Working Paper n°15

November 2008

GIS larsen

Laboratoire
d'Analyse
économique des
Réseaux et des
Systèmes
Energétiques

Generation adequacy and transmission interconnection in regional electricity markets

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November 2008

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Summary : Power system adequacy has currently public good features that cannot be entirely solved by electricity markets. Regulatory intervention is then necessary and old methods to assess adequacy have been used to help regulators to fix this market failure. In regional electricity markets, transmission interconnections play an important role in contributing to adequacy. However adequacy problem and related policy are mainly considered at a national level. This paper presents a simple model to study how the interconnection capacity interacts with generation adequacy. First results indicate that increasing interconnection capacity between systems improves adequacy up to a certain level; then further increases do not procure any adequacy improvements. Furthermore, besides adequacy improvement, increasing transmission capacity under asymmetric adequacy criteria or national system characteristics could create several externalities concerns. These results imply that regional coordination of national adequacy policies is essential to internalize adequacy cross-border effects.

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1. Introduction

The European Commission (EC) identifies "security of supply" as one of the three major goals in the liberalization of energy markets, besides to "competition" and "sustainability" (EC, 2007). However, the progressive reduction of generation capacity margins in electricity and the recent experiences of blackouts question the fulfilling of this goal. Electricity is an essential good and therefore, interruptions are hardly acceptable politically and socially (Helm, 2007). In electricity, security of supply, also called power system reliability, refers to two distinct but inherently related aspects: security and adequacy (Oren, 2007).[1]The first aspect is the ability of the power system to respond in real time to random situations (contingencies), such as outages of the thermal power plants, unpredictability of consumption and generation, sudden disturbances on the network, etc. The second aspect of reliability refers to the ability of the power system to meet the aggregate power and energy requirements of the consumption at any time. This feature is based on investment decisions in peak-load and base-load plants in order to monitor the growth of the demand and to supply sufficient reserve margin in the long term to cope with random events in short term and real time.

Generation adequacy is the long term generation component of reliability (Finon and Pignon, 2008). In theory, electricity markets should suppress the generation adequacy problem in a context with short-term demand elasticity and wipe its public good characters (Stoft, 2002). However, given electricity market failures[2], public authorities (e.g. regulator) should intervene and define additional market rules which contribute towards obtaining an optimal level of generation adequacy. Different approaches have been adopted in the world to ensure a sufficient level of adequacy: capacity payments, public strategic reserves, capacity requirement placed on suppliers with secondary markets, etc. In the last years, research has been concentrated on the design of these different generation adequacy mechanisms (Joskow, 2006; Cramton and Stoft, 2006; Finon and Pignon, 2008). But all of them remain based upon engineering planning criteria to measure adequacy (e.g. Loss of Load probability – LOLP) in order to make the adequacy policy setting.

Despite the interdependency between different systems in matter of reliability and beyond in matter of adequacy, it has been generally considered from a national point of view. Considering interactions in regional power systems is particularly important due to two factors: firstly, generation adequacy policies are mainly set up at the national level even in regional electricity markets (e.g. the European continental electricity market). Differences between regulatory policies may distort the normal

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[1] Firmness is an additional component related to security of supply in electricity (Perez Arriaga, 2007). This corresponds to a mid-term component and it is related to all actions undertaken to control the availability of power plants at mid-term horizon (e.g. maintenance, management of hydraulic stocks, etc.). Even if our results can be applied to adequacy as well as firmness, we do not treat specifically the firmness problem in this paper.

[2] Market failures (public good properties) come from the impossibility to supply a certain level of adequacy to individual consumers (i.e. under current technology, consumers cannot be disconnected individually when generation capacity is tight and admistrative rationing a necessity for the stability of the system). This non-excludability character provokes typical free-riding problems in case of bilateral treatments of supply security insurance (Finon and Pignon, 2008).

functioning of a regional market.[1] Secondly, the type and size of the adequacy problem in each system could be very different depending upon the type of generation units with their differences of exposure to specific randoms, their flexibility and the patterns of consumptions, etc. This second point is particularly important in Europe given the differences in the structures of their equipment fleets in national energy policies among European countries regarding nuclear and wind power.

The aim of this paper is to study how transmission interconnection capacity interacts with generation adequacy in a regional power system in order to derive regional policy implications. Firstly, using a simple adequacy model, this paper studies how interconnections interact with generation adequacy in regional power system. It shows that increasing interconnection capacity can improve adequacy (or reduce generation capacity requirements). We then analyze the externality concerns due to the differences in the patterns of demand and generation as well as in the generation adequacy policies that are adopted. These externalities cannot be internalized without a proper regional coordination of national adequacy policies.

The paper is organized as follows. Section 2 briefly explains the adequacy problem and the role of transmission interconnections. In Section 3 the model and the stylized system are presented. In Section 4 the results of simulations are shown and discussed putting emphasis on regional policy implications. Finally, Section 5 concludes.

2. Generation adequacy and the role of interconnection between systems

Electricity demand is known to be inelastic in the short-run. As demand and available generation capacity are not exactly known in advance, the risk of failure is never eliminated. Therefore demand may be higher than the instantaneously available capacity (Billinton and Allan, 1996). Generation adequacy policy consists in setting an admissible level of outage from the society point of view. It is determined by public authorities and affects the level of generation capacity that should be installed. Generation adequacy is not a new problem, but was differently managed before liberalization of electricity markets. Interconnection adds a new dimension in the approach of capacity adequacy in a system.

2.1. Generation adequacy before and after the liberalization

Before the liberalization of electricity market, reliability of electricity supply was managed by the vertically integrated utilities and controlled by public authorities. Decisions regarding new investments were determined by a capacity expansion plan which entailed enough generation margins while respecting a maximum level of risk of outage. A trade-off between the investment costs for new generation capacity in peaking units and the reduction in outage cost for consumers would in theory determine the optimal risk of outage (De Vries 2004). Although outage costs for consumers were hard to evaluate, adequacy criteria were validated by public authorities. Two methods of measurement were mainly used: deterministic and probabilistic.

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[1] It is important to note that sometimes public authorities do not define any criterion of adequacy considering that the « market » would solve the adequacy problem (see Pignon et al, 2007 for more details).

The typical adequacy criterion with deterministic methods is generation margin to be equal to a fixed percentage of the peak demand and operating reserve margins sufficient to cope with the most likely contingencies. One of the drawbacks of these methods is that they do not take into account the stochastic nature of supply and demand. Indeed, random events as uncertainty in customer demand, forced outages of generating units, intermittent production have an impact on the adequacy assessment.

Probabilistic methods provide therefore a more meaningful and realistic information about the random events that affect supply and demand (Prada and Ilic, 1999). Two criteria are often used: the Loss of Load Probability (LOLP), defined as the probability over some period of time that the power system will fail to provide uninterrupted service to customers and the Loss of Load Expectation (LOLE), defined as the expected amount of energy not served over some time frame. Note that typical rules used in generation expansion plan were expressed in terms of hours of outage in a year.

The new liberalized organization of the electricity industry implied a transformation of the planning system. Thus, the provision of long term generation reserves in deregulated systems depends on the degree of coordination among market participants resulting from the new institutional rules and regulatory instruments chosen. In theory this new regime should suppose that the market integrates a price-elastic demand function with price-responsive consumers with different willingness to pay for security of supply. This should replace the implicit security criteria used in the former industrial organization. It would require profound changes in contractual, metering and disconnecting technology. In fact current markets do not know individual consumers' willingness to pay for their electricity because it cannot implement it in a credible way (Pignon et al, 2007).

Since the level of reliability for most consumers cannot be individualized the market cannot alone solve the problem of adequacy because this technical impossibility to individualize transactions. To maintain a certain level of security of supply, some public authorities tend to intervene in the market through capacity market/obligations, capacity payments, etc. In addition to this problem (which is a classical problem of non-excludability of a public good) are added the effects of regulatory intervention to limit price spikes by a price cap to avoid problem of acceptability of reforms, as well as effects of transmission system operators (TSO)' excessive precautionary interventions by calling reserves in case of tight supply (Joskow, 2008). Indeed in the two cases there are reductions of hourly market prices and contraction of revenues perspectives of investors in peaking units, while it is very risky investments with high risk premium on their capital cost.

On the opposite others keep confidence in “energy only” markets hoping that consumers' behaviors and technology (in particular with deployment of smart meters) will adapt themselves. Proponents of this market design only accept as unique intervention of regulators in shortage periods (i.e. when demand is higher than available generation capacity) the definition of a price cap which is higher enough to promote the right level of generation capacity investment considering the marginal willingness to pay of consumers. Ideally, the price cap should be fixed equal to the utility of the marginal kWh consumed (the so-called Value of Lost of Load = VOLL), a condition for reaching an optimal level of investment in capacity (Stoft 2002).

Critics of the “energy only” market design argue that scarcity periods are propitious to market power exercise, with higher risks that constraint investment decision in peaking units and the tropism of transmission system operators to avoid power outages in priority on cost efficiency. This triggers the missing money problem (Joskow 2006). Those who do not believe “energy-only market” propose to complement the market design by different forms of capacity payments that try to smooth out the level of prices and to maintain an acceptable level of system reliability in any situation. However both parties agree that is currently difficult determine a representative VOLL function with differentiated willingness to pay for electricity in scarcity periods due to the lack of knowledge and experience of individual consumers to be confronted to real time prices. Therefore whatever the capacity mechanism implemented to solve the problem of adequacy, the regulator has to define implicitly or explicitly the level of adequacy to be reached, and not to let the market to determine it by confronting a demand and a supply of long term supply security.

Some regulators have decided to rely on the former adequacy criterion. In the countries with “energy only” markets, this criterion has a strictly informative function, while in other countries they are used as inputs of the capacity mechanism added to the market design (as for instance the capacity obligation with exchangeable capacity rights in the PJM).[1]

2.2. The impacts of interconnections on generation adequacy

It is well known that the historical role of interconnections is to ensure the short term reliability by pooling the production capacity on a larger scale (e.g. reducing the level of needed primary and secondary reserves (Menager 2002)). The constitution of regional electricity markets (such as the Internal Electricity Market in Europe and Regional Transmission Organizations as PJM in the US, etc.) assigned two additional roles to interconnections: to allow arbitrage between markets and to increase the level of competition inside each system. Moreover, the new investment cycle in generation in Europe puts the problem of adequacy at the center of debate. But the interaction between generation adequacy of a system and interconnection capacity needs to be considered while most generation adequacy studies do not take into account the influence of interconnection (or they do but in a very rough way) (Pignon et al., 2007).

For instance, in its System Adequacy Forecast (UCTE (2008)), the Union for the Coordination of Transmission of Electricity (UCTE) currently takes into account interconnections by identifying whether the observed residual generation capacity of a country is higher or lower than the net transmission capacity. It allows integrating the effect of limited transmission capacity in stressed periods. But it does not take into account the complementarities in the random generation capacity margins in neighboring countries. Although PJM (2005) uses probabilistic methods to take into account the uncertain nature of the generation margins, it assumes independence between these margins, and thus neglects correlations between the generation margins of the countries interconnected.

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[1] At this level of discussion, it is important to note that one can understand these old criteria as tools for the public authorities to set up the "adequacy model" parameters. For instance, to settle the level of "capacity payment" public authorities have to consider an objective risk of outage.

Given that between European countries interconnections are limited in capacity, how to take into account how each system could contribute to the reliability in the neighbours and vice versa? Considering the role of interconnections in the generation adequacy and its intrinsic pattern is necessary for several reasons:

- Firstly, interconnections can increase the security margin of a system through the difference in production and consumption patterns of the neighboring systems. The complementarities between production and demand patterns may make it profitable to develop a regional vision of generation adequacy and security of electricity supply. Such regional approach would allow each country to reduce its capacity margin requirement. Accordingly, there will be savings in investment and operating costs in each interconnected country. Even if the role of interconnections is similar to its historical role in the monopoly regime, the question here concerns the necessary mechanisms to take into account its role on the generation adequacy policies in the different countries.

- Secondly, dysfunctions may also be exported from one country to the other through interconnections as shown by recent blackouts.

- Thirdly, the lack of harmonization between power systems in terms of adequacy criteria and market designs could lead to a situation where consumers of a country may pay for the adequacy provided to consumers in the neighboring countries in a long term perspective. In others terms, thanks to interconnection some consumers may benefit from a risk-adverse generation adequacy criteria in a neighboring power system and have a relatively high level of security of supply without incurring the corresponding investment costs. This free-riding behavior may ultimately lead to a general decrease in the level of adequacy of the interconnected systems. This is the traditional free-riding and public goods financing problem when the cautious agents are compensated for the positive externality they procure to the other agents (Cornes and Sandler, 1986).

This raises policy issues: How to coordinate national adequacy policies? How to include the role of interconnection? To what extent it is useful to harmonize adequacy or interconnection capacity policies between liberalized electricity systems? In the next sections we shed light on these issues with a simple but relevant generation adequacy model that integrates the interconnection capacity and the adequacy resource which can be offered to a system by neighboring systems.

3. The model

This section presents the adequacy simulation model used to understand the interaction between adequacy and interconnection capacity. Only the role of interconnection capacity concerning adequacy is studied in this section; we do not deal with other valuable roles of interconnection capacity such as reduction of market power.

3.1. Adequacy model (one zone)

To model generation adequacy in zone i (national approach), we use a probabilistic method that characterizes a random variable called "margin" (M_i) that represents the difference between available generation capacity (G_i) and load (L_i) random variables.

$$M_i = G_i - L_i \qquad (1)$$

The variable “margin” allows evaluating the loss of load probability of the power system ($LOLP$). Loss of load probability represents the probability that load is higher than available generation capacity for a given moment, thus, this indicates the level of risk failure of the system. To evaluate whether a power system is adequate or not, we compare the current loss of load probability with an objective level ($LOLP_{obj}$). This objective level is determined by the public authorities and a value currently used in several countries is 0.01 or 1% risk (RTE 2007, PJM 2005).

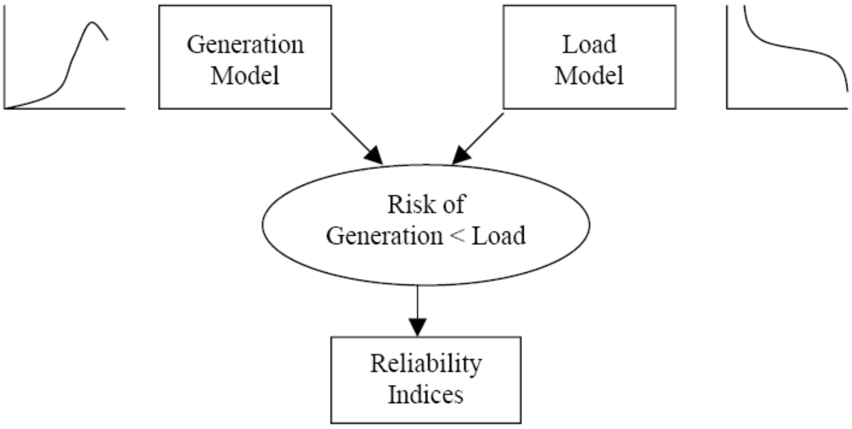
The adequacy method can be computed using the following equation:

$$LOLP_i = Prob\ (M_i \leq 0) \leq LOLP_{obj,i} \qquad (2)$$

The random variable “margin” is derived from the combination of a load model and a generation model (Fig. 1).

On the load side, we consider in the simulation model only the weather random events that affect the load random variable (L_i). On the generation side, we consider two different technologies: not correlated generation (G_i^{nc}) and correlated generation (G_i^{c}). Available generation capacity at a given moment is the sum of these technologies: $G_i = G_i^c + G_i^{nc}$. By not correlated technology, we mean a technology like thermal power plants which the random events that affect its available production mainly refer to outages in each power plant and are independent of weather, demand and others production technologies[1]. On the other hand, by correlated technologies, we refer to run-of-river or wind power plants, where the random event that affects the available production capacity is the intermittency in the supply of primary energy. These electricity production technologies are both correlated with the weather, and therefore, with demand. We will call this correlation the "national correlation" to distinguish it from the "regional correlations" between interconnected zones (see below).

Fig. 1. Adequacy model



source : Billington and Allan 1996

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[1] Note that this is an approximation because very hot seasons can provoke a general decrease in thermal power availability because the reduced cooling capacity of water sources.

Normal distributions are used to represent each one of random variables (G_i, L_i). Mean and standard deviation parameters for each normal distribution are defined. Table 1 shows the parameters of the probability distribution of each variable in the base case. These values could mimic a system of an important size in Europe (e.g. France, Germany).It is important to note that even if our model allows to simulate positive or negative correlations between correlated technology and load, we assume negative correlation (also called "anti-correlation"). This is the case in most European countries: in the winter when the low temperatures provoke a decrease in rain and, at the same time, demand increases for heating purposes.[1]

The probability distribution of the variable "margin" is obtained from a convolution[2] between probability distributions for both load and generation (see equation (1)).

Table 1. Data of base case system

	mean [GW]	standard deviation [GW]
Load (L_i)	81	6
Correlated Generation (G_i^c))	18	1.7
Non Correlated Generation (G_i^{nc}))	75	2
Objective Risk ($LOLP_{obj}$)	1 %	

Fig. 2. Convolution Diagram between Probability Distribution Function (PDF) of Generation Available Capacity and PDF of the Demand

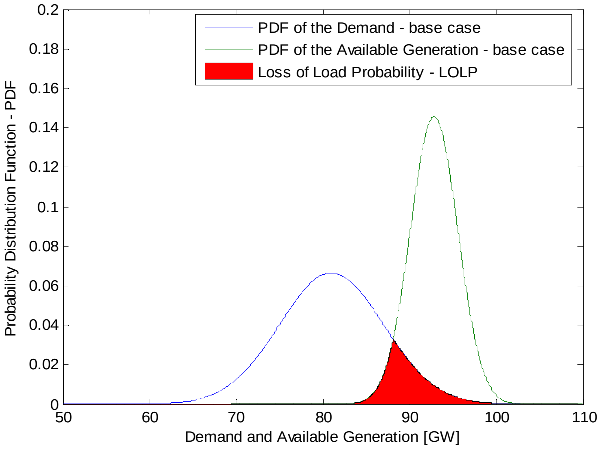

Fig. 3. PDF of the Available Generation Margin

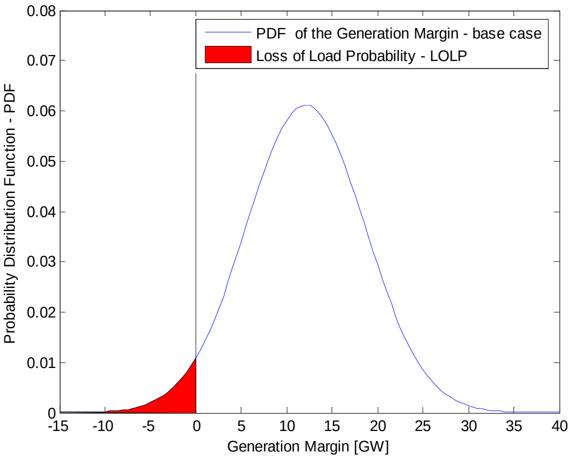

Figure 2 shows the probability distributions for each random variable (available generation capacity and demand) and the loss of load probability for the base case. Note that an outage will occur when the probability distribution of load is higher than

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[1] Contrary to hydroelectric power, wind power technology can be positively or negatively correlated with demand. In our paper we focus in generation technologies negatively correlated with demand such as hydroelectric power (see Cepeda et al 2008 for an analysis of wind power).

[2] In theory of probability, convolution is a mathematical operator for determining a probability distribution "output" given two probability distributions.

the generation. The loss of load probability (or LOLP) is represented by the shaded area under the curve of the probability distribution both of the demand and generation, when generation exceeds demand. Figure 3 shows the probability distribution of the variable "margin" and the lost of load probability that is equivalent to the shaded area in red in Fig. 2. Besides LOLP index calculation, we adapt this simple model to compute the generation margin needed for a given level of adequacy (Generation Margin Requirement (GMR). This criterion has the advantage of being more representative of power systems because it can be related directly to the risk level, the installed capacity and the peak load.

The $\overline{GMR}_i$ is computed by increasing the available generation capacity until a loss of load probability objective is achieved. For each value of generation margin an associated random variable M_i is derived. A higher generation margin moves the probability distribution of M_i to the right (see figure 3) reducing the loss of load probability. The Generation margin requirement ($\overline{GMR}_i$) is defined as the difference between the mean of generation capacity ($\overline{G_i}$) and the mean of peak load distribution($\overline{L_i}$) while the adequacy objective is achieved ($\overline{GMR}_i \rightarrow M_i^{GMR} \rightarrow LOLP_{obj}$).Mathematically, it may be calculated from the following equation:

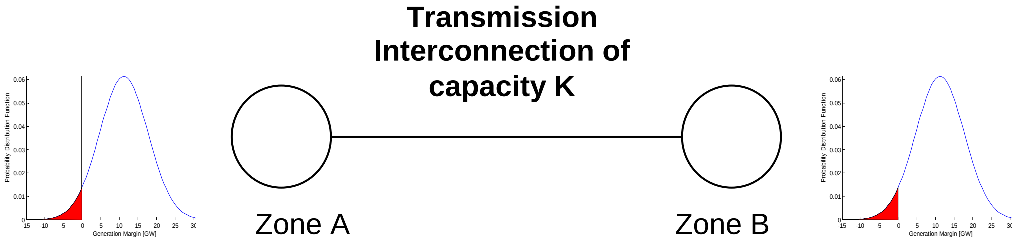
$$Prob\left(M_i^{GMR} \leq 0\right) = LOLP_{obj} \quad (3)$$

Until now only one-zone model (national approach) has been taken into account. In the following section we consider a model with two zones and the interaction of the interconnection capacity between zones.

3.2. Adequacy model and interconnection capacity

Based on (PJM, 2005 and 2007), (Choi J. et al., 2006) and (Pudjianto D et al., 2008), we have adapted the national analytical method to take into account interconnections. Our model considers a system made up of two zones interconnected by a transmission line of capacity K (see Fig. 4).[1] Transmission interconnection between zones is assumed perfectly reliable.[2]

Fig. 4. Scheme of the two-zone system



The simulation model computes Loss of Load Probability ($LOLP$) by using a “Monte Carlo” method for different values of transmission capacity. We simulate 10000 random numbers in Matlab from the bivariate normal distribution of probability (see Fig. 5). It allows us to consider the joint probability $Prob_{M_A,M_B}$ that the variable

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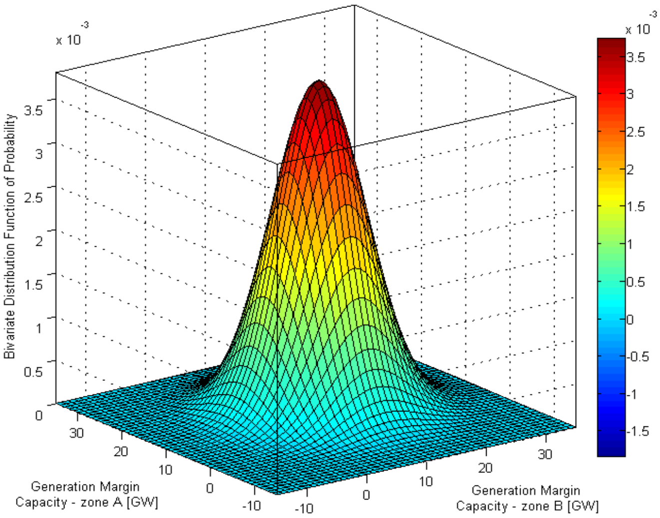
[1] It is important to note that we do not consider national transmission constraints within the zones.

[2] This assumption can be easily modified in order to consider more realistic examples. A probability distribution of the transmission line availability can be included in the model as well.

margin of zone A is M_A while the variable margin of zone B is M_B, for any value M_A and M_B taking into account the dependence between variables.

Fig. 5. Bivariate Distribution Function of Probability of the two-zone system



When considering two zones one clarification has to be made concerning correlations. We consider two types of correlations: “national correlations” and “regional correlations”. National ones refer to the existing correlation between load and “correlated” generation technology in each zone. Regional ones refer to correlations between both zones, that means correlations between each load ($L_A$and L_B), between each generation (G_A^c and G_B^c), and between load in a country and generation in the other one (L_A and G_B^c, L_B and G_A^c).

One important issue concerning adequacy with regional system is the way that “emergency” situations are managed when production-load balance in each zone is very tight. For the sake of simplicity we assume that regional system works completely under the principle of solidarity: each zone shares completely its available margin with the other zone (i.e. at each state of nature, one zone will collaborate with its neighbor). However, it is not yet clear in the European Union whether this solidarity principle is applied. In other terms, it is still not clear whether it is legal or not to stop an export of power capacity because of the national tight balance between demand and supply. Indeed, there appears to be contradictions between the national laws and the European Directive concerning emergency situations. On the one hand some national laws dictate that exports should be interrupted in case of emergency. While at the same time the SoS Directive, Article 4.3 states: "In taking the measures referred to in Article 24 of Directive 2003/54/EC (it refers to measures to be adopted in emergency situations) and in Article 6 of Regulation (EC) No. 1228/2003, Member States shall not discriminated between cross-border contracts and national contracts. This shows us that the rules and practices in terms of reliability of supply are not totally established.

Considering solidarity in the way to share the margins between zones, we can compute adequacy index and generation requirements. For instance, $LOLP_A$ for a regional system can be computed using the following equation (4) :

$$LOLP_A(K) = \underbrace{Prob\big((M_A \leq 0) \cap (K \leq |M_A|)\big)}_{Term\ 1} + \underbrace{Prob\big((M_A \leq 0) \cap (|M_A| \leq K) \cap (M_B \leq -M_A)\big)}_{Term\ 2} \quad (4)$$

where M_A and M_B are respectively the margin of each zone and K is the interconnection capacity between the two zones.

The first term of (4) corresponds to the probability of failure when zone A is unable to import its entire deficit capacity, because import is limited by the capacity of interconnection. The second term of (4) refers to probability of outage while the size of the interconnection is no more constraining, but the margin in zone B cannot compensate the deficit in zone A. As in the case with one zone, we have also adapted the model to compute the generation margin requirement ($\overline{GMR_i}$) for each zone and for each level of interconnection capacity.

4. On the role of interconnections in generation adequacy

In this section we use the model developed above to realize several simulations in order to show the role of interconnection on generation adequacy and the regional policy implications. In order to understand the role of interconnection capacity on generation adequacy, we do an analysis in progressive steps. In the first step (section 4.1), we study a symmetric two-zone system. It allows us to focus on the impact of the transmission capacity level on generation adequacy since we represent two interconnected zones with the same generation and demand patterns and the same generation adequacy objective. Since the state of nature of each random variable can be different even in this symmetric case, the interconnection will have an impact on adequacy. In the second step (section 4.2), an asymmetric two-zone system is studied, i.e. interconnected systems with different generation patterns, demand patterns or adequacy objective. In this analysis we illustrate externalities problems due to the lack of coordination in the national adequacy policies. For each case, simulations' results and policy implications as regards generation adequacy policy at the regional level in Europe are inferred[1].

4.1. Interconnection capacity as a way to improve generation adequacy

In order to focus on the effects of interconnections on generation adequacy in an isolated manner, a symmetric case, where both zones have the same size, the same production technologies, the same demand patterns and the same generation adequacy objective is analyzed. Table 2 sums up the zone A and zone B systems characteristics.

Table 2. Symmetric case

	Zone A/B	
	mean [GW]	**standard deviation [GW]**
Load (L_i)	81	6
Correlated Generation (G_i^c)	75	7.1
Non Correlated Generation (G_i^{nc})	18	0.5
Objective Risk ($LOLP_{obj}$)	1 %	

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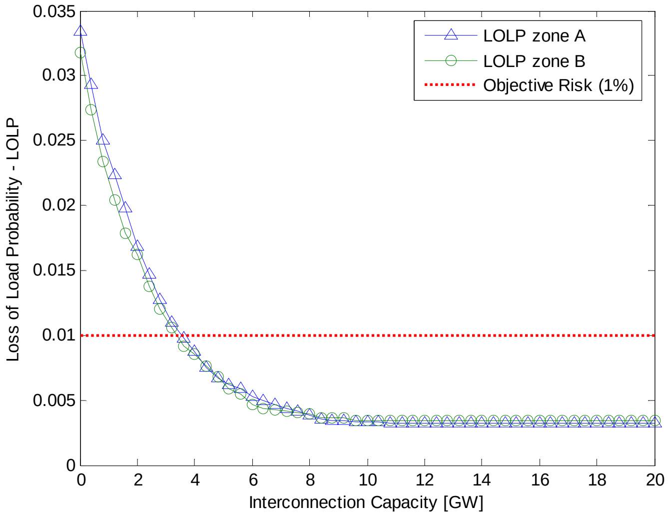
[1] This paper uses a simple two-zone model to develop results on interaction between systems in terms of adequacy. Further research is oriented towards extending this simple model to consider a network of 3 nodes and imperfect perfect reliability of transmission interconnections. But results are not intrinsically different from those presented here.

We first consider a case where there is no correlation between variables and then make sensitivity analysis in order to evaluate the impact of different “national” and “regional” correlations and finally derive the regional policy implications.

Base case (no correlations). In the first simulation we “connect” the two zones characterized in table 2 and compute LOLP index for different level of interconnection capacity (K=0 to 20 GW). Note that for this calculation a zero correlation is assumed between all the random variables of the model (zone A and B margins). Fig. 6 shows the results of this simulation. It can be seen that increasing transmission capacity between zones improves the generation adequacy (reduces $LOLP$) of each zone. Given the stochastic characteristics of power system, increasing the “size” of the system should improve the adequacy concerns. It indeed results from the diversification of risk due to imperfectly correlated random events. Nevertheless, figure 6 also shows that improvements in generation adequacy stop after a certain level of transmission capacity (here a transmission capacity around 8 GW or $LOLP_i$ =0.4%). At this level, it is not useful anymore to increase the interconnection capacity because it wouldn’t entail any additional benefit in terms of reducing the loss of load probability. $LOLP_i$ becomes a horizontal asymptote parallel to x-axis. That is due to the fact that the focus is on an increase in transmission capacity while the generation and demand patterns (mean and standard deviation) are kept constant.

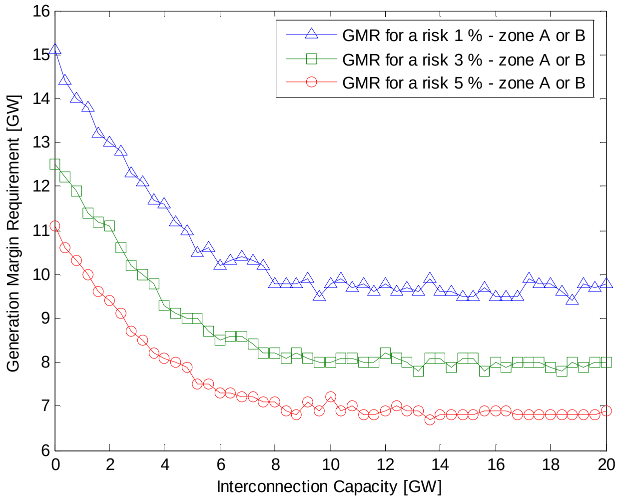
From Fig. 6 it can be seen that if each zone were "isolated" (i.e. interconnection capacity equal to zero), the level of adequacy of each zone ($LOLP_i$) would be higher than $LOLP_{obj}$ (=0.01, the horizontal red line). One way to reach the adequacy objective is to increase interconnection capacity between the two zones up to around 3.3 GW. This level is almost half of the interconnection capacity level from which there are no more additional benefits in reducing the failure risk. This means that increasing interconnection capacity from 3.3 GW will reduce the outage risk $LOLP_i$, but it would lead to over cost for the two zones given the objective level$LOLP_{obj}$.

Fig. 6. Loss of Load Probability (zone A and B) vs. interconnection capacity K



The same effects can be seen looking at the Generation Margin Requirement figures. Fig 7. illustrates the Generation Margin Requirement for different levels of risk: 1, 3 and 5%. Note that when the objective criterion increases, the GMR’s curves move downwards (less generation margin required) and to the left (less capacity interconnection required).

Fig. 7. Generation Margin Requirement for a risk 1, 3 and 5% (zone A and B) vs. interconnection capacity K



The level of interconnection capacity, from which there is no more reduction in the required margin for a given risk, is about 8 GW for a risk of 1% and rises to around 14 GW for a risk of 5%. This figure shows that there is a trade-off between generation capacity and transmission interconnection capacity in order to reach a given level of risk. This means that to achieve a given level of adequacy (e.g. $LOLP_{obj}$) it is possible to increase the “national” generation margin (increasing the generation installed capacity or reducing the load) or increasing the interconnection capacity.[1]

In this section we have studied the impact of interconnection on generation adequacy considering two symmetric systems and without any correlation between random variables. In the next section we introduce correlations.

Impacts of correlations between generation and/or demand patterns. Here the effect of correlations on the interaction between generation adequacy and interconnection capacity is analyzed. This analysis is quite important, since it provides results about how systems interact, which contributes to improve the coordination between regulators in terms of interconnected power systems adequacy. The correlations study is made in two stages: we first focus on the effect of national correlations[2] on the adequacy, without taking into account the regional correlations. In the second stage, the regional correlations[3] are integrated into our simulation model.

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[1] Note that the optimal level of interconnection capacity between zones, considering only the adequacy problem, depends on the relation between the (fixed) cost of increasing interconnection capacity and the (fixed) cost of increasing generation capacity.

[2] This corresponds to the correlation that exists between generation technologies and demand in each zone. For instance, the negative correlation that exists between run-of-the-river plants and demand.

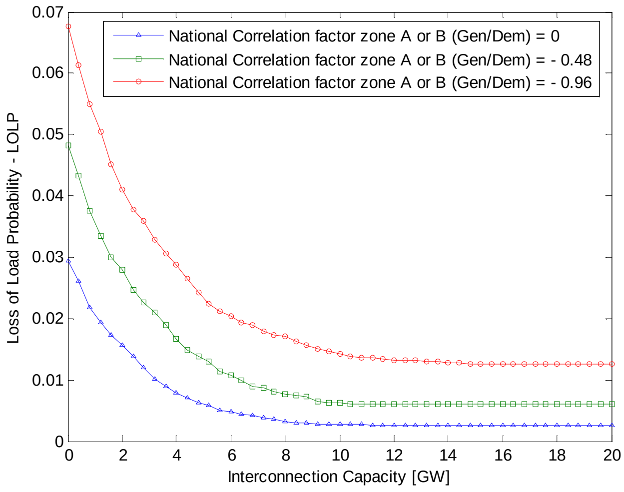
[3] This corresponds to the correlation that exists between generation technologies and demands for both zones. For instance, the positive correlation that exists between run-of-the-river generation between two zones.

In the analysis of national correlations, a negative correlation is considered between load and correlated generation technology.[1] Figure 8 illustrates a sensibility analysis to different values of the correlation factor ($CorrF_{L_i,G_i^c} = 0$, -0.46 and -0.96). The curves family shows that for a given interconnection capacity, a system will all the more easily increase its adequacy (i.e. decrease its $LOLP_i$) as the anti-correlation between load and generation is low. In other words, considering that temperatures decrease water input to the run of river power plants and increase the demand due to air conditioning; with a high anti-correlation factor, it will be more difficult for this system to improve its adequacy with the existing transmission and generation capacities that if the correlation factor had been very low. Therefore, the improvement of zones' adequacy depends strongly on national characteristics (generation and demand patterns).

We now extend the analysis to a system where the random variables (generation, load) may be regionally correlated. Fig. 9 shows the effects of regional correlations on generation adequacy in the two system zones.

Figure 9 illustrates the loss of load probability for different correlation factors between each zonal load. Since demand is strongly influenced by the weather, the correlation between two neighboring demands for electric power should be positive (using the following factor in the simulations: $CorrF_{L_A,L_B} = 0$, 0.46 and 0.96). As shown in figure 9, the higher the correlation between zonal loads, the lower the increase in generation adequacy due to a given cross-border transmission capacity. In addition, this effect is more important when the interconnection capabilities increase. The level of interconnection capacity at which national adequacies stops to improve decreases for more correlated loads.[2]

Fig. 8. Loss of Load Probability (zone A and B) vs. interconnection capacity K for different National Correlation Factors



We can conclude that correlation factors between random variables are important parameters in order to evaluate the role of interconnection capacity on generation

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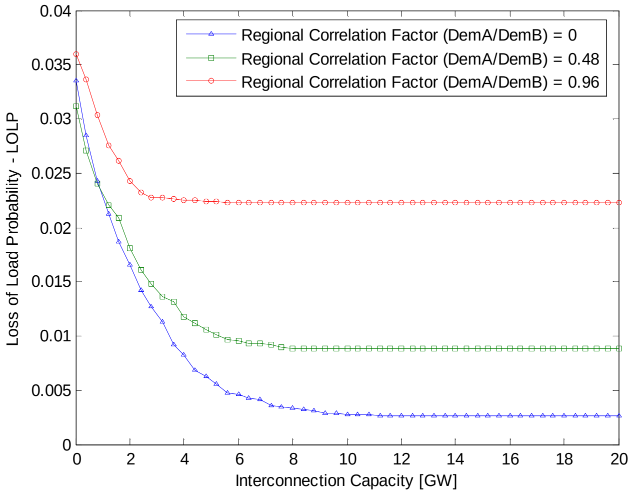
[1] Cf. section 3.1

[2] Correlations between generations in different zones and between generation and demand in different zones have similar effects concerning the impact of interconnection in adequacy. For instance, more correlated generations in different zones reduce the impact of increasing interconnection capacity between zones.

adequacy. This indicates that the effects of interconnection depend on particular characteristics of neighboring systems which have to be taken into account.[1]

Fig. 9. Loss of Load Probability (zone A and B) vs. interconnection capacity K for different Regional Correlation Factors of the Loads' zones



Policy implications. The results obtained through simulations using a symmetric case allow us to extract two main policy implications concerning regional systems: i) the economic efficiency of regional adequacy policy coordination and ii) this coordination has to take into account particular characteristic of each specific border.

Firstly, the choice of socially optimal level of interconnection between zones in a regional system implies a certain level of coordination at a regional level. The consumers in each zone can only « see » the level of adequacy of their own zone. But the level of adequacy comes from different kinds of investment in generation and transmission. Furthermore, increasing interconnection capacity in order to improve generation adequacy has its limits: further increases of interconnection capacity does not produce any adequacy improvement anymore. These elements indicate that the "optimal" level of interconnection capacity concerning adequacy has to be defined taking into account the characteristics of both systems (generation and load). For instance optimal combination between transmission capacity and generation capacity could be defined by calculating the ratio between generation and transmission interconnection cost. It is noteworthy that this possible trade-off between generation capacity and transmission capacity for achieving a level of adequacy is a strong rationale for long term coordination between zones in setting generation and transmission adequacy policies in each zone (Creti and Fabra, 2004). However, in Europe these policies are actually settled at a national level and no mechanism of coordination exists (Pignon et al 2007).

Secondly, as the effects of interconnection between two systems depend on each zone characteristics, the rules defining the coordination between them should be "border specifics". In other words, the uniformization of coordination rules, whatever the border considered may not be efficient because the effects of the interconnections are specific at each border and to each couple of countries. For

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[1] It is important to note, given the assumptions used for our model, that these results are not general for any power system, specially, where there are technologies positively correlated with demand such that the wind power. However, this analysis is outside the scope of this paper. For a deepening of this problematic see Cepeda et al (2008) and Karki et al (2005).

instance, it will be more efficient to improve adequacy through an increase in transmission capacity considering two specific countries (e.g. two countries with weak correlation between respective generation systems) than between two other countries (e.g. with strong correlations between generation systems). Alternatively, in this symmetric case an increase in interconnection capacity will be efficient by increasing adequacy by crossed interaction between systems which have a weak anti-correlation between generation and load, but the same will be less efficient between countries with a strong anti-correlation between generation and load.

4.2. Impacts of asymmetry in the interconnected power systems

Here, interconnected systems are analyzed under three scenarios of asymmetry: i) asymmetry in generation technologies (i.e. different technology mix and standard deviation but equal size in terms of mean value of available capacity), ii) asymmetry in size of the power systems (i.e. different mean value of total available capacity) and iii) asymmetry in adequacy criteria. In reality, each system has its own demand and generation patterns. In addition the adequacy objective chosen by each system may be different (e.g. costumers in two neighboring zones may value differently adequacy and therefore the adequacy objective chosen by the public authorities can be different).

Case 1 : asymmetry of the generation patterns in the interconnected power systems. Let us consider now that zone B has a generation structure with more correlated generation than zone A (cf. table 3). Zone B may represent a country with significant run of river generation (Norway, Brazil or Colombia for example). Zone A is similar to the preceding symmetric case, and the input data represent a country like England, Germany or the Netherlands where a large part of generation electricity comes from thermal power plants, whose availability is assumed independent of any other variable. Note that the total available capacity and the demand in each zone are equivalent to the symmetric case.

Table 3. Case 1: asymmetry on generation patterns

	Zone A		**Zone B**	
	mean [GW]	**standard deviation [GW]**	**mean [GW]**	**standard deviation [GW]**
Load (L_i)	81	6	81	6
Correlated Generation (G_i^c))	18	1.7	75	7.1
Non Correlated Generation (G_i^{nc}))	75	2	18	0.5
Objective Risk ($LOLP_{obj}$)	1 %		1 %	

Fig. 12 illustrates the Generation Margin Requirement (GMR) for an objective outage risk at 1% in each zone. We notice that zone B requires more generation margin than in zone A. This is because the available correlated generation is more important in zone B than in zone A (i.e. standard deviation of the correlated generation is four times greater in the zone A than in the zone B).

The difference between the GMR's curves (see figure 13) is mainly constant, around 5 GW approximately for any amount of capacity interconnection. This means that, although there is an asymmetry in the generation technology patterns, the effects of an additional increase in interconnection capacity are symmetric in both zones in absolute terms. This result indicates that for these cases of asymmetry, one can easily agree on rules to share the costs/benefits of interconnection capacity on adequacy.

Fig. 12. Generation Margin Requirement (zone A, B) vs. interconnection capacity K

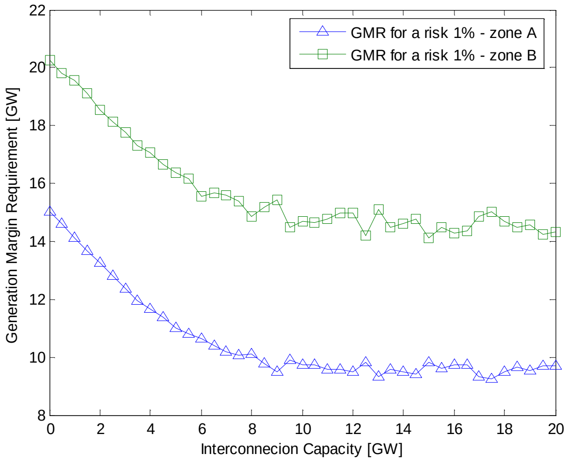
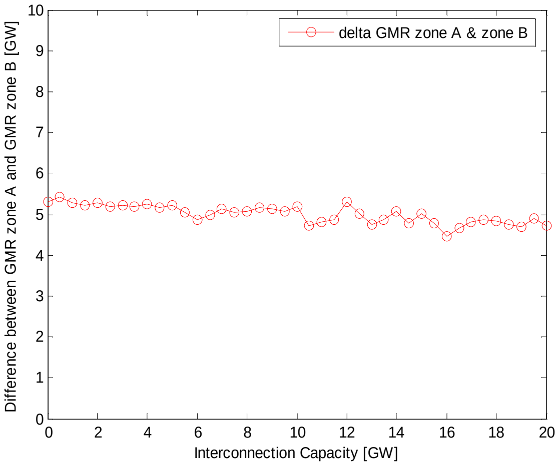


Fig. 13. Difference between GMR for zone A and zone B vs. interconnection capacity K



Case 2 : asymmetric in size (generation available capacity and demand). The power systems features for this case are illustrated in Table 4. Zone B has a lower installed generation capacity and a lower demand than zone A. Note that the technology mix (percentage of each technology) is kept constant. We aim to assess the impact of this asymmetry on the adequacy of the interconnected power systems. The results are illustrated in Figures 14 and 15.

Table 4. Case 2: asymmetry in size

	Zone A		**Zone B**	
	mean [GW]	**standard deviation [GW]**	**mean [GW]**	**standard deviation [GW]**
Load (L_i)	81	6	31	2.3
Correlated Generation (G_i^c)	18	1.7	6.8	0.7
Non Correlated Generation (G_i^{nc})	75	2	28.7	0.8
Objective Risk ($LOLP_{obj}$)	1 %		1 %	

Fig.14 illustrates the generation margin requirement for each zone. In the isolated case (interconnection capacity equal to zero), the generation margin requirement in each area is proportional to installed capacity of each area. Zone A is indeed 2.6 times zone B. However, an increase in the interconnection capacity leads to asymmetric benefits between both zones and there is no proportionality factor anymore.

Fig. 15 illustrates the difference between the generation margin requirements. Contrary to the asymmetric case 1, this difference is not constant and rises with the interconnection capacity. In other words, when there are two interconnected zones with asymmetry of sizes, all things being equal, the generation adequacy increases more for the smaller zone when interconnection increase.

Fig. 14. Generation Margin Requirement (zone A and B) vs. interconnection capacity K

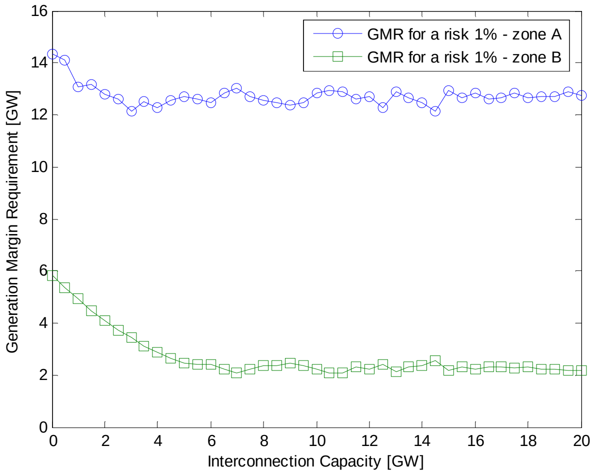
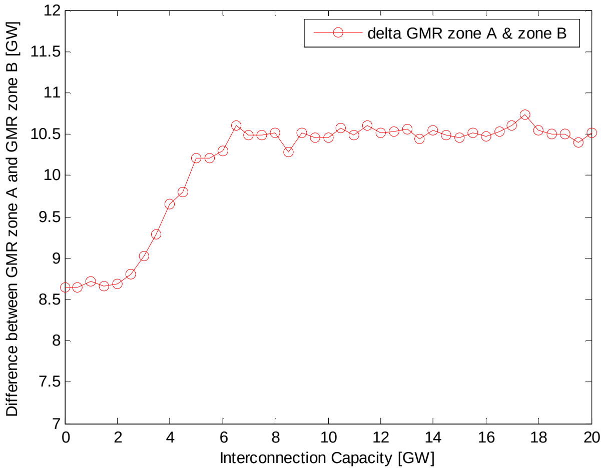


Fig. 15. Difference between Generation Margin Requirement zone A and B vs. interconnection capacity K



Case 3: asymmetry in adequacy objective. Let us consider now that zone B has an adequacy criterion less strict than zone A adequacy criterion (cf. table 5).[1] Fig.16 and 17 show the effects of different generation margin requirement between zone A (risk at 1%) and zone B (risk at 5%). Compared with the symmetric case (discontinuous line in the figure 16 -17, risk at 1% for both zones), the generation margin requirement in zone A increases when interconnection capacity increases. Conversely, the generation margin requirement in zone B decreases substantially when interconnection capacity increases. This means that the benefits of interconnection capacity on generation adequacy are not symmetrically shared between zones.

Table 5. Case 3: asymmetry in adequacy objective

	Zone A		Zone B	
	mean [GW]	standard deviation [GW]	mean [GW]	standard deviation [GW]
Load (L_i)	81	6	81	6
Correlated Generation (G_i^c))	18	1.7	18	1.7
Non Correlated Generation (G_i^{nc}))	75	2	75	2
Objective Risk ($LOLP_{obj}$)	1 %		5 %	

In economic terms, one can assert that this type of asymmetry creates positive externality that may lead to free-riding behaviors. But is this always true? It depends in fact on the characteristics of each interconnected power system and the current level of the interconnection capacity.

If we consider that the starting situation is with no interconnection, then every increase in interconnection capacity improves generation adequacy (GMR

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[1] To be discussed: This situation may arise for two reasons: i) Consumers in zone B can be much less sensitive to adequacy and value security of supply less than in zone A and ii) Public authorities in zone B may define a weaker objective anticipating the neighbor contribution to adequacy (free-riding) .

reduction). The free-riding behavior argument is therefore not valid in this case. Although zone A has to increase its generation margin as compared with the symmetric case, this increase is lower than in the isolated case. Even if the regulator's risk objective is high which leads to a high generation capacity requirement in zone A, it is nevertheless more efficient for this area to share transmission capacity with its neighbors for security purposes.

Fig. 16. Generation Margin Requirement (zone A, B) vs. interconnection capacity K

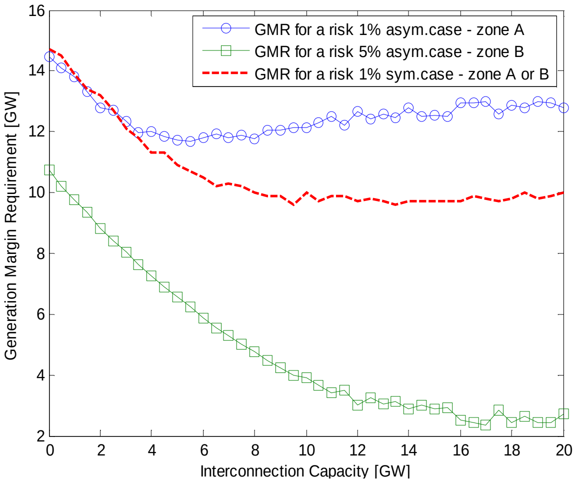
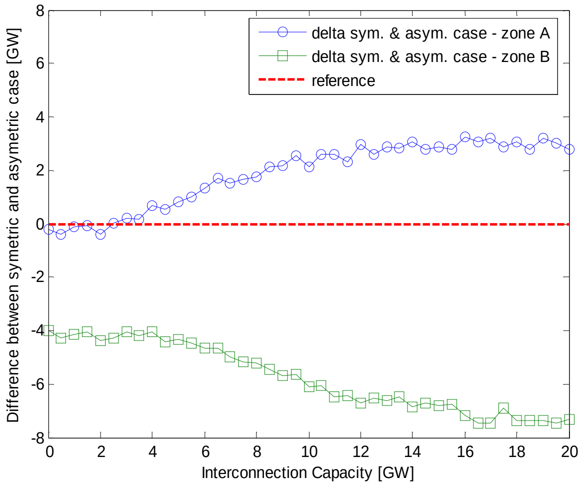


Fig. 17. Difference between symmetric and asy. case vs. interconnection capacity K



However, if we consider that the starting point is the one where the two zones share an interconnection of 4 GW, then the free-riding behavior argument becomes credible. The simultaneous rise in the GMR curve in zone A and decrease in the GMR curve in zone B indicate that the externality becomes “relevant”, that is to say that the free-riding behavior becomes a credible threat to generation adequacy.

Policy implications. Most of the European countries have asymmetric characteristics concerning generation, demand patterns as well as adequacy objectives. Because of the numerous determinants of generation technology choices (performance, costs, unit size, political will, etc.), there is a low probability in the medium term that European countries converge on technology mix. Given the difference in generation technologies and load pattern between the European countries, the effects of transmission interconnections from one couple of countries to another one are not identical. And this has policy implications concerning the allocation of costs/benefits of adequacy effects and the uniformization of these allocation rules. This means that we should take into account the potential conflicts that may be created and to define detailed efficient rules to share the costs/benefits between the different zones. Moreover, one “unified” regional policy based on cost /benefit sharing rules should also take into account the difference between each particular couple of countries.

Our results show that whatever the type of asymmetry between two systems (size, technology mix, adequacy objective), increasing interconnection capacity may yield to asymmetrical effects in each system. Because of this perspective, some countries may favor individual management of adequacy. However, from an economic point of view, others should voluntarily cooperate in the cases each one benefiting from the interconnection. In this case, this conclusion reinforces the one from the analysis of symmetrical cases: regional coordination of adequacy policy would give place to net benefits for each individual country.

5. Conclusion

Generation adequacy and the impacts of interconnection capacity are key issues in reliability of power systems. Using a simple two-zone adequacy model this paper shows the effects of transmission interconnection capacity on the generation adequacy under several cases: symmetrical (both zones have the same characteristics) and asymmetrical (zones have different characteristics) cases.

Considering symmetrical cases, results indicate non-surprisingly that increasing interconnection capacity between systems improves adequacy but only up to a certain level; then further increase does not produce any adequacy improvements. This effect depends on the desired level of outage risk in national system, and indicates that a trade-off exists between generation capacity and interconnection capacity in order to satisfy an objective of outage risk limitation. Furthermore, beside adequacy improvement, increasing transmission capacity under asymmetrical desired levels of risk could create several externality concerns.

Results developed in simulations indicate that regional coordination of adequacy policies is needed for two reasons. The first reason is related with the optimal choice of generation and interconnection capacity to achieve a given level of adequacy. As this optimality (or optimal situation) depends on the regional system characteristics some coordination is needed to find the socially optimal combination. The second reason is that a mechanism to share costs/benefits of interconnection capacity has to be implemented in order to avoid free-riding problem. Interconnection capacity can indeed create asymmetric effects in each zone (even if the whole system benefits) and countries may favor the management of the adequacy individually, without enjoying the benefits of integration (or increase of interconnection capacities). Finally, simulation results show that uniformization (one unique rule for everybody) as a way of coordination is not an optimal solution since the effects of interconnection capacity depend on the neighbor systems characteristics.

Regulators at the regional level should integrate into their rules, practices and decisions an overview of regional generation adequacy. An example of regional coordination is the way the security aspect in interconnected systems is managed. Indeed, to ensure the security at regional level each interconnected zone must provide spinning reserves according to its power systems features. Thus, spinning reserves contributes to ensure the supply-demand balance in real time. Although “security good” has different features with respect to the “adequacy good”, this example illustrates a successful regional coordination between interconnected power systems.

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