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RELIABILITY STANDARDS AND GENERATION ADEQUACY ASSESSMENTS FOR INTERCONNECTED ELECTRICITY SYSTEMS

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Reliability standards and generation adequacy assessments for interconnected electricity systems

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Abstract

This paper studies the use of national reliability standards, defined as loss of load expectation (LOLE) targets, in generation adequacy assessments when electricity systems are interconnected. We show that enforcing autarky reliability standards may still reach the welfare optimum in the presence of interconnections, but only under two conditions. First, installed generation capacities should be determined jointly, while considering the full power system. Second, LOLE calculations should fully internalize external adequacy benefits occurring in neighboring systems. Counter-intuitively, LOLE levels computed in adequacy assessment simulations should differ from their realized levels. We run a numerical application for a set of European countries and find that existing interconnections may lead to generation adequacy benefits of around one billion euros per year, by enabling a 18.9 GW decrease in generation capacity. In our case study, regional coordination is found to be more important than fully internalizing external reliability benefits in adequacy simulations.

Keywords: reliability standards, generation adequacy, security of supply, reliability, electricity interconnection

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I. INTRODUCTION

Because electricity supply interruptions have a high economic, social, and political cost, most countries or power systems run generation adequacy assessments to check if the system in place is likely to provide the desired level of supply reliability in the short run, and to assess whether additional power plants are needed in the medium and long run. In the latter case, adequacy assessments usually determine how much electricity generation capacity should be installed to meet a reliability standard. Even in places where wholesale electricity markets have been liberalized, the level of installed capacities that makes it possible to meet a given reliability standard is often a key input to capacity remuneration mechanisms or to future scenarios of the power system that are subsequently used in many public policy analyses [14].

Most reliability standards are expressed as the expected number of hours per year during which available generation capacity will not be sufficient to meet demand. The value of these loss of load expectation (LOLE) targets ranges from 2.4 hours per year (most U.S. systems), three hours per year (Belgium, France, Great Britain, Italy, Poland), four hours per year (Netherlands), four hours per year (Germany), to eight hours per year (Ireland, Portugal) [4]. In most cases, these values have not been updated in decades. They were thus derived at a time were interconnection capacity with neighbor power systems was absent or negligible.

Electricity systems are however becoming increasingly interconnected[1] and decision makers have realized that cooperation with neighboring systems might provide large generation adequacy benefits.[2] By helping neighbors at times of power scarcity, cooperating countries can indeed avoid some investments in peak generation capacity. Despite this fundamental change in the structure of power systems, generation adequacy assessments are still largely performed on a national basis, with each country making exogenous assumptions – based on either a unilateral or a partially coordinated analysis – about the ability of neighboring countries to export energy during scarcity events.

This paper studies how generation adequacy assessments should be run in intercon-

[1]For example in Europe, all but three member states have met the 2020 target to have a level of electricity interconnections of at least 10 % of installed generation capacity [15, 28]. In the United States, massive investments in regional interconnections are envisioned to support the proposed decarbonization of the electricity sector by 2035. Similarly, China's Global Energy Interconnection initiative aims at drastically increasing interconnection capacity between grid regions in China and envisions a worldwide energy grid that transmits clean energy across continents [12]

[2]Interconnection also leads to other benefits, such as fuel cost savings [27], decreasing market power [34, 39], cross-border balancing [38], sharing of reserve capacity [6], and better integration of variable and intermittent renewable generation [31].

nected systems in order to remain grounded in sound economic theory. Two questions are of particular interest. First, should the national autarky reliability standards be updated and, if so, how? Second, how critical is it that interconnected power systems coordinate their generation adequacy assessments? This topic is particularly relevant in Europe where a regional adequacy assessment, ran by the European Network of Transmission System Operators and based on input from national Transmission System Operators (TSOs), has to be implemented by the end of 2023 [2]. This single assessment will determine the need for generation capacity investments in the different countries simultaneously, based on national LOLE targets provided by Member States.[3]

Somewhat counter-intuitively, we find that enforcing national autarky reliability standards does not necessarily prevent reaching the welfare optimum. To reach the first-best outcome, it is however necessary that national LOLE calculations consider all lost load that can be avoided throughout the entire interconnected system thanks to additional capacity, instead of focusing only on domestic lost load. In other words, a country's LOLE calculations should fully internalize the generation adequacy benefits occurring in other parts of the interconnected system. As a result, at the optimum, realized national LOLE levels will be lower than the national autarky reliability standard. Interestingly, neither current industry practices nor the current version of the planned European adequacy assessment [2] seem to compute national LOLE levels in that manner. Similarly, the engineering literature usually takes reliability standards as given and compares them to simulated domestic LOLE levels.

We also demonstrate the need for regional coordination when generation adequacy assessments take into account the adequacy contribution of neighbors. Indeed, if the assumed contribution of neighbors in a national adequacy assessment differs significantly from realized levels, we show in an empirical application to European countries that welfare can decrease considerably, even relative to the outcome reached when national adequacy assessments neglect the presence of interconnections. By contrast, regional cooperation and coordination, as proposed by the European resource adequacy assessment methodology [2], can lead to significant welfare gains relative to the same benchmark.

A number of papers have studied the effect of interconnectors on generation adequacy. [10] run simulations for a two-country case study and highlight the importance of regional coordination. [18] generalizes their study to more than two countries and calculate in a simulation model the minimal generation capacity needed to meet exogenously given country-specific LOLE targets – in line with the European resource adequacy as-

[3] [1] has required all European countries to determine an explicit LOLE target, based on detailed studies of the value of lost load and the cost of new entry.

sessment methodology [2]. By contrast, our work does not take LOLE targets as given but simultaneously determines the optimal installed capacities and the LOLE levels, taking into account the fact that countries are interconnected. Our main contribution is thus to improve our understanding of how national or regional adequacy assessments should be run for interconnected power systems.

Because this paper focuses on the theoretical foundation for the use of reliability standards in an interconnected power system, we do not consider the full set of relevant considerations when assessing LOLE levels. These details are however important in practice to make sure that the simulated scenarios closely match actual system conditions. In particular, there is a growing literature on analyzing the contribution of operating reserves [19], storage [25], and variable renewables to improving system reliability [8, 32, 36]. In addition, in order to narrow focus on the economic intuition for why LOLE targets and regional coordination can maximize welfare, we only crudely account for uncertainty about load and renewable generation [18], and disregard generation outages [10].

The rest of the paper is organized as follows. Section 2 recalls the optimal reliability standard in the autarky case. Section 3 extends this framework to the case of interconnected power systems. In particular, we show the importance of both regional coordination and internalizing external adequacy benefits. We develop our model for two countries with equal VoLL, but also show that our results still hold with asymmetric VoLLs and can be extended to more complex power systems with many countries. Section 4 illustrates our theoretical findings by computing the magnitude of potential gains and losses – relative to installing autarkic capacities – of national, regional, and optimal adequacy assessments, using publicly available data from 11 European countries. Section 5 concludes.

II. OPTIMAL RELIABILITY STANDARD IN THE AUTARKY CASE

Building on [11], we first derive in a simple setting the well-known expression for the optimal reliability standard in autarky. Consider a single country and suppose that the residual demand (i.e. gross load minus output from intermittent zero-marginal-cost renewables) for electricity D is inelastic and distributed on $[\underline{D}, +\infty[$ according to a probability density function $f(D)$ which represents the distribution of possible net hourly demand levels. We denote $F(D) \equiv \int_{\underline{D}}^{D} f(x)dx$ the corresponding cumulative distribution function.

We model a single dispatchable generation technology, namely the one with the highest short-term marginal cost used to match demand in times of scarcity.[4] Historically, this marginal technology was a peaking thermal plant like a gas turbine but demand response might take its place in the future. The marginal technology is characterized by a long-term marginal capacity cost γ and a short-term marginal cost c. Hence, the investment cost to get a capacity K MW is γK, and the variable cost of producing D MWh of electricity is cD as long as $D \leq K$.

During extreme events when demand D is larger than installed capacity K, we assume that $D - K$ is curtailed at a marginal cost V, called the value of lost load (VoLL) V (in €/MWh) – without causing a system-wide blackout. In the case of random rationing, the VoLL is equal to the average willingness-to-pay for power of curtailed consumers. But as the cost of curtailment depends on the time, location, and consumer group [30], the single VoLL might more generally represent the most likely €/MWh cost of supply interruptions in terms of time, location, and interrupted consumer [1, article 7].

In our simple framework, ensuring capacity adequacy boils down to optimizing the level of installed generation capacity. Under the assumptions above, the same optimal capacity will be obtained when considering either (i) welfare-maximization, (ii) system costs' minimization, or (iii) perfect competition. We will thus use a cost-minimization approach. The cost-minimization problem with respect to the installed generation capacity K is:

$$\min_K \gamma K + \int_{\underline{D}}^{+\infty} c \cdot \min(D, K) f(D) dD + \int_K^{+\infty} V \cdot (D - K) f(D) dD \tag{1}$$

That is, total cost consists of the cost of investing in generation capacity, the cost of using that capacity, and the cost of interruptions in case of load curtailment. The optimal installed capacity K^* is then defined by the following well-known first-order condition [11]:

$$(V - c) \Pr [D > K^*] = \gamma \tag{2}$$

This expression is very intuitive: generation capacity should be installed up to the point where the marginal cost of generation investment (right-hand side) equals the marginal avoided cost of interruptions (left-hand side) [7, 35, 37]. The left-hand side might be interpreted as the net VoLL multiplied by the expected frequency of lost load events, i.e. the number of hours per year where some load needs to be curtailed. The second-order

[4] Accounting for all inframarginal technologies (e.g. coal, combined-cycle gas turbine, nuclear, gas turbine,etc.) would change total costs, but not the marginal expressions of optimal reliability.

condition for minimum is easily shown to be satisfied.

Rearranging equation (2) leads to the following proposition.

Proposition 1 (Optimal reliability standard in the autarky case). *The first-order optimality condition may be implemented by enforcing a reliability standard:*

$$LOLE \equiv \Pr\left[D > K^*\right] = \frac{\gamma}{V - c} \equiv \alpha \tag{3}$$

In words, this equation may be interpreted as "installed capacity should be such that the expected fraction of hours during which some energy is not served is equal to α." The expected fraction of hours where some load must be curtailed is called the "loss of load expectation" (LOLE). The LOLE target α is known as the autarky reliability standard, defined as the ratio of the long-term marginal capacity cost and the net VoLL.

Typical orders of magnitude that have been considered in Europe for the value of the parameters are $\gamma \simeq 60$k€/MW/year and $V \simeq 20$ k€/MWh (c is neglected relative to V). This back-of-the-envelope calculation hence yields an autarky reliability standard of $\alpha = 3$ hours per year.

III. NATIONAL RELIABILITY STANDARDS AND ADEQUACY ASSESSMENTS FOR INTERCONNECTED POWER SYSTEMS

3.1. Framework and notations

We now extent the previous framework to the case of interconnected power systems. As in the autarky case, countries or regions must decide how much generation capacity to install. However, they now have to take into account the fact that interconnectors can help to reach the desired level of electricity supply reliability. In order to simplify notations and highlight economic intuitions, we first focus on the two-country case and postpone the discussion of the general case to paragraph 3.7.2.

Let D_i with $i \in \{1, 2\}$ be the hourly net demand level in country i, whose installed capacity is K_i. The vector (D_1, D_2) is distributed according to a density f on $[\underline{D}_1, +\infty[\times [\underline{D}_2, +\infty[$. Both countries are interconnected, with (exogenous) cross-border capacities L_{12} and L_{21}, where L_{ij} is the available transmission capacity from country i to country j. Consistently with the Net Transfer Capacities (NTC) models currently in use in most of Europe,[5] national power networks, Kirchhoff voltage law and power losses are

[5] The European Commission, NRAs, TSOs, consulting firms, etc. typically rely on such models for decision-making purposes. This approach is for example the one used in Europe within the Ten-Year Network Development Plan (TYNDP). Moving from an NTC to a flow-based model is actually

neglected in our simplified framework.[6]

3.2. Country-specific LOLE levels are no longer unambiguously defined

To fix ideas, let's assume for now that the installed capacities (K_1, K_2) are exogenously given. Load may then have to be curtailed for two different reasons. First, total installed capacity may be insufficient to serve total demand. This happens during hours where $D_1 + D_2 > K_1 + K_2$. Second, a single country may have a domestic capacity shortage, and available import capacity may not be high enough to close the gap. For example, such a situation would arise for country 1 when $D_1 > K_1 + L_{21}$. The gray shaded area in Figure 1 highlights the demand realizations (D_1, D_2) for which some load must be curtailed, given interconnector capacities L_{12} and L_{21} and installed capacities K_1 and K_2.

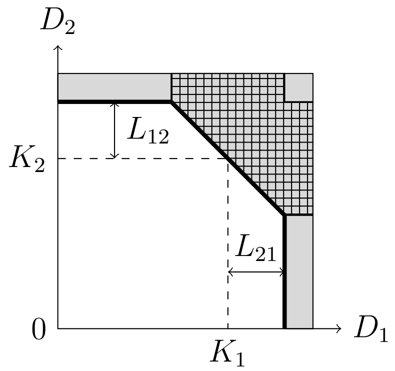

Figure 1: Lost-load region (gray shaded area) for given installed generation capacities (K_1, K_2) and interconnection capacities (L_{12}, L_{21}). For demand realizations in the hatched area, it is ambiguous whether load will be curtailed in a single country or in both.

Importantly, and by contrast to the autarky case, the LOLE metric is no longer unambiguously defined for each country taken in isolation.[7] For demand realizations in the hatched area of Figure 1, load needs to be curtailed but curtailments may happen either in a single country or in both. Indeed, if $K_1 - L_{12} < D_1 < K_1 + L_{21}$, country 1 may or

one of the five main challenges identified by ENTSO-E itself for the future of adequacy assessments (https://www.entsoe.eu/outlooks/eraa/). It thus lies beyond the scope of this paper.

[6]While this assumption was reasonable in the case of vertically integrated utility that chose both power plant locations and transmission grid upgrades, this may prove a strong assumption when reliability standards are used in the context of interconnected countries, especially when assessing the value of new interconnectors. Indeed, the security of supply benefits of a new transmission line are likely to significantly depend on its location on the network, and the ability of the network to inject/consume additional power at the nodes to which the new power line connects [29].

[7]As we discuss in paragraph III.6, realized LOLE levels are however likely to be unambiguous in practice if each country prioritizes its own load. Beyond political considerations, assuming non-zero power losses for the interconnector would also argue for prioritizing domestic load. Paragraph 3.7.1 illustrates how our results generalize in an intuitive way when the methodology to compute country-specific LOLE is exogenously given.

may not experience lost load depending on how the interconnector is operated. Symmetrically, if $K_2 - L_{21} < D_2 < K_2 + L_{12}$ whether or not country 2 has to curtail load is ambiguous.

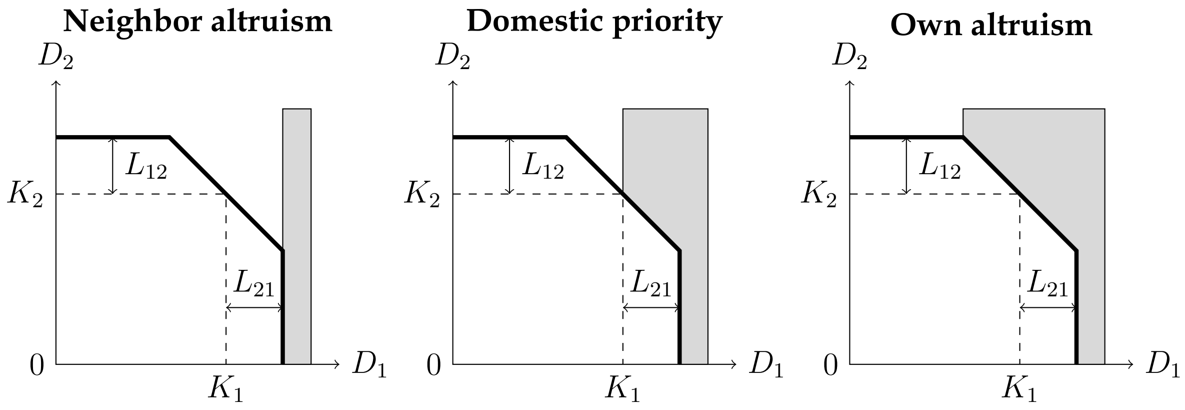

Figure 2: LOLE region of country 1 (gray shaded area) depending on the load curtailment priority rule assumed and for given installed generation capacities (K_1, K_2) and interconnection capacities (L_{12}, L_{21}).

Given installed generation and interconnection capacities, Figure 2 shows in gray the LOLE region for country 1, depending on which country is curtailed first when available generation is not sufficient. We display three possible load curtailment priority rules (from the perspective of country 1):

- **Neighbor altruism:** country 1 may assume that imports from country 2 are always available as long as the import capacity is not constrained, even when country 2 is itself experiencing a capacity shortage;
- **Domestic priority:** country 1 may assume that country 2 will first use its generation capacity to serve its domestic demand, only offering to export electricity from its excess capacity;
- **Own altruism:** country 1 may prioritize exports to country 2, even when this choice makes it necessary to curtail domestic load.

Assuming neighbor altruism (left panel on Figure 1), country 1 only expects loss of load when $D_1 > K_1 + L_{21}$, because imports from country 2 are expected to be available at all times. By contrast, expected loss of load for country 1 is higher when assuming own altruism (right panel on Figure 1), because country 1 is willing to curtail its own load to prioritize exports to country 2.

3.3. Installed capacities prescribed by generation adequacy assessments depend on the assumed load curtailment priority rule

A *generation adequacy assessment* is a simulation exercise where country-specific LOLE levels are computed. This exercise generally aims at making sure that each country meets its *reliability standard*. This reliability standard is expressed as $\widehat{LOLE}_i \equiv \widehat{\alpha}$, where $\widehat{LOLE}_i$ is the LOLE level computed for country i during the generation adequacy assessment and $\widehat{\alpha}$ is the reliability standard.

As discussed above, the LOLE level $\widehat{LOLE}_1$ obtained for country 1 in the context of a generation adequacy assessment will depend on (i) how much capacity is installed in country 2 ; and (ii) load curtailment priorities in times of scarcity. This paragraph focuses on the latter point, and the next paragraph discusses the former.

Figure 3 illustrates how the installed capacity for country 1 prescribed by a reliability standard $\widehat{\alpha}$ depends on the assumed load curtailment priority rule. Taking the installed capacity K_2 in country 2 as given, it shows the installed generation capacity that would be prescribed by a generation adequacy assessment for country 1 under respectively the neighbor altruism, the domestic priority, and the own altruism priority rule. It is clear that installed capacity increases the more a country prioritizes serving load in the neighboring country.

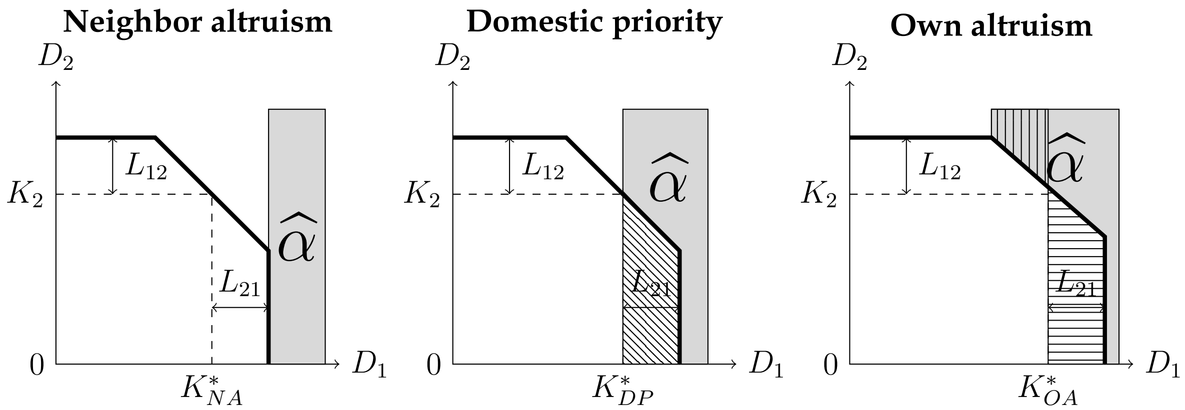

Figure 3: Installed capacity in country 1 depends on the load curtailment priority rule used in its generation adequacy assessment, given installed capacity K_2: $K^*_{1,NA} \leq K^*_{1,DP} \leq K^*_{1,OA}$.

Figure 3 also shows that installed capacity under the domestic priority rule is always lower than in autarky if there are benefits from interconnection, i.e. if there are load realizations in the diagonally hatched area. Country 1 can then install less generation capacity because it is able to get some power in times of scarcity from country 2 through the interconnection.

For the case of the own altruism rule, installed capacity is lower than the autarky capacity $K^*_{autarky}$, as long as the probability of load realizations in the horizontally hatched area is larger than the probability of load realizations in the vertically hatched area. In summary:

$$K^*_{1,NA}(K_2) \leq K^*_{1,DP}(K_2) \leq \min\left(K^*_{1,OA}(K_2), K^*_{1,autarky}(K_2)\right) \tag{4}$$

We further expect that $K^*_{1,OA}(K_2) \leq K^*_{1,autarky}(K_2)$ will hold in most applications.

3.4. National vs regional adequacy assessments

Beyond the assumed load curtailment priority rule, the LOLE region for country 1 depends on the installed capacity K_2 in the neighbor country. In what follows, we will distinguish two cases.

First, we will call *national adequacy assessments* the situation where $\widehat{LOLE}_1$ (resp. $\widehat{LOLE}_2$) is computed while making an exogenous assumption regarding installed capacity K_2 (resp. K_1) in the neighbor country. In other words, country 1 makes an explicit assumption about the installed capacity K_2 and solves for its "adequate" installed capacity $K_1^\dagger$ defined as $\widehat{LOLE}_1(K_1^\dagger, K_2) \equiv \widehat{\alpha}$. Similarly, country 2 makes an explicit assumption about the installed capacity K_1 (which may differ from $K_1^\dagger(K_2)$) and solves for its "adequate" installed capacity $K_2^\dagger$ defined as $\widehat{LOLE}_2(K_1, K_2^\dagger) \equiv \widehat{\alpha}$. As previously discussed, computing $\widehat{LOLE}_i$ itself supposes to make an assumption regarding load curtailment priority rules. The "national adequacy assessments" case would correspond to a situation where each country runs its own adequacy assessment in isolation, without necessarily coordinating with its neighbors.

Second, we will call *regional adequacy assessment* the situation where $(\widehat{LOLE}_1, \widehat{LOLE}_2)$, and thus (K_1, K_2), are computed simultaneously. In other words, the adequacy assessment consists in solving jointly for $(K_1^\dagger, K_2^\dagger)$ such that $\widehat{LOLE}_1(K_1^\dagger, K_2^\dagger) = \widehat{LOLE}_2(K_1^\dagger, K_2^\dagger) \equiv \widehat{\alpha}$. Again, computing $\widehat{LOLE}_i$ requires to specify which country/countries have to curtail load in times of scarcity. The "regional adequacy assessment" case would correspond to a situation where a coordinating entity is in charge of assessing generation adequacy for the interconnected power system.

The outcome of either type of adequacy assessments is a pair of installed capacities $(K_1^\dagger, K_2^\dagger)$ which are deemed necessary to meet the reliability standard $\widehat{\alpha}$ in each country. These installed capacities will take different values depending on (i) whether the adequacy assessment is national or regional, and (ii) which curtailment priority rule is assumed in generation adequacy simulations when computing country-specific LOLE levels.

3.5. First-best outcome

In this section, we characterize the cost-minimizing outcome for the power system as a whole. As in the autarky case, the optimal levels of installed capacity are obtained by minimizing the cost of investing in generation capacity, the cost of using that capacity, and the cost of interruptions in case of involuntary load curtailment. However, in this case we are minimizing total costs for both countries. This exercise yields the following proposition, formalizing the first-order conditions that define optimal installed capacities when two countries are interconnected:

Proposition 2 (Optimal reliability standard in the two-country case). *The first-order conditions for cost-minimization are:*

$$\widehat{LOLE}_1 = \widehat{LOLE}_2 = \frac{\gamma}{V - c} \equiv \alpha \tag{5}$$

where

$$\begin{cases} \widehat{LOLE}_1 \equiv \Pr\left[D_1 > K_1 + L_{21}\right] + \Pr\left[\{D_1 + D_2 > K_1 + K_2\} \cap \{K_1 - L_{12} \leq D_1 \leq K_1 + L_{21}\}\right] \\ \widehat{LOLE}_2 \equiv \Pr\left[D_2 > K_2 + L_{12}\right] + \Pr\left[\{D_1 + D_2 > K_1 + K_2\} \cap \{K_2 - L_{21} \leq D_2 \leq K_2 + L_{12}\}\right] \end{cases} \tag{6}$$

In other words, each country may keep their autarky reliability standard target $\alpha = \frac{\gamma}{V-c}$ as long as they correctly compute the LOLE levels $\widehat{LOLE}_i$ in their adequacy assessments.

Proof. See Appendix A. ■

Just as in the autarky case, the first-order conditions stipulate that generation capacity should be installed up to the point where the marginal cost of generation capacity equals the marginal expected avoided cost of interruptions. Conveniently, they can be rewritten for each country i as $\widehat{LOLE}_i = \alpha$, where α is the autarky reliability standard. In other words, updating historical reliability standards is not necessarily needed when countries interconnect.

As discussed in Section III.2, country-specific LOLE levels are ambiguous for interconnected power systems. Proposition 2 hence clarifies how country-specific LOLE levels should be computed in adequacy assessments in order to make sure that enforcing autarky reliability standards indeed minimize total system costs. More specifically, equations (6) show that lost load should be assumed to occur not only when a country has a capacity shortage that cannot be alleviated by imports (first term), but also when the system as a whole is experiencing a capacity shortage and some interconnection capacity is available to export electricity (second term). That is, hours where additional domestic capacity could have decreased lost load in the neighbor country should also be counted as lost load hours.

The approach for computing country-specific LOLE levels prescribed by Proposition 2 aligns with economic intuition. Indeed, it states that expanding generation capacity K_1 does not only decrease the expected lost load in country 1, but also expected lost load in country 2, and that this latter positive externality should be fully taken into account. In other words, *when performing its domestic adequacy assessment, a given country should fully internalize the security of supply benefits that its installed capacity provides to his neighbor.*

Corollary 1. *In the two-country case, the"own altruism" curtailment priority rule must be assumed when performing generation adequacy assessments for the autarky reliability standard to yield the welfare optimum. In addition, the adequacy assessment must be regional unless each country correctly anticipates the equilibrium installed capacity of its neighbor.*

Proof. The regions described by equations (6) correspond to the LOLE region of the own altruism rule on Figure 2. In addition, the expression for $\widehat{LOLE}_i$ depends on both K_1 and K_2 so that optimal capacities needs to be determined jointly in a regional assessment. □

It is important to stress that Corollary 1 does not say that the "own altruism" rule should be enforced in the context of real-life operations. Indeed, it is doubtful that a country that has sufficient domestic capacity will purposely choose to curtail its own load to help a neighboring country meet its electricity demand. However, the Corollary states that, *in the context of adequacy assessment simulations with country-level reliability standards*, the "own altruism" rule should be assumed when computing the LOLE level of a given country. This approach makes sure that each country fully internalizes the positive effect of its own generation capacity on the security of supply of its neighbor.

3.6. Simulated vs realized LOLE levels

The previous section showed that the optimal installed capacities can be found by solving $\widehat{LOLE}_1 = \widehat{LOLE}_2 = \alpha$, provided $\widehat{LOLE}_i$ is correctly computed. In the two-country case, the correct computation of $\widehat{LOLE}_i$ supposes to use the "own altruism" priority rule when computing the LOLE level of a given country.

In actual operations however, domestic load is likely to be served in priority.[8] In actual operations, European TSOs are indeed required to prioritize meeting their domestic

[8] We rule out inappropriate state interventions in electricity crises which may for example artificially limit cross-border flows and/or cross zonal transmission capacities through NTC calculations [16].

electricity demand before using interconnectors to help neighboring TSOs in emergency situation [15, article 14(1)]. As a result, *realized* LOLE levels will be equal to:

$$\begin{cases} LOLE_1 \equiv \Pr\left[D_1 > K_1 + L_{21}\right] + \Pr\left[\{D_1 + D_2 > K_1 + K_2\} \cap \{K_1 \leq D_1 \leq K_1 + L_{21}\}\right] \\ LOLE_2 \equiv \Pr\left[D_2 > K_2 + L_{12}\right] + \Pr\left[\{D_1 + D_2 > K_1 + K_2\} \cap \{K_2 \leq D_2 \leq K_2 + L_{12}\}\right] \end{cases} \tag{7}$$

In other words, realized LOLE levels will differ from the levels $\widehat{LOLE}_i$ computed in the context of generation adequacy assessments.

Corollary 2. *At the optimum, realized LOLE levels will be lower than the LOLE levels computed in the context of adequacy assessment simulations, and thus lower than the reliability standard for the optimal installed capacities. Indeed:*

$$\begin{cases} \widehat{LOLE}_1 \equiv LOLE_1 + \Pr\left[\{D_1 + D_2 > K_1 + K_2\} \cap \{K_1 - L_{12} \leq D_1 \leq K_1\}\right] \\ \widehat{LOLE}_2 \equiv LOLE_2 + \Pr\left[\{D_1 + D_2 > K_1 + K_2\} \cap \{K_2 - L_{21} \leq D_2 \leq K_2\}\right] \end{cases} \tag{8}$$

which implies:

$$\begin{cases} LOLE_1 \leq \widehat{LOLE}_1 = \alpha \\ LOLE_2 \leq \widehat{LOLE}_2 = \alpha \end{cases} \tag{9}$$

For example, when the long-term marginal capacity cost is 60 k€/MW/year and the value of lost load is 20 k€/MWh, the optimal realized LOLE levels will be weakly lower than 3 hours per year.

3.7. Extensions

3.7.1. Generalizing to asymmetric VoLLs

We assumed so far that both countries use the same VoLL. In practice this value may differ across countries [3]. In this paragraph, we discuss how Proposition 2 generalizes to a situation where the two countries have VoLLs V_1 and V_2, with $V_1 \neq V_2$.

As previously discussed, we assume that each country prioritizes its own load in times of scarcity.[9] We then minimize total long-term costs subject to this curtailment priority rule and get the following Proposition.

[9]By contrast, strict cost-minimization with asymmetric VoLLs would suggest to prioritize meeting demand in the country with the highest VoLL in times of joint scarcity but such a scenario seems unlikely to materialize in practice.

Proposition 3 (**Two-country case with asymmetric VoLLs**). *The first-order conditions for cost-minimization are:*

$$\widehat{LOLE}_1 = \frac{\gamma}{V_1 - c} \equiv \alpha_1 \tag{10}$$

$$\widehat{LOLE}_2 = \frac{\gamma}{V_2 - c} \equiv \alpha_2 \tag{11}$$

where

$$\begin{cases} \widehat{LOLE}_1 \equiv LOLE_1 + \dfrac{V_2 - c}{V_1 - c} \Pr\left[\{D_1 + D_2 > K_1 + K_2\} \cap \{K_1 - L_{12} \leq D_1 \leq K_1\}\right] \\ \widehat{LOLE}_2 \equiv LOLE_2 + \dfrac{V_1 - c}{V_2 - c} \Pr\left[\{D_1 + D_2 > K_1 + K_2\} \cap \{K_2 - L_{21} \leq D_2 \leq K_2\}\right] \end{cases} \tag{12}$$

and realized LOLE levels $LOLE_i$ are given by equations (7).

Proof. See Appendix A. □

Proposition 3 shows that, in order to keep using their autarky reliability standards α_1 and α_2, countries should make sure to internalize in their LOLE calculations the adequacy benefits occurring in the neighbor country. Indeed, in both equations (12), the second term on the right-hand side corresponds to demand realizations where the considered country does not have to curtail its domestic load (since its installed capacity is sufficient to serve its own load) but could decrease the magnitude of the load curtailments incurred by its neighbor by increasing its installed capacity. Because lost load in the neighbor country is assumed to have a different social value, the lost load hours of the second term should be weighted by the ratio of net VoLLs. Note in particular that when $V_1 = V_2$, Equation (12) simplifies to Equation (8).

3.7.2. Generalizing to N countries

While generalizing our results to power systems with N countries and complex interconnection patterns requires more cumbersome notations, the intuition behind our previous results remains valid. In other words, both coordinating regionally and fully internalizing external generation adequacy benefits are needed to reach the first-best outcome.

Assessing whether a given neighbor country "needs help" in a given hour is however harder to characterize in terms of priority rules. Yet, as in the two-country case, it is possible to define a methodology to compute country-specific LOLE levels $\widehat{LOLE}_i$ such that enforcing autarky reliability standards remains consistent with total cost minimization. This result is summarized in the following Proposition.

Proposition 4 (Optimal reliability standard in the N-country case). *The first-order conditions for cost-minimization can be written as:*

$$\widehat{LOLE}_1 = ... = \widehat{LOLE}_N = \frac{\gamma}{V - c} \equiv \alpha \tag{13}$$

where $\widehat{LOLE}_i$, computed in the adequacy assessment simulations, consists of all hours when marginally increasing installed capacity K_i could reduce the amount of curtailed energy anywhere in the interconnected power system.

Proof. See Appendix B. ■

Proposition 4 generalizes the economic intuition derived from the two-country case. First, the computation of $\widehat{LOLE}_i$ depends on the installed capacities in all countries, highlighting the need for regional coordination. Second, this computation should not only consider domestic adequacy benefits, but also make sure to internalize adequacy benefits occurring in neighbor countries.

IV. APPLICATION TO WESTERN EUROPE

In this section, we use data from 11 European countries or groups of countries to assess the magnitude of the achievable welfare gains due to decreased adequacy needs when countries interconnect. We further explore under which condition these gains may be reaped.

4.1. Approach

Our approach consists in comparing the total annual cost (in M€/year) – defined as the sum of the capital cost of investing in generation capacity and the opportunity cost of curtailed energy – under different scenarios. Because we do not model inframarginal generation technologies and neglect short-term generation variable costs, the total cost under a single scenario is not particularly informative. Short-term variable costs would however be roughly the same under all scenarios as long as the peaker technology is always marginal in all countries in times of scarcity. As a result, the differences in total costs between two scenarios do correspond to the differences that would be obtained from a more detailed representation of the power system.

We compare four approaches to enforce a national reliability standard of $\alpha = 3$ hours per year when running generation adequacy assessments (we assume a VoLL of 20 k€/MWh and a marginal long-term investment cost of 60 k€/MW/year).

1. **Autarkic adequacy assessments:** each country runs an adequacy assessment that ignores contributions from neighboring countries when computing the LOLE level – i.e. they install the autarky capacity defined by equation (3). However, the actual operations of the power system do account for the possibility of imports/exports. As a result, realized LOLE levels are typically smaller than three hours per year.
2. **National adequacy assessments:** each country runs its adequacy assessment while incorrectly accounting for the contribution of neighboring countries to its generation adequacy. More precisely, national adequacy assessments are assumed to (i) only take into account direct neighbors (whose interconnections with other countries are neglected), and to (ii) make the naive assumption that neighboring countries will install their autarkic capacities. Because of the latter overly optimistic assumption, we envision this case as a sort of worst-case scenario for uncoordinated assessments.
3. **Regional adequacy assessment:** a single regional adequacy assessment is run. The full power system is modeled and the installed generation capacities are determined jointly for all countries. It aims at achieving *realized* LOLE levels of three hours per year in each country.
4. **Optimal adequacy assessment:** we implement Propositions 2 and 4, modeling the full power system, jointly determining installed capacities in all countries, and fully internalizing the adequacy benefits occurring in neighbor countries.

Beyond total costs, we report the total installed capacity and realized LOLE level (averaged across countries). Given the discrete nature of the input data and the assumption of lossless interconnectors, country-level outcomes are not unique. We report the values obtained using greedy algorithms which initially set capacities at the historical maximum load, and update capacities at each iteration based on the difference between current and targeted LOLE levels (computed according to the assumptions of the scenario of interest) until a fixed point is reached. Although obtained country-level capacities can differ significantly if other seed values are used, the aggregate metrics we report are fairly stable. In particular, total cost is unique for the optimal adequacy assessment scenario.

In all scenarios, we compute *realized* LOLE levels as follows. First, we identify the hours during which the country of interest should be considered as experiencing a lost-load event in the context of an optimal adequacy assessment. These hours correspond to demand realizations appearing in the formula for $\widehat{LOLE}_i$ from Propositions 2 and 4.

For each of these hours, we then check whether the country of interest has sufficient domestic capacity to supply its own demand, which can happen due to external adequacy benefits (i.e. situations where increasing capacity in one country that has sufficient capacity could nonetheless alleviate load curtailments in a neighbor country). All such hours are no longer considered as lost load hours for the country of interest.

We implement our approach for a set of 11 European countries,[10] assuming a reliability standard of $\alpha = 3$ hours per year. We first consider each of the 15 directly-interconnected country pairs taken in isolation. In other words, we consider each country pair as a separate power system composed of only two countries and ignore other interconnectors. We then run a numerical application for the complete interconnected power system.

4.2. Data

Our data are compiled from the ENTSOE-Transparency platform [13] and cover January 2016 to December 2019. For 11 European countries (or group of countries), we retrieve hourly gross load, hourly generation from wind and solar and net transfer capacity (NTC) at each border. We compute net hourly demand levels by substracting the hourly generation from wind and solar from the hourly gross load.

Table 1 provides summary statistics for the timeseries of hourly net load. Mean hourly net consumption ranges from 2.3 GWh for Ireland to 50 GWh for France. Table 1 also shows the installed capacity that would be optimal under autarky, as defined in Proposition 1.

Table 2 provides the matrix of median NTCs for each border where an interconnection exists. Because they do not correspond to physical characteristics of the interconnectors but instead derive from *ad hoc* calculations that try to account for the fact that day-head markets ignore physical network constraints, NTC values fluctuate over time and often depend on the direction of power flows.[11] Our 11 countries are linked through 15 interconnections. Our empirical application hence studies a fairly complex power system.

4.3. Results

Table 3 shows the obtained results for the 15 country pairs taken in isolation. Total costs are the sum of annualized investment costs (assuming a cost of 60 k€/MW/year), which are obtained from our four scenarios for adequacy assessment methodologies, and of the opportunity cost of unserved energy (assuming a value of lost load at 20

[10] The load from Germany, Austria and Luxembourg is aggregated.
[11] In practice, only the DC interconnections with Great Britain have symmetric NTC values.

Table 1: Summary statistics of net hourly load [MW] in the 11 studied countries.

Country	Mean	P95	$K^*_{autarky}$	Maximum
Belgium	8,826	11,391	13,173	13,464
Denmark	2,061	4,075	5,265	5,584
France	50,019	71,582	88,837	90,723
Germany-Austria-Luxembourg	46,875	68,304	82,137	84,104
Great Britain	29,921	42,852	54,437	57,362
Ireland	2,322	3,593	4,555	4,846
Italy	29,086	41,065	48,101	49,336
Netherlands	12,329	15,963	18,046	18,468
Portugal	4,184	6,271	8,180	8,444
Spain	21,674	29,832	36,078	37,451
Switzerland	6,697	8,324	9,662	10,893

Note: Germany load is aggregated with Austria and Luxembourg. When real-time consumption was missing, day-ahead forecast was used instead. Outlier observations for which day-ahead forecast and real-time realization differed by more than 30% were replaced by median values.

Table 2: Median NTC [MW] for each border between the 11 studied countries.

From \ To	BE	DK	FR	DE-AT-LU	GB	IE	IT	NL	PT	ES	CH
Belgium			700					1,200			
Denmark				1,285							
France	2,000			1,200	2,000		2,681			2,500	3,000
Germany-AT-LU		2,100	1,800				272	1,468			2,400
Great Britain			2,000			980		1,016			
Ireland					707						
Italy			995	100							1,810
Netherlands	950			1,468	1,016						
Portugal										3,000	
Spain			2,200						2,100		
Switzerland			1,200	5,200			2,759				

Note: missing observations were replaced by the median value of NTC for the corresponding interconnection. When hourly NTC data was not available, daily or weekly forecast NTC values were used instead.

k€/MWh), where the calculation of the volume of unserved energy account for the security of supply benefits enabled by sharing installed capacities through interconnectors.[12]

Table 3: First panel : total costs in autarky [million €/year], and changes in total costs for the other scenarios (a negative sign corresponds to cost savings). Second panel: average realized LOLE for the two countries (computed using the domestic priority rule) under each scenario. Third panel: obtained total installed capacity (sum of both countries) under each scenario.

	Total costs (M€)				Average realized LOLE (hours)				Total installed capacity (MW)			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Country-pair	Autarky	ΔNational	ΔRegional	ΔOptimal	Autarky	National	Regional	Optimal	Autarky	National	Regional	Optimal
Belgium-France	6142.2	2.9	-1.4	-3.0	1.1	3.6	3	2.1	102,010	101,120	101,315	101,772
Belgium-Netherlands	1875.2	7.6	-2.7	-3.4	0.6	5	3	1.8	31,219	30,757	30,962	31,082
Denmark-Germany	5278.1	15.5	-3.0	-7.8	1.1	3.9	3	1.6	87,402	85,962	86,646	86,859
France-Germany	10283.3	-19.3	-29.9	-36.9	1	3.6	3	2.4	170,974	168,142	168,748	169,435
France-Great Britain	8612.7	-66.5	-66.5	-66.5	0.9	3	3	3	143,274	140,633	140,633	140,633
France-Italy	8224.2	-137.6	-137.6	-137.6	0.6	3	3	3	136,938	133,456	133,456	133,456
France-Spain	7495.1	-89.9	-126.2	-134.7	0.1	4.2	3	2.1	124,915	120,410	121,230	121,643
France-Switzerland	5933.9	1.8	-0.6	-2.5	1	3.4	3	2.2	98,499	97,863	97,983	98,322
Germany-Italy	7902.9	-2.0	-2.0	-2.0	2.6	3	3	3	130,238	130,092	130,092	130,092
Germany-Netherlands	6061.4	5.8	1.5	-1.1	1.4	3.1	3	2.5	100,184	99,310	99,527	99,975
Germany-Switzerland	5563.2	10.0	0.4	-0.5	1.2	3.4	3	2.1	91,799	90,974	91,394	91,718
Great Britain-Ireland	3597.2	-8.2	-10.9	-11.9	1.1	3.2	3	2.4	58,992	57,964	58,511	58,511
Great Britain-Netherlands	4392.9	-11.2	-9.9	-12.1	1.5	3	3	2.4	72,483	70,848	71,208	71,208
Italy-Switzerland	3465.8	-7.2	-34.4	-49.5	0	5.5	3	1.5	57,763	55,667	56,348	56,610
Portugal-Spain	2680.1	-1.6	-5.6	-6.3	1.4	3.8	3	2.1	44,258	43,100	43,447	43,724

Overall, the outcome reached by a regional assessment that uses realized LOLE levels instead of the correct ones $\widehat{LOLE}_i$ is often very close to the optimal one in terms of total costs. However, it differs significantly from the optimal benchmark for a number of country pairs (e.g. France-Germany, France-Spain, or Italy-Switzerland). In particular, in two cases, the installed capacities obtained with an incorrect regional assessment yield total costs that are slightly *higher* than the total costs obtained with autarky installed capacities. Indeed, because the domestic priority rule ignores a fraction of the security of supply benefits obtained by the neighboring country, too little capacity ends up being installed. The subsequent increase in the opportunity cost of unserved energy happens to outweigh the savings in investment costs. In both cases, the corresponding inefficiencies are however relatively small. By contrast, naive national adequacy assessments can yield very contrasted outcomes. In some cases, e.g. France-Great Britain or France-Italy, maximum achievable cost savings are realized. In other cases, e.g. Belgium-Netherlands or Denmark-Germany, the outcome reached is significantly more costly than the autarky outcome due to an underinvestment in generation capacities.

[12]Note that the metric we report as "total costs" ignores both fuel costs and the decrease in investment costs that may be achieved through the use of a portfolio of generation technologies. As a result, this number should not be taken at face value. However, differences in total costs across scenarios are meaningful because they do capture the first-order impact of alternative adequacy assessment methodologies. Indeed, during hours of peak consumption, the relevant economic trade-off is the choice between investing in more peaking capacity or accepting that higher load curtailment levels in expectations (fuel costs

Table 4: Results for the complete interconnected power system of 11 countries

	(1) Autarky	(2) National assessments	(3) Regional assessment	(4) Optimal
Total costs (M€/year)	22,108	22,385	21,254	21,244
Total installed capacity (GW)	368.5	340.6	348.7	349.6
Average realized LOLE	0	10.6	3	2.3

Table 4 shows the obtained results for the 11 countries and 15 interconnectors considered as a single power system. Installing autarky generation capacities is found to induce a total cost of 22,108 M€. Autarky capacities add up to almost 370 GW.[13] Conditional on having installed these generation capacities, the realized LOLE (averaged over countries) is negligible – much below the LOLE target, as also noted by [26]. The first-best outcome would however be to downsize the generation fleet by 18.9 GW and curtail more load in expectation. Corresponding expected savings of total costs are very significant and amount to 864 M€/year.

Perhaps somewhat surprisingly, the installed capacities computed under an imperfect regional assessment amount to 854 M€/year, which represents 99% of achievable savings. The obtained total installed capacity is comparable to the first-best benchmark (349 GW vs 350 GW). However, country-level installed capacities can differ significantly, and may not be unique. For some countries, the difference in obtained installed capacity under ACER's methodology and the first-best benchmark is found to exceed 10% of the first-best capacity. This observation thus calls for caution when using the outcome of adequacy assessments as an input for setting country-level assumptions or targets for installed generation capacity.

Finally, our application to the full power system illustrates that naive national adequacy assessments can, under an arguably worst-case scenario, yield a very sub-optimal outcome. Indeed, because countries assume in their domestic adequacy assessment that their neighbors have installed their autarkic capacities, they all overestimate the extent to which they can rely on interconnectors, and thus end up significantly downsizing their generation fleet. As a result of this coordination failure, realized total installed capacity is 9 GW lower than under the optimal outcome. Total costs exceed the autarky cost by several hundred millions euros per year because of the resulting massive amount of load curtailments.

being negligible relative to the value of lost load).

[13]This is an underestimation of the actual total capacity, as we neglect generation that is needed for ancillary services.

V. CONCLUSION

Using a theory model and an empirical application, we show that the widely-used national LOLE target – equal to the ratio of the long-term marginal capacity cost and the net VoLL – can still be used in generation adequacy assessments when several electricity systems interconnect. To that aim, country-specific LOLE calculations should account for lost load that is avoided throughout the entire interconnected system thanks to additional domestic capacity, instead of only considering lost load within the borders of the considered country.

Importantly, our paper also emphasizes the need for regional coordination, because the outcome of adequacy assessments in interconnected systems crucially depends on the available imports from neighbors in times of scarcity. We show in our empirical application that a coordinated regional adequacy assessment yields considerable welfare benefits, while uncoordinated national assessments can backfire and decrease welfare even below the outcome reached with autarkic installed capacities. In our case study, regional coordination is found to be more important than fully internalizing external adequacy benefits in adequacy simulations. This result somewhat questions the relevance of maintaining national generation adequacy assessments and reliability standards in the context of highly interconnected power systems. However, ensuring national security of supply involves high economic, social, and political stakes. Policy-makers may thus be reluctant to transfer this responsibility to a supra-national level. Interestingly, we find that, while not being necessary, maintaining national generation adequacy standards does not prevent interconnected power systems to reach an efficient outcome, provided that countries coordinate during the generation adequacy assessment, as proposed by the European resource adequacy assessment [2].

Given the importance of ensuring reliable electricity supply, there is ample room for further work on reliability standards and generation adequacy. With new storage technologies, demand response and variable renewables, it is increasingly challenging to correctly estimate VoLL, long-term marginal capacity cost, the probability of future peak load and the probability distribution of generation availability. In particular, the August 2020 and February 2021 rolling blackouts in California and Texas have stressed the importance of energy availability – like natural gas or coal – for generation adequacy.

Finally, in this paper we study how interconnections affect the optimal level of generation capacity. Another important question is to better understand how this optimum may be reached in liberalized electricity markets in the presence of heterogeneous national policies (e.g. capacity mechanisms, price caps), levels of market power, and risk aversion [5, 17, 20–22, 24], and how to mitigate the inefficiencies and strategic interactions that might arise from these differences [9, 23, 33, 40]. Exploring these issues in future research could provide additional insight to policymakers on the design of generation adequacy assessments, and on the relevance of maintaining national reliability standards.

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APPENDICES

A. PROOFS

To simplify notations and without loss of generality we set $\underline{D}_1 = \underline{D}_2 = 0$.

Proof of proposition 2

Proof.

The cost minimization problem is then:

$$\begin{aligned}
\min_{K_1,K_2} \quad & \gamma(K_1+K_2) \\
& + \int_0^{K_1-L_{12}} \int_0^{K_2+L_{12}} c\,(D_1+D_2) f(D_1,D_2)\, dD_2 dD_1 \\
& + \int_0^{K_1-L_{12}} \int_{K_2+L_{12}}^{+\infty} \left[c\,(D_1+K_2+L_{12}) + V\,(D_2-K_2-L_{12})\right] f(D_1,D_2) dD_2 dD_1 \\
& + \int_{K_1-L_{12}}^{K_1+L_{21}} \int_0^{K_1+K_2-D_1} c\,(D_1+D_2) f(D_1,D_2)\, dD_2 dD_1 \\
& + \int_{K_1-L_{12}}^{K_1+L_{21}} \int_{K_1+K_2-D_1}^{+\infty} \left[c\,(K_1+K_2) + V\,(D_1+D_2-K_1-K_2)\right] f(D_1,D_2) dD_2 dD_1 \\
& + \int_{K_1+L_{21}}^{+\infty} \int_0^{K_2-L_{21}} \left[c\,(D_2+K_1+L_{21}) + V\,(D_1-K_1-L_{21})\right] f(D_1,D_2)\, dD_2 dD_1 \\
& + \int_{K_1+L_{21}}^{+\infty} \int_{K_2-L_{21}}^{+\infty} \left[c\,(K_1+K_2) + V\,(D_1+D_2-K_1-K_2)\right] f(D_1,D_2) dD_2 dD_1
\end{aligned}$$

For better understanding, Figure A.1 shows the areas corresponding to the six double integrals of the cost minimization problem.

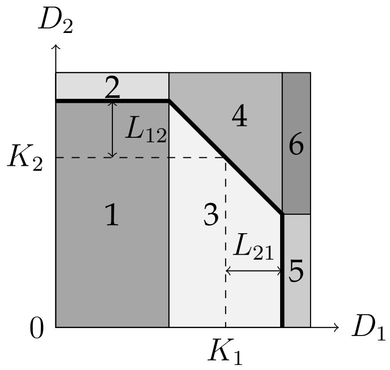

Figure A.1: Areas corresponding to the six double integrals of the cost minimization problem.

The first-order condition with respect to K_1 equals:

$$
\begin{aligned}
&\gamma + \int_{0}^{K_2+L_{12}} c\,(K_1 - L_{12} + D_2) f(K_1 - L_{12}, D_2)\, dD_2 \\
&+ \int_{K_2+L_{12}}^{+\infty} \left[c\,(K_1 + K_2) + V\,(D_2 - K_2 - L_{12})\right] f(K_1 - L_{12}, D_2) dD_2 \\
&+ \int_{0}^{K_2-L_{21}} \left[c(K_1 + L_{21} + D_2)\right] f(K_1 + L_{21}, D_2) dD_2 \\
&- \int_{0}^{K_2+L_{12}} \left[c(K_1 - L_{12} + D_2)\right] f(K_1 - L_{12}, D_2) dD_2 \\
&+ \int_{K_1-L_{12}}^{K_1+L_{21}} c\,(K_1 + K_2) f(D_1, K_1 + K_2 - D_1)\, dD_1 \\
&+ \int_{K_1-L_{12}}^{K_1+L_{21}} \int_{K_1+K_2-D_1}^{+\infty} (c - V) f(D_1, D_2) dD_2 dD_1 \\
&- \int_{K_2+L_{12}}^{+\infty} \left[c\,(K_1 + K_2) + V\,(D_2 - L_{12} - K_2)\right] f(K_1 - L_{12}, D_2) dD_2 \\
&+ \int_{K_2-L_{21}}^{+\infty} \left[c\,(K_1 + K_2) + V\,(D_2 + L_{21} - K_2)\right] f(K_1 + L_{21}, D_2) dD_2 \\
&- \int_{K_1-L_{12}}^{K_1+L_{21}} c\,(K_1 + K_2)\, f(D_1, K_1 + K_2 - D_1) dD_1 \\
&- \int_{0}^{K_2-L_{21}} \left[c\,(D_2 + K_1 + L_{21})\right] f(K_1 + L_{21}, D_2)\, dD_2 \\
&+ \int_{K_1+L_{21}}^{+\infty} \int_{0}^{K_2-L_{21}} (c - V) f(D_1, D_2) dD_2 dD_1 \\
&- \int_{K_2-L_{21}}^{+\infty} \left[c\,(K_1 + K_2) + V\,(L_{21} + D_2 - K_2)\right] f(K_1 + L_{21}, D_2) dD_2 \\
&+ \int_{K_1+L_{21}}^{+\infty} \int_{K_2-L_{21}}^{+\infty} (c - V) f(D_1, D_2) dD_2 dD_1 = 0
\end{aligned}
$$

Which simplifies to:

$$\gamma + \int_{K_1+L_{21}}^{+\infty}\int_{0}^{+\infty}(c-V)f(D_1,D_2)dD_2dD_1 + \int_{K_1-L_{12}}^{K_1+L_{21}}\int_{K_1+K_2-D_1}^{+\infty}(c-V)f(D_1,D_2)dD_2dD_1 = 0$$

■

Proof of proposition 3

Proof. With asymmetric VoLLs and short-term operation rules that prioritize domestic load, the cost minimization problem becomes:

$$\begin{aligned}
\min_{K_1,K_2} \quad & \gamma(K_1+K_2) \\
& + \int_{0}^{K_1-L_{12}}\int_{0}^{K_2+L_{12}} c\,(D_1+D_2)f(D_1,D_2)\,dD_2dD_1 \\
& + \int_{0}^{K_1-L_{12}}\int_{K_2+L_{12}}^{+\infty} \left[c\,(D_1+K_2+L_{12}) + V_2\,(D_2-K_2-L_{12})\right] f(D_1,D_2)dD_2dD_1 \\
& + \int_{K_1-L_{12}}^{K_1+L_{21}}\int_{0}^{K_1+K_2-D_1} c\,(D_1+D_2)f(D_1,D_2)\,dD_2dD_1 \\
& + \int_{K_1-L_{12}}^{K_1}\int_{K_1+K_2-D_1}^{+\infty} \left[c\,(K_1+K_2) + V_2\,(D_1+D_2-K_1-K_2)\right] f(D_1,D_2)dD_2dD_1 \\
& + \int_{K_1}^{K_1+L_{21}}\int_{K_1+K_2-D_1}^{K_2} \left[c\,(K_1+K_2) + V_1\,(D_1+D_2-K_1-K_2)\right] f(D_1,D_2)dD_2dD_1 \\
& + \int_{K_1}^{\infty}\int_{K_2}^{\infty} \left[c\,(K_1+K_2) + V_1\,(D_1-K_1) + V_2\,(D_2-K_2)\right] f(D_1,D_2)dD_2dD_1 \\
& + \int_{K_1+L_{21}}^{+\infty}\int_{0}^{K_2-L_{21}} \left[c\,(D_2+K_1+L_{21}) + V_1\,(D_1-K_1-L_{21})\right] f(D_1,D_2)\,dD_2dD_1 \\
& + \int_{K_1+L_{21}}^{+\infty}\int_{K_2-L_{21}}^{K_2} \left[c\,(K_2+K_1) + V_1\,(D_1+D_2-K_1-K_2)\right] f(D_1,D_2)\,dD_2dD_1
\end{aligned}$$

Figure A.2 shows the areas corresponding to the eight double integrals of the cost minimization problem.

In regions 1 and 3, load can be supplied in both countries. In regions 2 and 4, only country 2 curtails load (since $D_1 \leq K_1$). The amount of energy curtailed however depends on whether the interconnector is used at full capacity (region 2) or not (region 4). In region 6, both countries need to curtail load. Finally, in regions 5, 7 and 8, only country 1 is curtailing load (since $D_2 \leq K_2$). Again, the amount of energy curtailed however depends on whether the interconnector is used at full capacity (region 7) or not (regions 5 and 8).

First-order conditions with respect to K_1 and K_2 yield equations (12). ■

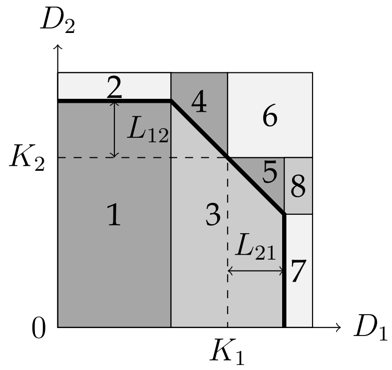

Figure A.2: Areas corresponding to the eight double integrals of the cost minimization problem with asymmetric VoLLs.

B. GENERALIZATION TO THE N-COUNTRY CASE

Two-country case

We discuss for now the two-country case to illustrate the intuition behind our methodology to compute $\widehat{LOLE}_i$. Our objective is to show that we can define a methodology to assess – in the context of adequacy assessment simulations – the probability $\widehat{LOLE}_i$ of curtailing load in country i such that setting a target $\widehat{LOLE}_i = \alpha$ for all countries minimizes total costs.

$\widehat{LOLE}_i$ is formally the expectation over demand realizations (D_1, D_2) of a function $LL_i(.)$:

$$\widehat{LOLE}_i \equiv \mathbb{E}_{(D_1,D_2)}\left[LL_i(D_1, D_2 \mid K_1, K_2, L_{12}, L_{21})\right] \tag{B.1}$$

where LL_i takes the value 1 if a demand realization (D_1, D_2) should, given installed capacities K_1, K_2, L_{12}, L_{21}, be considered (in adequacy assessment simulations) to trigger load curtailments in country i.

From the first-order condition of Proposition 2, we get the following corollary:

Corollary 3. *In the two-country case, country-specific reliability standards are consistent with the first-best outcome if LL_i is constructed as follows:*

1. *Identify the subset of countries $Z^* \in \{\emptyset, \{1\}, \{2\}, \{1, 2\}\}$ that is experiencing the most severe capacity shortage:*

$$Z^* =$$

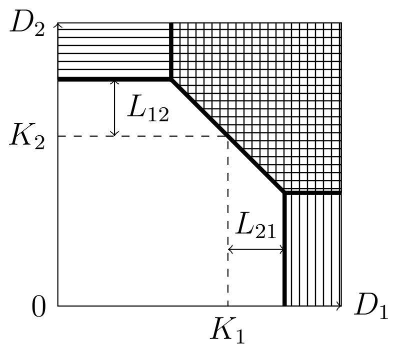

Figure B.1: Illustration of how country-specific LOLE should be computed in adequacy assessments to ensure that enforcing the autarky reliability standard remains consistent with welfare maximization. Demand realizations that fall in the area with vertical (resp. horizontal) lines imply curtailments in country 1 (resp. country 2). Lost-load is considered to happen in both countries in the grided area.

$$\begin{cases} \emptyset & \textit{if } \max(D_1+L_{21}-K_1, D_2+L_{12}-K_2, D_1+D_2-K_1-K_2, 0) = 0 \\ \{1\} & \textit{if } \max(D_1+L_{21}-K_1, D_2+L_{12}-K_2, D_1+D_2-K_1-K_2, 0) = D_1+L_{21}-K_1 \\ \{2\} & \textit{if } \max(D_1+L_{21}-K_1, D_2+L_{12}-K_2, D_1+D_2-K_1-K_2, 0) = D_2+L_{12}-K_2 \\ \{1,2\} & \textit{if } \max(D_1+L_{21}-K_1, D_2+L_{12}-K_2, D_1+D_2-K_1-K_2, 0) = D_1+D_2-K_1-K_2 \end{cases}$$

2. *Then define LL_i as follows:*

$$LL_i(D_1, D_2 \,|\, K_1, K_2, L_{12}, L_{21}) = \begin{cases} 1 & \textit{if } i \in Z^* \\ 0 & \textit{otherwise} \end{cases}$$

In words, Corollary 3 states that for each demand realization (D_1, D_2) where shedding load is necessary ($Z^* \neq \emptyset$), adequacy assessment simulations should identify the subset of countries for which the capacity shortage is the most severe. The capacity shortage faced by a group of countries is defined as total load minus domestic and import capacities, assuming full availability of imports. In the context of adequacy assessments, lost load should be assumed to take place in each country that belongs to this subset of countries. Figure B.1 illustrates graphically that this approach is consistent with welfare-maximization first-order conditions for the two-country case. Indeed, taking for example the perspective of country 1, the area covered by vertical stripes does correspond to the LOLE region under the own altruism rule in Figure 2

Extension to N countries

We denote $\mathbf{D} \equiv (D_1, ..., D_N)$ the realization of the vector of demand in each country for a given hour and $\mathbf{K} \equiv (K_1, ..., K_N)$ the vector of installed capacities. We further denote L_{ij} the interconnection capacity from country i to country j. Our objective is to define for which realizations of $\mathbf{D}$ adequacy assessment simulations should consider that lost load occurs in country i given installed capacities $\mathbf{K}$ and $\{L_{ij}\}_{ij}$.

To do so, we define:

$$Z^*(\mathbf{D}\,|\,\mathbf{K}, L_{ij}) \equiv$$
$$\begin{cases} \underset{Z\subseteq\{1,\dots,N\}}{\text{argmax}} \sum_{i\in Z} D_i - \sum_{i\in Z} K_i - \sum_{j\notin Z}\sum_{i\in Z} L_{ij} & \text{if } \underset{Z\subseteq\{1,\dots,N\}}{\max} \sum_{i\in Z} D_i - \sum_{i\in Z} K_i - \sum_{j\notin Z}\sum_{i\in Z} L_{ij} > 0 \\ \emptyset & \text{otherwise} \end{cases}$$

For given $\mathbf{K}$ and $\{L_{ij}\}_{ij}$, we will show that the adequacy assessment should consider that lost load occurs in country i for hourly demand realization $\mathbf{D}$ if, and only if:

$$i \in Z^*(\mathbf{D}\,|\,\mathbf{K}, L_{ij}).$$

We start by showing that, when a demand vector is not feasible, the amount of electricity curtailed is:

$$LL(\mathbf{D}\,|\,\mathbf{K}, L_{ij}) \equiv \max_{Z\subseteq\{1,\dots,N\}} \sum_{i\in Z} D_i - \sum_{i\in Z} K_i - \sum_{j\notin Z}\sum_{i\in Z} L_{ij}$$

Let E be the quantity of electricity curtailed in a non-feasible state. For a given subset $Z \subseteq \{1, \dots, N\}$ of countries, we denote:

$$LL(Z\,|\,\mathbf{D}, \mathbf{K}, L_{ij}) \equiv \max\Big(\sum_{i\in Z} D_i - \sum_{i\in Z} K_i - \sum_{j\notin Z}\sum_{i\in Z} L_{ij}; 0\Big)$$

Because any subset of countries cannot procure more electricity than the sum of their domestic and import capacities, we have for all $Z \subseteq \{1, \dots, N\}$:

$$E \geq LL(Z\,|\,\mathbf{D}, \mathbf{K}, L_{ij})$$

and thus:

$$E \geq LL(\mathbf{D}\,|\,\mathbf{K}, L_{ij})$$

Reciprocally, let Z^* be the largest set of countries where load may need to be curtailed despite using all the capacity of installed generators and interconnectors. For any partition $\{z_1, \dots, z_p\}$ of Z^*, that is mutually exclusive subsets of Z^* such that $\cup_{i=1}^{p} z_i = Z^*$, we have:

$$LL(Z^* \,|\, \mathbf{D}, \mathbf{K}, L_{ij}) \geq \textstyle\sum_{i=1}^{p} LL(z_i \,|\, \mathbf{D}, \mathbf{K}, L_{ij})$$

In other words, looking separately at the constraints faced by sub-groups of countries cannot imply higher amounts of lost load. As a result:

$$E \leq LL(Z^* \,|\, \mathbf{D}, \mathbf{K}, L_{ij}) \leq LL(\mathbf{D} \,|\, \mathbf{K}, L_{ij})$$

We thus have $E = LL(\mathbf{D} \,|\, \mathbf{K}, L_{ij})$.

Short-term cost Knowing how much energy is curtailed in each demand state, the short-run cost $c_{SR}(\mathbf{D} \,|\, \mathbf{K}, L_{ij})$ to serve a vector of demand $\mathbf{D}$ is:

$$c_{SR}(\mathbf{D} \,|\, \mathbf{K}, L_{ij}) = \left(\sum_{i=1}^{N} D_i - \max(LL(\mathbf{D} \,|\, \mathbf{K}, L_{ij}), 0) \right) \times c + \max(LL(\mathbf{D} \,|\, \mathbf{K}, L_{ij}), 0) \times V \tag{B.2}$$

Long-term cost Let $f(.)$ denote the probability density of demand vectors $\mathbf{D}$. The long-term cost $c_{LR}(\mathbf{K} \,|\, L_{ij})$ of installing capacities $\mathbf{K}$ is:

$$c_{LR}(\mathbf{K} \,|\, L_{ij}) \equiv \gamma \sum_{i=1}^{N} K_i + \int_{\mathbf{D}} c_{SR}(\mathbf{D} \,|\, \mathbf{K}, L_{ij}) f(\mathbf{D}) d\mathbf{D} \tag{B.3}$$

First-order conditions: From Equation (B.2), we have:

$$\partial_{K_i} c_{SR}(\mathbf{D} \,|\, \mathbf{K}) = \begin{cases} -(V - c) \text{ if } i \in Z^*(\mathbf{D} \,|\, \mathbf{K}) \\ 0 \text{ otherwise} \end{cases}$$

As a consequence, minimizing long-term costs with respect to $\mathbf{K}$ yields the first-order conditions:

$$\forall i \in \{1, ..., N\}, \int_{\mathbf{D}} \mathbf{1}_{i \in Z^*(\mathbf{D} \,|\, \mathbf{K})} f(\mathbf{D}) d\mathbf{D} = \alpha \tag{B.4}$$

where $\mathbf{1}_{i \in Z^*(\mathbf{D} \,|\, \mathbf{K})}$ is a dummy variable that takes the value 1 if country i is in $Z^*(\mathbf{D} \,|\, \mathbf{K})$ and 0 otherwise.

The underlying intuition is the same as in the two-country case. For each hour, one must identify the set of countries facing the most stringent level of scarcity. All countries belonging to that set must then be considered to incur lost-load for this hour.