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INTERDEPENDENCIES IN SECURITY OF ELECTRICITY SUPPLY

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Abstract

The analysis of security of electricity supply (SoES) is particularly complex due to, among others, the liberalisation process and the increasing penetration of renewable energies. Larsen et al. (2016) propose a framework based on twelve dimensions to evaluate SoES for a single jurisdiction. However, actions aimed at improving one dimension might impact others negatively, adversely affecting the overall system. Understanding how these dimensions are interrelated is thus a prerequisite for appropriate planning and resource allocation. We apply a Cross Impact Analysis (CIA) to these twelve dimensions to determine the degree to which the different dimensions depend on each other. From this we derive an influence diagram to visualise the interdependencies and a scatter plot to categorise the dimensions as independent, driver, connector or outcome. The connecting dimensions are the central elements of the feedback mechanisms of SoES, reinforcing or balancing the effect of other dimensions. Actions targeting the dimensions categorised as drivers or connectors are potentially the more effective ones a regulator can take, as the consequences will gradually ripple through the system. They affect system-wide performance, but not necessarily in the desired direction. Having an integral view of the dimensions' interdependencies provides a better understanding of the higher-order changes an intervention may cause. This enables policymakers and regulators to identifying where in the system to intervene to achieve the desired effect with the least amount of resources and with as few undesirable side-effects as possible.

Keywords: Security of supply, electricity, energy security, cross-impact factor analysis

1. INTRODUCTION

Over the last decade, security of supply has become increasingly important for the electricity sector in many countries. There have been a number of reasons for this interest, including concerns about limited investment and premature close-downs of thermal capacity (Gosden, 2016). This, combined with a lack of investments in other areas of the electricity system (in particular transmission), integration of renewables (PV and wind), and a general uncertainty concerning the regulatory institutions, has led to a renewed focus on security of supply (OFGEM, 2015). However, there is no clear consensus on how best to evaluate the security of supply in electricity systems.

Over the last four decades, a number of frameworks for evaluating energy security have been developed. However, most of these frameworks focus on oil and gas, and contain only limited detail about the electricity sector, see for instance (Jewell et al., 2014). More recently, frameworks for assessing specifically the electricity sector have been proposed. These take a macro-level view, tending to consider relatively few factors (APEREC, 2007). The objective of many of these frameworks is to compare the level of security of supply across countries by aggregating the different aspects into a single value (Sovacool et al., 2011). While this approach provides a ranking among countries, it is not particularly useful for regulators and policymakers to identify where in the electricity system future problems are to be expected, nor to identify some form of “best practice”, as energy markets differ considerably across countries. A framework that can help to assess and pinpoint future issues in security of supply needs to provide a more detailed picture of the situation, taking into account the intertemporal aspects, to enable decision makers to act before a problem occurs: delays between decisions, actions and their consequences influence how a system evolves. The focus should be on evaluating a single jurisdiction over time, not on comparisons.

Larsen et al. (2016) propose a framework, which focuses on 12 dimensions, to evaluate security of electricity supply in a jurisdiction. This framework differs from previous work through its emphasis on

the temporal evolution of each dimension. The relative importance of the different dimensions depends on the characteristics of the jurisdiction being studied; no attempt is made to combine them into a single measure. In this paper, we extend their analysis by investigating the interdependencies between the 12 dimensions of their framework. This is important as electricity systems can be seen as a complex system where any intervention is bound to have second and higher-order implications on the performance of system as a whole. While several authors have pointed out the existence of interdependencies among dimensions, they do not represent these explicitly, nor do they assess their importance. One of the exceptions is Ren and Sovacool (2014), who do consider interdependencies in an energy system, but focus on the metrics rather than on the dimensions. Based on the direct and indirect influences of each metric, they categorise factors linked to each metric as either a cause or an effect. However, this approach relies excessively on qualitative metrics and does not provide a holistic view of the interactions among their dimensions. Our aim is not only to identify the interdependencies and assess the strength and importance of each, but also to provide a general framework to interpret such interdependencies.

Why is understanding these interdependencies important? Firstly, as mentioned above, one should realise that evaluating security of electricity supply (SoES) implies dealing with a system where intervening in one part might not only affect –positively or negatively– this part, but also other parts of the system, enhancing or resisting the intended change (Senge, 1990). A system's view of the problem is thus necessary to understand the system's behaviour and prevent potential (undesirable) side-effects of any action. Secondly, due to limited resources authorities must often rely on incremental measures to improve SoES. These can start chain reactions well before the measures are fully implemented, causing unintended knock-on effects. While these could be positive, they more often than not are undesirable, reducing the impact of the initial intervention on the targeted dimension, and causing one or more other dimensions to deteriorate.

An example of this can be found in Kruyt et al. (2009), who argue that while increasing cross-border links improves availability, it makes a country more vulnerable to the geopolitical situation. Likewise, there is a tension between environmental targets (environmental sustainability) and low energy costs (economic sustainability), since responding to environmental challenges typically leads to higher generation costs. This occurred for instance in Germany, where the increasing penetration of variable renewable energy sources (VRES) aimed at achieving the country's environmental targets has led to higher electricity tariffs, as the cost of subsidies (charged to consumers) exceeds the decrease in wholesale prices (BMW, 2016). This has in turn led to concerns about the economic sustainability of Germany's industrial production (Fraunhofer ISI, 2015). Increased VRES penetration is also forcing many countries to implement capacity mechanisms in order to ensure the financial viability of thermal plants; examples include the UK, Germany and France (Linklaters, 2014). Hence, a policy aimed at decreasing the environmental impact of electricity systems has resulted in higher costs (lower affordability) and higher incentives for thermal units (inefficient regulatory framework). Other examples involve the reform process, with one of the best known cases being the 2000-2001 crisis in California: market failures and the uncertainty caused by the transition have led to generation capacity shortages (lower capacity adequacy), high wholesale prices (sustainability of the distribution companies) and even blackouts (reliability) (McNamara, 2002).

These are just some examples among many that illustrate the complexity of decision-making and its system-wide consequences. There is thus a need to understand what the consequences of an intervention are before any change is implemented (Morecroft, 2015). This will enable decision-makers to improve planning and allocate resources more efficiently.

This paper is organised as follows. We start in section two with a short review of the 12 dimensions proposed in Larsen et al. (2016). Section 3 introduces the method we propose for analysing the inter-dependency among these dimensions using a small-scale example. This is followed by a detailed

discussion using a full-scale illustration. We conclude with a discussion of the strengths and limitations of the proposed framework.

2. SUMMARY OF THE FRAMEWORK FOR EVALUATION OF SOSE

EURELECTRIC defines security of electricity supply as “the ability of the electrical power system to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner, relating to the existing standards and contractual agreements at the points of delivery” (Eurelectric, 2004). Building on this view, Larsen et al. (2016) developed a comprehensive framework, to assess security of supply. They argue that the evolution of these dimensions should be assessed over time and that no single indicator can characterise the level of security of supply in an electricity system. They also propose metrics to track the evolution of these different dimensions.

Their framework is composed of 12 main dimensions, several of which have sub-dimensions; an overview is given in Table 1. It takes into account physical, political and behavioural aspects of electricity supply. Examples of physical dimensions include generation adequacy and grid condition. Regulatory efficiency and geopolitical factors are examples of political factors. The behavioural aspect relates mainly to socio-cultural factors.

Table 1. The 12 dimension of the framework for evaluating security of supply in electricity proposed by Larsen et al. (2016).

Dimensions	Description	Metric
1. Generation adequacy	Extend to which domestic generation capacity can meet domestic demand in the short and medium term	Lowest hourly de-rated capacity margin (OFGEM, 2013; WECC, 2009) Energy margin (Osorio and van Ackere, 2016)
2. Resilience	Ability to recover from disruptive events, whether caused by environmental, technical or human factors	Herfindahl - Hirschman Index (HHI) of concentration of generation technologies (Kruyt et al., 2009)
3. Reliability	Ability to provide uninterrupted supply	System Average Interruption Duration Index (SAIDI: ratio between annual customer-minutes without service and number of customers in the system)
4. Supply flexibility	Ability to deal with unpredictable variations in supply (e.g. due to intermittent production sources)	Ratio between available flexible load that could be supplied in an hour (hydro and thermal) and maximum load supplied by VRES over the last year
5. Grid		
- Capacity adequacy	Congestion of power lines, leading to inefficient allocation of resources, and increasing the risk of blackout due to the difficulty of reallocating flows in the event of outages or grid failures	Index of locational marginal prices (measure of dispersion of zonal prices) or Congestion charge per MWh depending on the congestion management measure (Alomoush, 2005)
- Ageing	Grid disruptions due to more frequent technical failures, higher maintenance needs and increased fragility to adverse weather conditions	Average age of the grid
6. Demand management		
- Conservation	Temporary reduction in demand that can be achieved when supply/demand balance is tight.	Volume of interruptible contracts (to be subtracted from demand when computing de-rated margin)

Dimensions	Description	Metric
- Efficiency	The ratio of energy service to the energy required to deliver that service	Electricity intensity: ratio between electricity consumption and GDP (Gouveia et al., 2014)
- Demand flexibility	Potential for Load-Shaping (improve the match between the demand and the generation profile)	Flexible demand relative to total demand
7. Regulation efficiency		
- Market performance	Prevention of market power	HHI of concentration of generating companies
- Incentives for conventional generators	Need to provide additional incentives for conventional generators to ensure their availability to contribute to generation adequacy	Subsidy to conventional generators per MWh
8. Sustainability		
- Demand side – Affordability	Households' ability to pay	Electricity costs as share of median wage
- Supply side – Profitability	Viability of conventional and peak-load generators	Load factor of conventional and peak generators
- Environmental	Environmental impact of generation	Carbon emissions per MWh
- Fossil fuel dependency	The extent to which electricity supply depends on exhaustible natural resources that will eventually need to be replaced	Ratio between current fossil-based generation and the expansion potential of renewable energies generation
9. Geopolitics		
- Import dependency	Dependency on imports, both directly (electricity) and indirectly (fuel to generate electricity)	Fraction of domestic consumption covered by electricity imports and electricity generated by imported fuels
- Vulnerability	Dependency on a limited number of sources for imports of electricity and fuel to generate electricity	HHI of geographical concentration of imports HHI of concentration of imports by type (electricity and fuel)

Dimensions	Description	Metric
10. Socio-cultural factors	Extend to which public opinion can impact the planning and construction decisions, slowing down the process	Ratio of effective planning and construction time over minimum required time
11. Terrorism	Risk of disruption due to malevolent actions affecting generation or transport facilities	Business cost of terrorism from the World Economic Forum Report
12 Access	Extend to which households are connected to the grid	Access rate to the grid

3. METHODOLOGY

In our discussion of the interdependence of the dimensions of security of supply we use Cross Impact Analysis (CIA), a method developed to understand the structure underlying a set of variables. This method was initially introduced by T.K. Gordon and O. Helmer at the Rand Corporation for the Kaiser Aluminium Company in 1966 (Gordon, 1994). It was designed to eliminate some disadvantages of the Delphi method, which ignores potential interdependencies between future events (Daim et al., 2013). The method, which explicitly establishes the relationships among relevant factors, initially focused on technological issues. However, it has been shown to be equally useful in other areas. For instance, it has been applied to analyse socio-economic problems, such as the evaluation of global-warming mitigation options (Hayashi et al., 2006), spread of HIV/AIDS (Pedamallu et al., 2012) and barriers to investment in solar energy (Medina et al., 2015). CIA identifies directional causal relationships between the relevant variables and helps to assess the strengths of these relationships (Twiss, 1992). One of its main advantages is its high flexibility; it is particularly well suited for discussions among stakeholders due to its transparent analytical logic (Weimer-Jehle, 2006).

CIA is based on a dyadic comparison and consists of three steps. The first step is to establish for each factor how strong an effect it has, if any, on each of the other factors. This is done by using a simple square matrix with one line and one column for each factor. The strength of the impact is expressed using a simple numerical scale, usually ranging from 0 (no influence) to a maximum of 2 or 3 (maximum impact); integer values between 0 and the maximum are used to indicate a moderate impact. Starting from this matrix, we present two complementary ways of visualising the interactions between the dimensions. The first approach focuses on the role of each dimension in the system by categorizing them as a driver, connector, outcome or independent variable. The second one aims to provide a global view of the main influences, including the identification of possible feedbacks. Here the focus is generally restricted to the stronger links, i.e., values of 2 on a scale from 0 to 2, or 3 on a scale from 0

to 3.

To illustrate this method we present a small-scale example, including only four dimensions (generation adequacy, access, socio-cultural factors and reliability), using a scale from 0 to 2. Table 2 presents a cross-impact matrix for these dimensions. The first line indicates that generation adequacy influences neither socio-cultural factors nor access, but has a strong impact on reliability. Indeed, capacity shortages lead to blackouts. Moving down, we see that socio-cultural factors affect generation adequacy: people's attitude towards certain technologies can threaten the installation of new plants (e.g., NIMBY phenomena towards wind energy (Cicia et al., 2012; Whitcomb and Williams, 2008)), or force dismantling of existing plants (e.g., nuclear power in Italy, Sweden, Germany and Switzerland (Bradford, 2012)). The level of access to electricity affects generation adequacy, as more demand leads to tighter capacity margins: while one expects grid expansion, and the resulting incorporation of new demand, to take place progressively to limit the impact on system reliability, delays in bringing new plants online may cause problems. Finally, reliability influences socio-cultural factors as experiencing blackouts is bound to reduce people's opposition to the construction of generation plants or power lines, or increase their tolerance towards certain generation technologies. The sums of the rows and columns indicate respectively to what extent a dimension influences (row totals) and is influenced by (column totals) the other dimensions. Each dimension is thus characterised by two values (how much does it influence the other dimensions, to what extent is it influenced by the other dimensions), which are used to create a scatter plot (Figure 1). Next, we calculate the average of the row and column totals to subdivide the plot into four quadrants.

Table 2. A simplified example of a cross impact matrix.

	Generation adequacy	Socio-cultural factors	Access	Reliability	Influence on
Generation adequacy		0	0	2	2
Socio-cultural factors	2		0	0	2
Access	1	0		0	1
Reliability	0	1	0		1
Influence by	3	1	0	2	

The dimensions in the upper left quadrant, e.g., socio-cultural factors, are the drivers of the system: they significantly affect, but are barely influenced by, the other dimensions. The dimensions in the upper right quadrant, e.g., generation adequacy, are to be interpreted as connecting variables: they influence, and are influenced by, the other dimensions. They are the central elements of the system, reinforcing or offsetting the effect of other dimensions. Changes in the dimensions of the upper two quadrants are likely to significantly impact other dimensions, thus affecting system-wide performance, not necessarily in the desired direction.

Dimensions in the lower right quadrant, e.g., reliability, are the outcomes: they are influenced by, but exert little influence on, other dimensions. For instance, reliability cannot be improved directly. Consequently, rather than attempting to influence these dimensions, policies should focus on improving the dimensions that influence them. In our example, providing the adequate conditions for new investments in generation capacity allows increasing the system's reliability. Finally, dimensions in the lower left quadrant, e.g., access, are fairly independent: they neither influence, nor are influenced by, other dimensions. Policies targeting the dimensions in the lower two quadrants are thus less likely to have system wide implications.

Figure 1. A simplified scatter diagram based on the cross impact matrix in Table 2.

This categorization, based on the aggregate influence of each element, is useful to identify on which dimensions interventions should focus. However, their centrality in the system remains unknown. Figure 2 provides a visual representation of the causal relationships identified in Table 2. This enables us to gain a better understanding of the causal chains: how does a change in one dimension impact the other dimensions, and thus the entire system. Given a scale from 0 to 2, one can choose to include only the stronger links (values of 2, bold arrows in Figure 2) or all links (i.e., also including the values of 1, dashed arrows in Figure 2). Focusing first on the stronger links, this diagram illustrates that *Socio-cultural factors* influence *Generation adequacy*. For instance, resistance to certain technologies (e.g., the repeated referendums against nuclear plants in Switzerland (Federal Administration, 2016)), or a more general opposition to new generation projects (e.g., a contributing factor to the Californian crisis (Sweeney, 2002)) can result in a shortage of generation capacity. Favouring one particular technology

(e.g. hydro in Colombia (Larsen et al., 2004)) can result in an inadequate generation mix. The resulting inadequate generation capacity will in turn decrease the *Reliability* of the electricity system.

However, this is not the end of the story. The reduced reliability increases the frequency of blackouts, which over time is likely to mitigate opposition to new generation capacity, i.e., there is a (weaker) link from *Reliability* back to *Socio-cultural factors*. Thus, while the classification driver / connector / outcome is useful to get an overall picture, one should be aware of the presence of such non-linearities: the system includes feedback loops. Finally, also note that *Access* lies on the boundary of this small example: it is not subjected to any influences and only has a minor influence on the other elements.

Figure 2. A simplified influence diagram based on the cross impact matrix in Table 2.

4. RESULTS

We now analyse the full set of 18 dimensions and sub-dimensions of Larsen et al. (2016)'s conceptual model of security of electricity supply presented in Table 1. Table 3 shows the cross-impact matrix, using a scale from 0 to 2. We merge *demand efficiency* and *demand conservation* into a single sub-dimensions, *demand efficiency and conservation*, as they play very similar roles in the system. For similar reasons we have merged *market performance* and *incentives for conventional generators* into *regulatory performance*.

When applying this framework for a specific jurisdiction, is it essential to involve the main shareholders (political authorities, regulator, producers, distributors and consumers) to insure that the matrix provides a realistic, unbiased view of the situation in that jurisdiction. The values given in the matrix are an illustrative example of an electricity system; they are country and system specific. For instance, the impact of socio-cultural factors on grid capacity would be comparatively stronger in countries with a direct democracy (e.g., Switzerland), while fossil fuel dependency would be irrelevant in regions which are close to 100% hydro (e.g., Norway). Similarly, considering the *Geopolitics - import vulnerability* dimension, while the Ukraine is highly dependent on respectively gas imports from Russia (Kovacevic, 2009) and, the USA's reliance on imported fuels to generate electricity is significantly less (BP, 2016a).

Table 3. Illustrative full-scale cross-impact matrix.

	Generation adequacy	Resilience	Reliability	Supply flexibility	Grid capacity adequacy	Grid ageing	Demand efficiency and conservation	Demand flexibility	Regulatory performance	Economic sustainability - supplier profitability	Economic sustainability - affordability	Environmental sustainability	Fossil fuel dependency	Geopolitics – Import dependency	Geopolitics - Vulnerability	Socio-cultural factors	Terrorism	Access	
Generation adequacy		2	2	0	0	0	0	0	1	2	2	0	0	2	0	0	0	0	11
Resilience	0		2	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	4
Reliability	0	0		0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	3
Supply flexibility	0	1	2		0	0	0	0	0	1	0	0	0	0	0	0	0	0	4
Grid capacity adequacy	0	2	2	0		1	0	0	1	0	2	1	0	1	1	0	0	0	11
Grid ageing	0	1	1	0	1		0	0	0	0	1	0	0	0	0	0	0	0	4
Demand efficiency and conservation	2	1	0	0	2	0		0	0	1	1	2	1	1	0	0	0	0	11
Demand flexibility	1	1	1	0	2	0	0		1	1	1	2	0	0	0	0	0	0	10
Regulatory performance	1	1	1	1	1	0	0	0		2	2	1	1	1	0	0	0	0	12
Economic sustainability - supplier profitability	2	1	0	0	0	0	0	0	2		1	0	0	0	0	0	0	0	6
Economic sustainability - affordability	0	0	0	0	0	0	1	1	0	0		0	0	0	0	1	0	0	3
Environmental sustainability	0	0	0	1	0	0	0	0	1	1	1		1	1	0	2	0	0	8
Fossil fuel dependency	0	2	1	1	0	0	0	0	0	0	0	2		1	1	0	0	0	8
Geopolitics - Import dependency	1	1	1	0	0	0	0	0	1	2	0	0	0		2	0	0	0	8
Geopolitics - Vulnerability	0	0	1	0	0	0	0	0	0	0	1	0	0	0		0	0	0	2
Socio-cultural factors	2	1	0	0	2	0	1	2	1	0	1	2	2	1	0		0	1	16
Terrorism	1	0	2	0	2	0	0	0	0	1	1	1	0	0	0	1		0	9
Access	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0		4
	12	14	16	3	11	1	2	3	11	11	14	11	5	9	4	6	0	1	

The second step in the analysis is to create a scatter plot to visualise the aggregate role of each variable. This plot is shown in Figure 3.

Figure 3. Scatter plot.

To understand the role of each dimension in the system, it is useful to discuss the four quadrants of the scatter plot in turn. The upper left quadrant contains dimensions that significantly influence other dimensions but are themselves fairly independent of the other dimensions. In other words, these are the dimensions policy makers should be most careful with, as they have significant spill-over effects on other parts of the system. First, consider the dimensions that the regulator and policy makers have direct influence on: *demand efficiency and conservation*, *demand flexibility* and *fossil-fuel dependency*. Efforts to influence any one of these will have little or no direct effects. Rather, the consequences will materialise in the medium- to long-term. Consequently, action needs to be initiated well in advance of

the occurrence of a potential crisis, requiring authorities to take a long-term perspective. Actions targeting these dimensions are potentially the more effective ones a regulator can take, as the consequences will gradually ripple through the system, while their impact will not be mitigated by spill-over effects. However, these longer-term effects can be positive or negative. For instance, a *demand efficiency and conservation* measures will improve *generation adequacy*, *grid capacity adequacy* and *environmental sustainability*, as well as lower the need for imports, all of which are positive. However, the economic sustainability of generators (*supplier profitability*) could be negatively affected.

Next, consider *socio-cultural factors* which are an important driver of the system. While regulators or policy makers can try to influence the public opinion, they cannot impose their point of view. Grassroots organizations can exert a significant influence on the electricity system by mobilising the public. Examples include the lengthy delays in building the new north-south transmission lines in Germany (Steinbach, 2013) and anti-nuclear movements who have successfully prevented the construction of new nuclear plants and speeded up the decommissioning of existing plants (Cicia et al., 2012; Hill, 1983; Kato et al., 2013). Finally, *terrorism* can have a significant influence on the security of supply as physical destruction or cyber-attacks disrupt transmission and generation (NRC, 2012). Countries with a significant exposure to such threats should plan remedial action. For instance, the Colombian system operator has developed considerable capabilities to quickly restore transmission capacity after violent disruptions (Carvajal et al., 2013).

The upper right quadrant contains the dimensions that are both influenced by and have an influence on other dimensions. The regulator has a high degree of control over *grid capacity adequacy* and *generation adequacy*. The impact can be direct, via incentives to expand or dismantle assets (*regulatory performance*), or indirectly by encouraging *demand efficiency and conservation* measures. Policy makers also have a certain degree of control over the *environmental sustainability*, for instance

by setting a target for the share of renewables or emission limits for power plants. However, other factors, such as *fossil-fuel dependency*, limit their room for manoeuvre. *Environmental sustainability* in turn influences other dimensions, such as *supplier profitability* and *affordability* (customer tariffs).

The elements in the lower right quadrant are influenced by other dimensions, but have limited knock-on effects. We can think of these as the outcome of choices made for the other dimensions, i.e., a type of dependent variables. Consider for instance *reliability*, which is determined among others by the choices made w.r.t. *generation* and *grid capacity adequacy* and *supply flexibility*, but has very limited influence on any other dimension. A regulator interested in modifying these outcome dimensions should consider intervening upstream, influencing dimensions in the upper left and (to a lesser extend) upper right quadrants. For instance, demand management measures can be an alternative to investments in generation capacity and grid expansion.

Finally, in the lower left quadrant we find dimensions that have few connections to the other dimensions in the electricity system. These dimensions (e.g., *grid ageing*) are neither directly influenced by other dimensions, nor do they exert a strong impact on them; the relationships are limited to second order effects (e.g., effect of the age of the grid on reliability).

The influence diagram capturing the strongest links of Table 3 (values of 2) is shown in Figure 4. The middle panel includes the more technical aspects, i.e., those related to the electricity supply and the transportation. *Grid capacity adequacy* is a key connector. Demand drives the need for grid capacity, while *socio-cultural factors* can be a major barrier to increasing this capacity. *Grid capacity adequacy* in turn affects three of our four outcome dimensions: *affordability*, *reliability* and *resilience*. *Resilience* affects *reliability*, as do *supply flexibility*, *terrorism* and *generation adequacy*, while it is itself dependent on *generation adequacy* and *fossil fuel dependency*.

Figure 4. Influence diagram

As in any market, electricity wholesale prices typically reflect scarcity of resources (Stoft, 2002). Low *generation adequacy* drives prices up, which threatens *affordability*, particularly for unregulated consumers and industrial consumers, and improves *supplier profitability*. This encourages generators to invest, increasing generation adequacy. The inherent delays of this process are the cause of the over- and under-investment cycles that characterise many electricity markets (Arango and Larsen, 2011; Bunn and Larsen, 1992). Insufficient *generation adequacy* will worsen *import dependency* within the limits of the available cross-border transmission capacity, negatively affecting the *profitability* of the national suppliers; not only will they be less likely to invest, they may even be induced to retire

existing plants. The role of neighbouring countries will become more central in increasingly interconnected electricity markets. High *import dependency* increases the jurisdictions' *vulnerability* as they do not have control over the jurisdictions from which they import.

The right panel focuses on the customer-side and the environment. *Demand flexibility* and *demand efficiency and conservation* influence *environmental sustainability* through their impact on peak demand and total demand. *Socio-cultural factors* and *environmental sustainability* interact, as the former affect what is achievable in terms of environmental targets, while a highly polluted environment increases people's awareness of the importance of *environmental sustainability*.

The left panel focuses on the government and external factors. External factors such as *terrorism* influence technical aspects tightly related to the physical availability of electricity, i.e., *grid capacity adequacy* and *reliability*. Dimensions on which the government exercises an important control are *fossil fuel dependency* and *regulatory performance*. The former not only threatens the *environmental sustainability*, but also renders the jurisdiction's generation vulnerable to international market shocks (*resilience*). The latter impacts the economics of the system. When low *supplier profitability* endangers *generation adequacy*, the regulator may choose to intervene to encourage investments (*regulatory performance*). Such intervention can take the form of direct subsidies, as is often the case for renewables (Fronzel et al., 2010), or of various forms of capacity mechanisms (Finon and Pignon, 2008). The cost of such interventions is usually charged to consumers through taxes and levies, which affects *affordability*. Regulatory decisions (e.g. price caps) often have opposite effects on *supplier profitability* and *affordability*.

To illustrate how the scatter plot and influence diagram can guide policymaking, we next discuss three essential SoES issues relating respectively to *socio-cultural factors*, *economic sustainability* and *environmental sustainability*.

Why should policy makers care about socio-cultural factors?

From Figure 3 we see that *socio-cultural factors* are the strongest driving force of the system. Such factors include, among others, consumption habits, preferences for certain technologies and the NIMBY phenomenon. Consumption habits determine the consumption patterns, which affect *demand flexibility*. A willingness to shift load away from periods with high fossil-based generation, to periods with a high level of renewable generation (sun at noon or windy periods), reduces the use of polluting generation sources (Lund et al., 2015).

People's preference for (or rejection of) certain technologies affects several dimensions. For instance, Shih et al. (2016) documents concerns about nuclear power in Taiwan, while a recent survey in Italy revealed that most people supported solar energy (Cicia et al., 2012). Rejection of thermal generation in favour of PV decreases fossil fuel dependency and improves *environmental sustainability*.

But *socio-cultural factors* can have a negative impact on the environment through the NIMBY phenomenon: people who do support renewable energies in principle still oppose wind and hydropower projects in their area. For instance, despite a supporting governmental policy, there was no expansion of wind capacity in Switzerland in 2014 due to opposition from people living near the proposed locations opposed the plans, arguing the impact of wind turbines on the landscape (Le Temps, 2014). Similarly, while opinion polls in the USA indicate a strong support for renewable energies, specific projects often face strong opposition from the local population (Petrova, 2016). An extreme case occurred in Falmouth, Massachusetts: a wind turbine was shut down after several years of operation, following a lawsuit arguing noise disturbances (CapeCodTimes, 2016).

From this discussion we can conclude that if policy makers or regulators decide to decrease *fossil-fuel dependency* by increasing the share of renewables, they need to communicate this aim clearly and insure that the population adheres to this objective; such a change cannot be achieved without a broad support. There is evidence that trust in the local government (Sun et al., 2016a, 2016b) and

community-level engagement in the decision-process (Petrova, 2016) are key factors to alleviate the NIMBY factor. This also holds for grid infrastructure: an effective communication strategy focusing on why the new transmission lines are required is essential. Failing to gain sufficient public support can significantly delay, and in some cases stop projects. One illustration of this is the north-south transmission line in Germany, which should enable transporting the wind energy produced near the northern shore to the industrial users in the south (Karnitschnig, 2014).

The problem of capacity cycles in a decentralised system

Cycles in generation capacity have been observed, among others, in the England and Wales market (Arango and Larsen, 2011). These are a consequence of the long delays in the feedback loop linking supplier profitability and capacity investments. *Supplier profitability* depends on prices and production volumes. Prices typically reflect capacity margins (*generation adequacy*). In periods of excess capacity, low prices and load factors drive profitability down, leading to an investment freeze. Only when the capacity margin decreases do prices and load factors increase, leading to investment decisions. However, the delays in bringing new capacity online result in periods of very tight capacity margins, and high prices. This, together with the lack of coordination of investments in generation, which is typical of competitive markets, exacerbates these cycles (Ford, 1999).

This cyclicalality leads to uncertainty, inducing regulators to attempt to dampen the cycles by introducing capacity mechanisms (*regulatory performance*). Examples include Sweden, Germany and Belgium (Linklaters, 2014). This support provides a more stable profit for generators, which helps ensure timely investment decisions, thus stabilizing the system. Dampening the capacity cycles is also important to be able to provide stable electricity prices to industrial, commercial and residential users. While this stability may come at the cost of higher average electricity prices (Arango and Larsen, 2011),

the country's economy benefits from the positive impact on investments (de Vries and Heijnen, 2008; Hach and Spinler, 2014) and consumers exposed to market prices face less risk (de Vries, 2007).

The existence of cross-border trade renders the problem more complex. Many countries import electricity from neighbouring countries, either because imports are cheaper than local sources or because capacity is inadequate to meet local demand. For instance, Italy has been a net importer from Switzerland since 2002 (SFOE, 2016), despite having idle capacity (e.g., in 2015, 43% (213 TWh) of the total electricity offered by Italian generators were not dispatched in 2015 (GME, 2016)), while Switzerland is a net importer in winter due to the lower availability of hydropower (SFOE, 2015). Imports lead to lower prices and displace local generation, reducing the profitability of the local producers. Thus, capacity mechanisms and the resulting investment decisions in one country affect generator profitability in other countries, complicating the task of the regulator. For instance, the significant share of renewables in Germany, combined with the high degree of interconnectedness of the European market have caused prices to drop across some European markets. This has put a significant financial strain on conventional plants in several countries. Examples include gas plants being decommissioned in Belgium (La Libre, 2014), Germany, UK and France (Bloomberg, 2013) and Swiss hydropower plants issuing profitability warnings (Wuthrich, 2016).

An additional worry is the reliability of imports should a problem arise in the exporting country. This has led countries to use capacity mechanisms to keep conventional power plants on-line to limit import dependency, despite very low load factors (Oseni and Pollitt, 2016). For instance, due to the lack of trust in Russian imports, the Finish system operator has implemented a strategic reserve (about 10% of local capacity) (Ochoa and Gore, 2015). Also, a country might be keen to limit cross-border capacity expansions if its neighbour has less-expensive electricity: the price-lowering effect of increased cheap imports would not only reduce the TSO's congestion rents, but also the profitability of local generators (Jakottet, 2012).

The conclusion is that while capacity mechanisms currently are the most commonly used regulatory approach to stabilise electricity markets there is as yet no evidence of one “best policy” for this complex task; both the characteristics of the market under consideration, and that of its neighbours need to be taken into account. Any intervention is likely to negatively affect electricity tariffs as the cost of such support mechanisms must somehow be charged to the consumers.

Limiting the negative side-effects of improved environmental sustainability

During the last two decades, environmental sustainability has received increasing attention and become a central element of energy policy. Although the COP21 agreement is far from ideal, it is a major achievement: it is the first time that all the major parties, including the EU, United States and China, have been able to reach a consensus. However, aspirations and achievements vary considerable across countries: while the EU has committed to specific goals in terms of absolute greenhouse gas (GHG) emission reductions (at least 40% by 2030 and 80-95% by 2050 from 1990 levels), China’s pledges are vague (a reduction of 60-65% in CO₂ intensity by 2030 from 2005 levels, with emissions peaking ‘around’ 2030) (European Parliament, 2015). While there are several aspects to environmental sustainability, emissions are one of the major concerns. This explains why the discussion of fossil-fuel dependency has often taken centre stage in negotiations and energy planning, as a shift away from these will reduced emissions and improve the environment.

Fossil-fuel dependency objectives take the form of either a target share of renewable energy or a reduction in the absolute level of greenhouse gas emissions. More developed countries have the economic resources to move to renewable generation, thus significantly reducing emissions. This is not the case of countries at an early stage of electrification and industrialization: their energy consumption will increase over the foreseeable future, resulting in increased emissions despite an increasing share of renewables. For instance, renewable energies share in primary energy consumption and the overall

non-fossil fuels share have increased in BRICS countries between 2010 and 2015, but due to the consumption increase (from 3,974 to 4,751 million tonnes oil equivalent), CO₂ emissions have also increased (from 12,137 to 13,779 million tonnes CO₂) (BP, 2016b). Moreover, GHG emissions (of which CO₂ emissions are the main source) are expected to increase by 2030 in all these countries, threatening the achievement of their individual COP21 pledges (Climate Action Tracker, 2015). Considering world-wide electricity production, the share of fossil-based generation has remained stable at about 65% since 1990; nonetheless fossil-based generation has increased from 7,567 to 15,962 TWh between 1990 and 2015 (BP, 2016a). There also are technological limits to the feasibility of renewable targets as most of these are intermittent: their production patterns do not necessarily match demand patterns, creating difficulties in terms of grid balancing. This leads to higher needs for, among others, flexible generation sources and storage capacity (Lise et al., 2013).

Setting renewable targets will not suffice to reduce emissions; alternative actions are needed. Significant progress could be achieved by decreasing consumption through demand efficiency and conservation, leading to fewer emissions by reducing the need for generation and transmission capacity. Many developed countries are increasingly emphasizing the need to reduce demand, or at least limit its growth (European Commission, 2014). Policies include increased taxation of electricity consumption and free advice on how to save energy. Demand reductions, typically encouraged by policy-makers, can be achieved in a number of ways, ranging from short-term actions such as energy efficient electrical hardware (e.g., fridges and low energy bulbs) to longer term initiatives (e.g., energy efficient buildings). For instance, electricity consumption in 2015 (2,706 TWh) in the EU28 was the lowest since 2003 (European Commission, 2016).

Another measure is load shifting. This, unlike demand efficiency measures, relies highly on people's behaviour. While this does not reduce total demand, it shaves demand peaks and enables an optimal utilization of renewable generation (Lund et al., 2015). We can thus conclude that, despite the higher

cost of renewables, load reduction and load shifting measures enable achieving emission reduction objectives, while limiting the price increases.

5. DISCUSSION AND CONCLUSION

Why do regulators and policymakers need to get a better understanding of electricity systems? Before deregulation, managing a centrally controlled system was a challenging technical (and at times economic) task (Dyner and Larsen, 2001). Taking Europe as an example, 15 years ago no one imagined that security of supply might become an issue in a not so distant future. Since deregulation started about two decades ago, the level of complexity has increased due to market-based prices, absence of centrally controlled and coordinated investments, increased interconnectedness with other countries, and a large penetration of intermittent renewable energy generation. This increasing complexity makes it more and more difficult to achieve an overall understanding of all the relevant aspects. Furthermore, no single authority is in control as most decisions are decentralised. To influence the direction in which the system is moving, regulators and policymakers must rely on indirect means, such as selected incentives, or bans on particular investments or practices. Consequently, they need a sound understanding of the overall system and its interdependencies to make sure the lights stay on.

While Larsen et al. (2016)'s framework provides a comprehensive picture of the different factors affecting security of supply of electricity, our work goes a step further, focusing on the interaction between these factors. We propose a three-stage approach. In a first stage, stakeholders use CIA to identify the essential interrelationships of the electricity system in their jurisdiction. In a second stage, the resulting matrix is visualised using a scatter plot (macro-view) and an influence diagram (micro-view). The former, based on the aggregate impact of each dimension, enables categorizing these according to their role in the system: driver, connector, outcome or independent element. The latter focusses on the strongest relationships between pairs of dimensions. In a third stage, these two visual

aids are used to guide discussion about key questions concerning the system. We briefly summarise these three stages and discuss their complementarity.

The first step, using CIA to create the matrix, helps establishing the underlying structure of the electricity system. This step, which should involve all stakeholders, provides an opportunity to create a shared understanding of the main issues (Lindgren and Bandhold, 2003). The CIA method is particularly useful as an initial step, as it is simple and easy to understand; it provides a platform for a (hopefully constructive) discussion of the different influences. Its micro-level approach, which forces participants to concentrate on one causal effect at a time, limits the scope for political gaming. The resulting matrix thus yields an unbiased, as objective as possible, representation of the interdependencies in the electricity system. It provides a comprehensive overview of how influential the different dimensions are and gives clear indications to policymakers of where future interventions could usefully be focused.

The second step, which consists of drawing the scatter plot and influence diagram based on the CIA matrix, enables the stakeholders to visualise the interdependencies. The scatter plot shows clearly how much influence each dimension has on the overall system, which is important to guide the choice of interventions. If regulators or policy makers attempt to exert a direct influence on dimensions of the lower quadrants, the consequences will be relatively contained, as there will be little spill-over to other parts of the electricity system. However, this also implies that such interventions will not be leveraged, i.e., there will be few, if any, indirect benefits as these dimensions do not influence others. Additionally, interventions targeted at dimensions in the lower right quadrant may have little long-lasting effect, as these dimensions are strongly impacted by events in the other parts of the system. For instance, in the presence of high electricity tariffs caused by inadequate transmission or generating capacity, improving affordability by providing subsidies to low income families is a short-term fix; the problem will persist as long as the root of the problem is not dealt with. The opposite argument holds for dimensions in the

upper quadrants. As these exert the most influence on the system, one should expect spill-over effects, leading to a form of chain reaction. We know from systems thinking that this will include unanticipated higher-order effects, some of which (if not most) may well work against the desired result of the intervention (Senge, 1990).

The second visualization tool, the influence diagram, is complementary to the scatterplot as it allows us to get a better understanding of the higher-order changes an intervention may cause. The diagram enables us to identify the other dimensions it will directly and significantly influence. Getting a better appreciation of the second- and third-order influences offers several advantages. First, by focusing on interventions with positive spill-over effects, we can achieve a higher reward to effort ratio. Also, the influence diagram creates awareness of the possible unanticipated side effects, enabling us to avoid interventions whose negative side-effects on another dimension would partly offset the expected benefits. This increases the likelihood of successfully solving a problem without creating new ones.

These first two steps of the process thus provide us with:

- A clear understanding of which dimensions have the highest potential to successfully change the behaviour of the system (the matrix and scatter plot);
- An awareness of the extent to which a change in one dimension might or might not affect other dimensions (the scatter plot);
- An overview of the main influences among the variables, providing insight into the second and higher order consequences of an intervention (influence diagram);
- An overall appreciation of how (un)stable the system is (influence diagram and scatter plot), which will guide the choice among possible interventions: in an unstable system apparently minor changes can have major consequences.

These elements provide a solid foundation for policymakers and regulators on which to base their decisions, the final step of the analysis. When dealing with complex systems, such as electricity supply,

it is essential that the consequences of any intervention are understood as fully as possible before it is implemented. This enables identifying where in the system one should intervene to achieve the desired effect with the least amount of resources and with as few undesirable side-effects as possible.

Like any method, the approach we suggest has limitations one should keep in mind. Firstly, all jurisdictions are different; it is important that each be assessed on its own terms, taking into account its specificities. A given factor could be essential in one jurisdiction, but only play a minor role in another one. An example of this is import dependency, which is relevant in some jurisdictions (e.g., Chile depends on imported gas (80%), oil (95%) and coal (93%) (EIA, 2016)), while other jurisdiction are (close to being) self-sufficient (e.g., the USA, reduced energy import dependency from 30% in 2005 to 10% in 2014 (The World Bank, 2016)). Secondly, the approach we propose is subjective; the knowledge and expertise of the users is essential to ensure that the values in the matrix reflect the actual situation. The likelihood of this being the case increases when several people, representing the different stakeholders, evaluate the matrix independently before discussing any discrepancies. As for any approach requiring qualitative assessments, one should keep in mind that the quality of the output is no better than that of the inputs. Third, the weights inserted in the matrix are a way to categorise the importance of the links between the different dimensions. While this leads to a categorization of the different dimensions, it does not lead to a ranking of these; it does not reflect the relative importance of the dimensions.

Applying our approach to the framework described in Larsen et al. (2016) provides a tool that is relatively simple to implement, and able to provide policy makers and other stakeholders with the overall view they need to guide their policy and decision making. While we believe that the method discussed here is useful and will help regulators achieve a better understanding of the system, leading to more effective interventions, we do recognise that it is not a silver bullet that will solve all problems. It provides guidelines and suggestions concerning the effectiveness and consequences of an

intervention in the system and should be interpreted as such. The proposed approach is a starting point, aimed at getting an overall picture of the system and the key interactions; it is complementary to traditional methods such as cost-benefit analyses. It should lead to better regulatory and investment decisions by identifying the key leverage points and avoiding unanticipated side-effects.

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