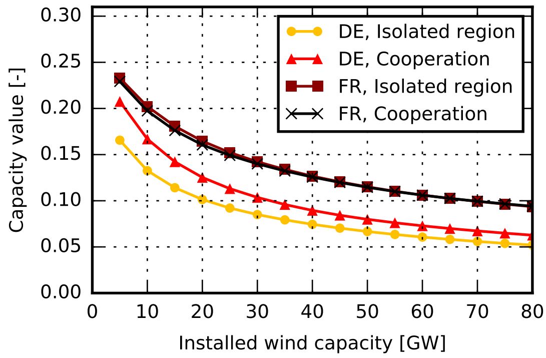
(c) Wind power in GB and FR, respectively, for two-region system GB - FR | LOLE = 3



(d) Wind power in DE and FR, respectively, for two-region system DE - FR | LOLE = 3



(e) Wind power in GB and FR, respectively, for two-region system GB - FR | EEU



(f) Wind power in DE and FR, respectively, for two-region system DE - FR | EEU

Figure 3: Capacity value of wind power for isolated and cooperating two-region systems Great Britain (GB) - France (FR) (left) and Germany (DE) - France (FR) (right) with different reliability targets. Upper graphs: LOLE = 0, middle graphs: LOLE = 3, lower graphs: corresponding EEU (GB 3.72 GWh, FR 6.17 GWh, DE 2.43 GWh)

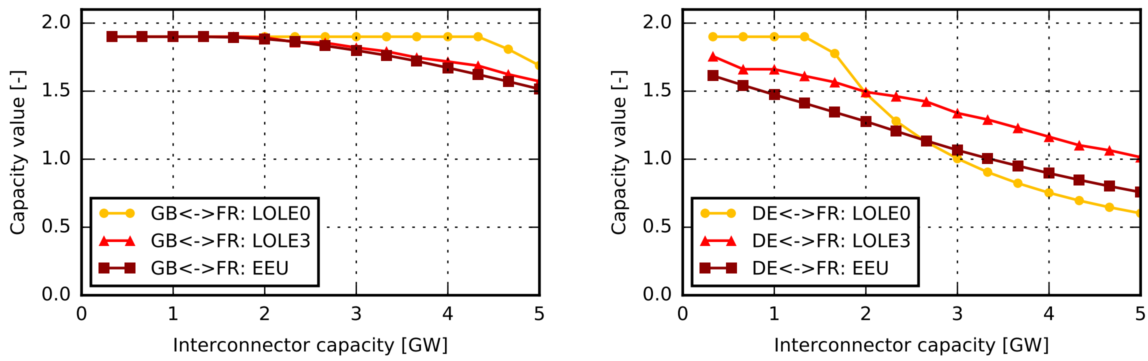


Figure 4: Capacity value of interconnectors for cooperating two-region systems Great Britain (GB) - France (FR) (left) and Germany (DE) - France (FR) (right) with different reliability targets: LOLE = 0, LOLE = 3, and corresponding EEU: GB 3.72 GWh, FR 6.17 GWh, and DE 2.43 GWh

ering all system interactions under the assumption of cooperation, and compare it to the results in isolated regions. Moreover, we calculate the reliability contributions of individual technologies.

Requirements for equivalent firm capacity. The equivalent firm capacity aggregated over Europe as a function of the reliability target EEU for isolated regions and cooperating regions is shown in Figure 5. Recall that for the case of isolated regions, Problem (9) is solved for each country individually, and the firm capacity requirements are summed up to obtain the red line, while the yellow line results from an integrated optimization including interconnection (i.e., Problem (11)).

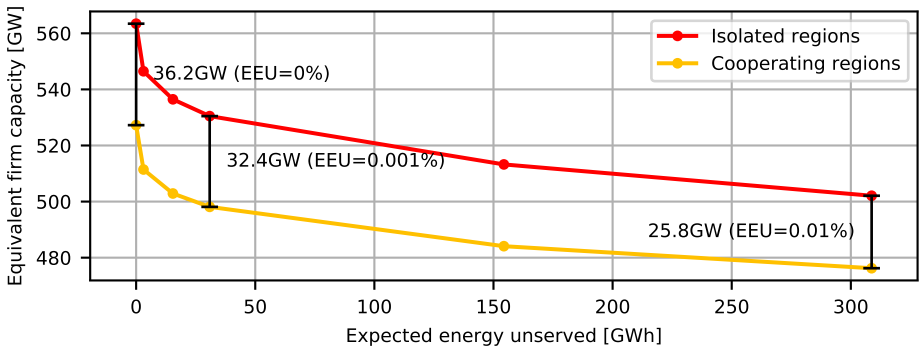


Figure 5: Capacity requirements aggregated over Europe as a function of EEU with the respective gains from cooperation (marked in black)

We observe that – as expected – relaxing the reliability target reduces the required level of equivalent firm capacity. While capacity requirements are reduced more significantly when moving away from an EEU of zero, reductions become smaller for further relaxations of the reliability target. The capacity savings induced by European cooperation (compared to isolated efforts) are significant and range from 36.2 GW for EEU = 0 % to 25.8 GW for EEU = 0.01 %. This corresponds to a relative reduction of 6.4 %-5.1 %. When valuing the reduced capacity needs with 400 EUR/kW (i.e., typical investment costs of an open-cycle gas turbine which can be regarded as safe back-up capacity), the gains from cooperation amount to 10.3 - 14.5 bn EUR.

Even though capacity requirements are generally decreased with relaxed targets, region-specific gains from cooperation are more diverse (Figure 6). For instance, in Denmark, at a reliability level of EEU = 0.001 % of annual load, the reduction in equivalent firm capacity is lower than for EEU = 0.01 %. Therefore, cooperation not only affects efficiency (i.e., the overall amount of capacity needed), but also entails distributive effects. The region-specific capacity savings for EEU = 0.001 %, which corresponds roughly to LOLE = 3, range from 82 to 6430 MW. Comparing to the market size in the respective countries, we find relative capacity savings of 1.6 % - 30.7 % with respect to the region-specific peak load.

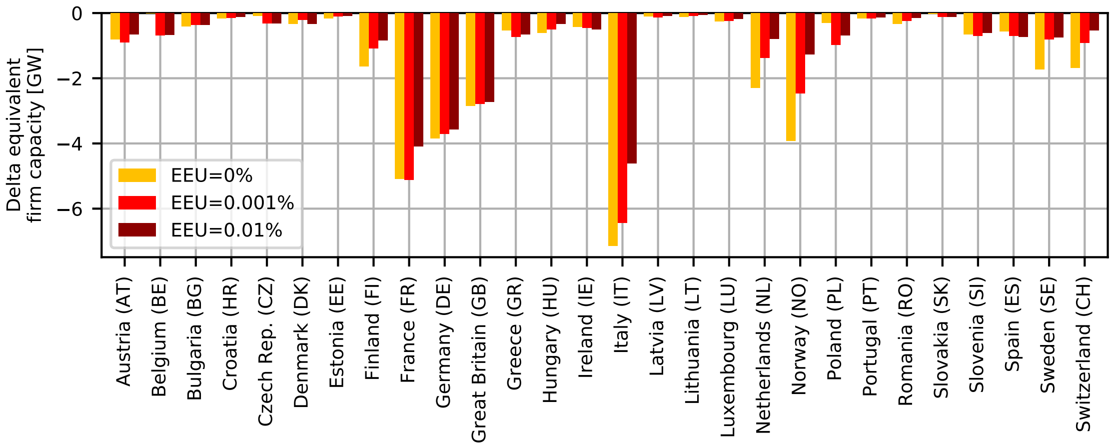


Figure 6: Gains from cooperation: Reduction in equivalent firm capacity with cooperation of total system (EU), compared to isolated regions

Comparison of firm capacity requirements to European generation capacities. To put the above results into context, statistical data on installed generation capacities in Europe as well as their derating factors (i.e., technical availabilities) were collected in order to obtain derated capacities installed in each country which can be compared to our results for an optimized system.[15] Net generation capacities were obtained for the year 2016 from ENTSO-E (2016b), while historical derating factors are available in VGB and Eurelectric (2012) and dena (2010). Wind power was derated according to the results which will be presented hereafter. Meanwhile, two comments are noteworthy: First, the comparison builds on systems with different levels of reliability: it is predefined in our model results, but endogenous in the real system. And second, summing up the derated capacities across Europe can only be directly compared to the case of isolated regions, but not to the firm capacity requirements in the cooperating regions case. This is due to that in our model we consider transmission constraints between countries, while the summation of European derated capacities would assume a copper plate.

From these data, the derated installed capacity for each country can be derived. Aggregated over Europe, it amounts to 650 GW and is considerably higher than the equivalent firm capacity resulting from our optimization. Specifically, even for the case of $\mathrm{EEU} = 0$, the derated capacity is 87 GW higher than in our optimized isolated regions, and 123 GW higher than for our interconnected and cooperating regions. Even though this gives a clear indication that Europe as a whole might have a conservative level of installed capacities, the picture needs to be complemented with a more detailed analysis on a more disaggregated regional level. This is done in Figure 7, where the equivalent firm capacity for isolated and cooperating regions is compared to the 2016 derated capacities in the respective region, for a reliability level of $\mathrm{EEU} = 0.001\,\%$ of annual load. As expected from the Pan-European comparison, the derated capacity typically exceeds the equivalent firm capacity requirements in most regions (most significant overcapacities are observed for Germany, Italy and Spain). However, there are also cases for which the derated capacity is lower than the equivalent firm capacity requirements, namely in Finland, France, Lithuania and Luxembourg, basically reflecting a strong need to import electricity during times of peak demand. Indeed, these findings are in line with recent adequacy assessments (e.g., ENTSO-E (2017)).

The capacity value of wind power. Figure 8 shows the region-specific capacity value of wind power in 2014 with respect to two different system boundaries. It ranges broadly from 3.2 % to 25.5 % in isolated, and from 3.8 % to 29.5 % in cooperating regions (i.e., on a European level).[16] Noticeably, changing the system boundaries from isolated to cooperating entails

[15]Note that this approach is not meant to be a full-fledged adequacy assessment of the European power system. Especially, the capacity derating builds on the simplification that generation capacities are sufficiently small and outages statistically independent. Moreover, derating factors are assumed to be constant throughout the year, including times of scarcity.

[16]Note that Slovakia (SK) is not shown in this figure due to missing wind power data for that region.

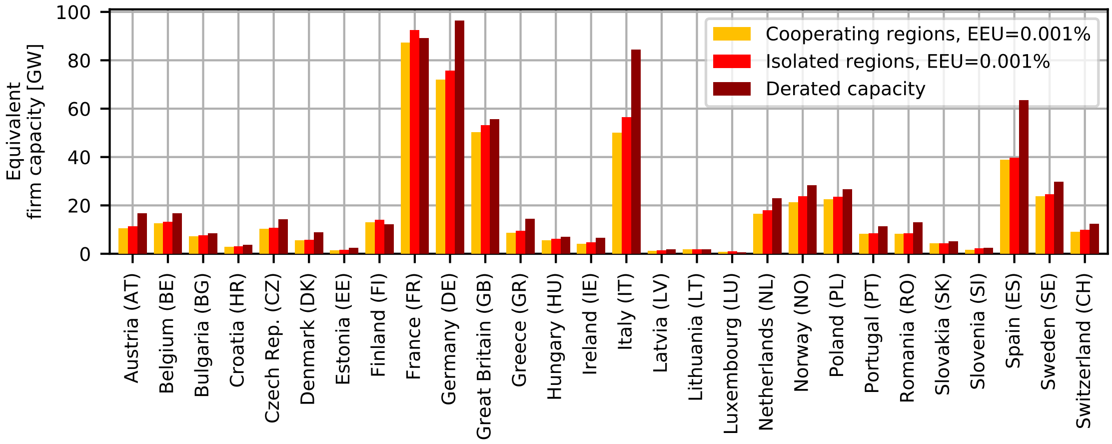


Figure 7: Equivalent firm capacity for isolated and cooperating regions compared to existing derated capacities

increasing capacity values for some of the regions (e.g., for wind in Germany), but also adverse effects (e.g., for wind in France). This is due to the fact that the load profile wind power needs to match is changed, while it is unclear a priori whether this is facilitating or complicating the task.

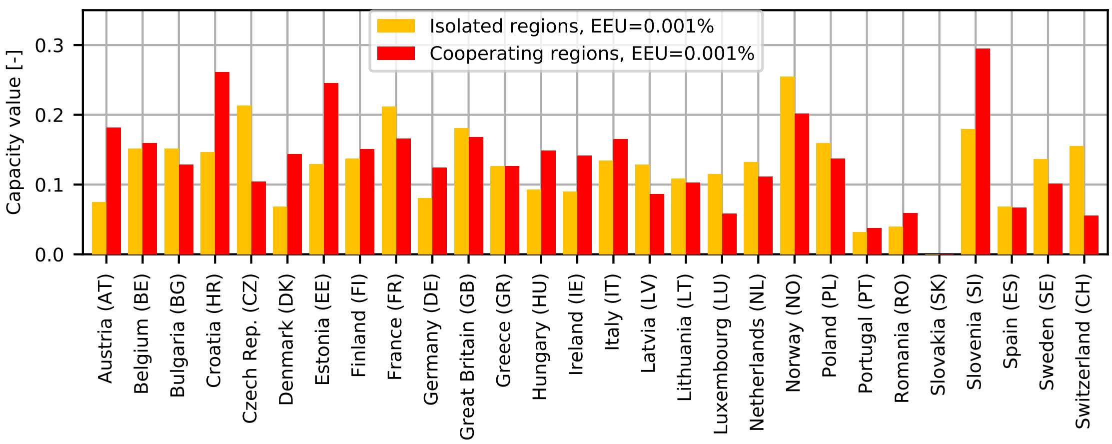


Figure 8: Region-specific capacity value of wind power with respect to total system (EU) for isolated and cooperating regions

The influence of the reliability level on the capacity value of wind power (in case of cooperation on an EU level) is shown in Figure 9. We observe that in tendency, lower reliability levels have an increasing effect on the capacity value of wind. For perfectly reliable systems (EEU = 0%), the analysis is limited to the peak residual demand hour, and thus very sensitive. Therefore, the capacity values vary considerably depending on the respective generation level in that particular hour.

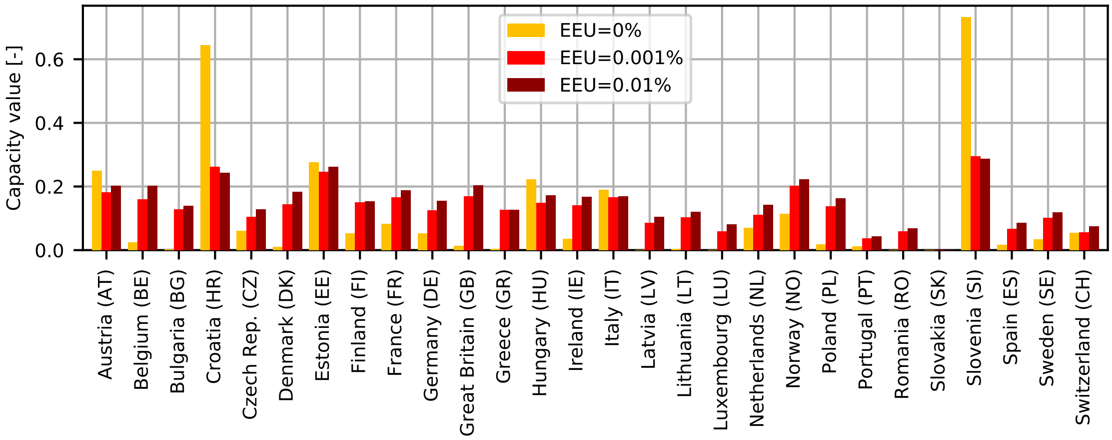


Figure 9: Region-specific capacity value of wind power with respect to total system (EU) for different reliability levels EEU

Besides the optimized values, our modeling framework also allows to determine marginal capacity values of technologies. This is done by substituting the nominal capacity parameters with variables and adding additional constraints fixing the variables to the nominal capacity parameters. This seemingly cumbersome formulation helps us to derive the marginal capacity value via the Lagrange multiplier. We find that for wind power, marginal values are smaller but close to the actual values, due to decreasing returns to scale. Thus, marginal values differ most for regions with large amounts of wind power being installed, such as Germany or Denmark, for instance. The detailed results can be found in the Appendix.

The capacity value of interconnectors. Figure 10 shows the capacity values of the existing interconnector capacities in 2016 with respect to the total system for different reliability levels EEU. Results are driven by the difference in demand and generation profiles, as well as their correlation. Some less embedded regions take particular advantage when being interconnected, i.e., Great Britain, Italy, and Romania. The interconnector from/to the Iberian Peninsula (FR-ES) is also highly beneficial to ensure reliability of supply in an efficient way. Marginal values are again shown in the Appendix.

5. Conclusion

Reliability of supply is of key importance in any power system. In order to achieve reliability targets efficiently, balancing effects and gains from cooperation may be deployed by

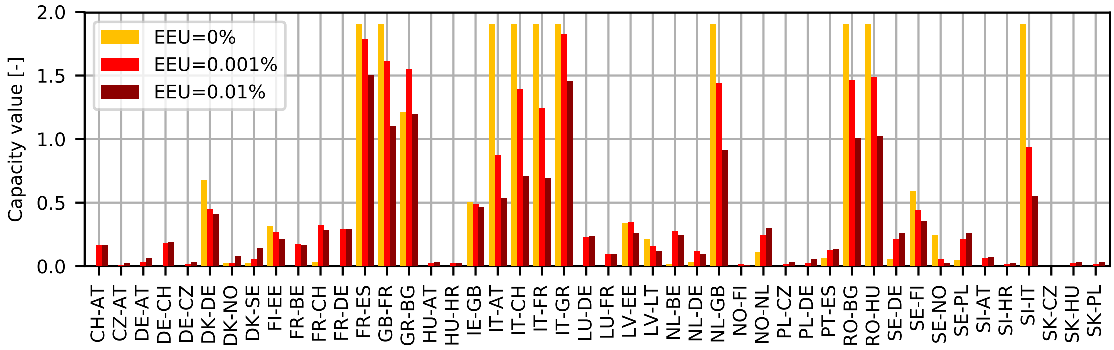


Figure 10: Capacity values of interconnectors between two regions with respect to total system (EU)

means of large-scale interconnected systems. In practice, however, reliability is often considered on a narrow spatial scale (e.g., national). Furthermore, it lacks consistent approaches to consider interdependencies with other regions along with scarce transmission capacities.

In this paper, we have therefore developed a comprehensive computational framework to determine the efficient amount and location of firm generation capacity needed to achieve reliability targets in multi-regional systems with constrained transmission capacities. In addition, the model allows to value the contribution of individual technologies to reliability, such as wind power in a particular region or specific interconnectors.

Calibrated with a detailed dataset for Europe, our calculations show that there are indeed large benefits from cooperation: compared to an isolated region-by-region approach, the amount of firm capacity to meet a perfectly reliably system may be reduced by 36.2 GW (i.e., 6.4 %) when considering reliability in an cooperative manner, which translates to 14.5 bn Euro when valued with typical investment costs of an open-cycle gas turbine. Individual countries could reduce their amounts by up to 31.8 %. In this cooperative solution, some interconnectors contribute substantially – in both directions – with up to their technical maximum. Especially valuable are the interconnectors from/to Great Britain, Italy, and Romania, as well as the interconnector between France and Spain. Capacity expansions at those borders would therefore help most to further reduce the need for firm generation capacity. Despite its fluctuations, wind power in European countries would in the cooperative solution be able to contribute with 3.8 - 29.5 % of its nominal capacity to the reduction of necessary firm generation capacity, compared to a capacity value of 3.2 - 25.5 % when considering reliability in isolated countries.

As an additional key insight, we find that the amount and distribution of reliable capacity as well as the contribution of individual technologies strongly depend on the specific reliability target required from the system. For instance, pushing the target from an Expected Energy Unserved of 0.001 % of annual load to perfect reliability requires 29.1 GW of additional firm capacity in a coordinated European solution, and 33.0 GW for isolated target fulfillment. Therefore, targets should be carefully revisited and chosen to avoid substantial economic inefficiencies.

Based on our model, we are able to show that cooperation can lead to significant reductions of firm capacity and costs (36.2 GW, 14.5 bn Euro). Nevertheless, it has to be kept in mind that the values are based on a zonal model accounting for NTCs. This means the numbers are based on a high abstraction of the real network by introducing NTCs and not accounting for internal network congestion within the zones. On the one hand, this may lead to an overestimation of the potential benefit if internal network congestions are the limiting factor. On the other hand, if the possible flows between zones are higher than the NTCs it may lead to an underestimation. Besides technical feasibility, countries need also be open to cooperate to provide a secure supply of electricity. While a reduction in costs for end consumers seems to be a promising incentive to do so there may be national motivations that hinder cooperation.

Therefore, our paper could be extended in several directions: The network infrastructure could be represented in more detail, e.g., by means of full-fledged load flow equations in our optimization framework. Strategic interactions between regions could be considered to investigate (and eventually, facilitate) the process of cooperative actions. The model could also be extended to tackle the problem of optimal reliability targets by a more detailed and endogenous representation of the supply, transmission and demand side including their cost structures.

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6. Appendix

The marginal capacity value of wind power in case of cooperation is shown in Figure 11 for different reliability targets EEU. One can observe that a higher reliability level has no clear directional influence on the capacity value of wind power.

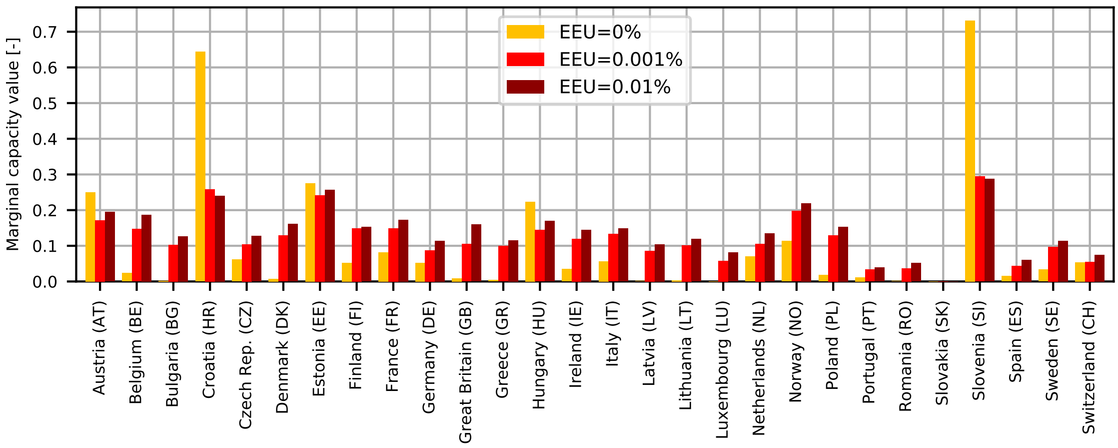

Figure 11: Region-specific marginal capacity value of wind power with respect to total system for different reliability levels EEU

Figure 12 shows the marginal capacity values of interconnectors. As expected, in line with the capacity values derived in Figure 10, the marginal capacity values of the interconnectors of little interconnected regions are highest. This points to the insight that an expansion of these interconnectors would be most beneficial with respect to system reliability in case of cooperation.

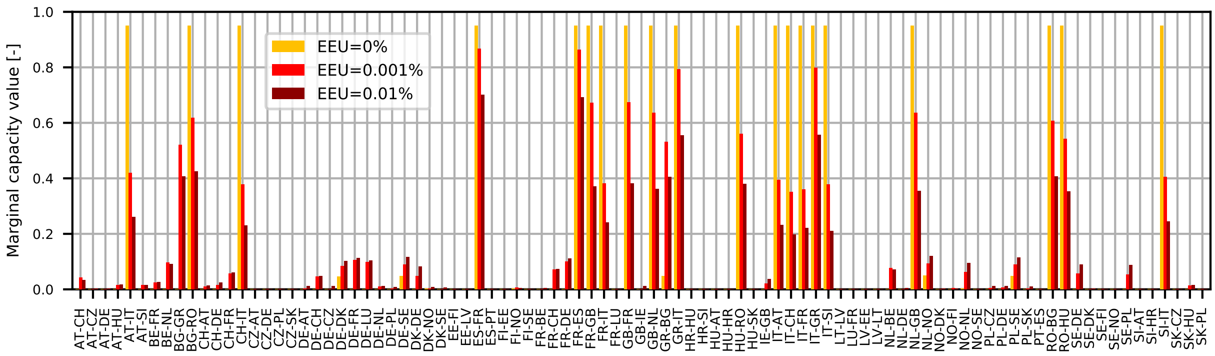

Figure 12: Marginal capacity values of interconnectors between two regions with respect to total system (EU)

In Table 2, installed wind capacities per region in 2014 are depicted.

Austria (AT)	2.01 GW	Belgium (BE)	1.83 GW	Bulgaria (BG)	0.59 GW
Switzerland (CH)	0.06 GW	Czech Republic (CZ)	0.30 GW	Germany (DE)	35.19 GW
Denmark (DK)	4.64 GW	Estonia (EE)	0.29 GW	Spain (ES)	22.24 GW
Finland (FI)	0.52 GW	France (FR)	9.14 GW	Great Britain (GB)	12.08 GW
Greece (GR)	1.40 GW	Croatia (HR)	0.22 GW	Hungary (HU)	0.51 GW
Ireland (IE)	2.00 GW	Italy (IT)	8.80 GW	Lithuania (LT)	0.20 GW
Luxembourg (LU)	0.06 GW	Latvia (LV)	0.05 GW	Netherlands (NL)	3.14 GW
Norway (NO)	0.84 GW	Poland (PL)	3.24 GW	Portugal (PT)	4.68 GW
Romania (RO)	2.55 GW	Sweden (SE)	3.17 GW	Slovenia (SI)	0.01 GW
Slovakia (SK)	0.01 GW				

Table 2: Installed wind capacities in 2014