Energy 135 (2017) 598–609

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Interdependencies in security of electricity supply

Sebastian Osorio [a, *], Ann van Ackere [a], Erik R. Larsen [b]

[a] University of Lausanne, Faculty of Business and Economics (HEC Lausanne), Quartier UNIL-Dorigny, Anthropole, 1015 Lausanne, Switzerland
[b] Aarhus University, School of Business and Social Sciences, Bartholins Allé 10, 8000 Aarhus C, Denmark

ARTICLE INFO

Article history:
Received 27 February 2017
Received in revised form
20 May 2017
Accepted 16 June 2017
Available online 20 June 2017

Keywords:
Security of supply
Electricity
Energy security
Cross-impact factor analysis

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. [1] 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 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. Actions targeting the drivers or connectors are potentially the more effective ones a regulator can take, as the consequences will gradually ripple through the system. 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.

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 [2]. 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 [3]. 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 [4]. More recently, frameworks for assessing specifically the electricity sector have been proposed. These take a macro-level view, tending to consider relatively few factors [5]. 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 [6]. 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.

[1] 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

* Corresponding author.
E-mail addresses: sebastian.osorio@unil.ch (S. Osorio), ann.vanAckere@unil.ch (A. van Ackere), erik.larsen@mgmt.au.dk (E.R. Larsen).

http://dx.doi.org/10.1016/j.energy.2017.06.095
0360-5442/

second and higher-order implications on the performance of the 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 [7], 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 [8]. 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 Ref. [9], 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 [10]. This has in turn led to concerns about the economic sustainability of Germany's industrial production [11]. 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 [12]. 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) [13].

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 [14]. This will enable decision-makers to improve planning and allocate resources more efficiently.

Our paper makes the following contributions. First, we study interdependencies only in the electricity sector. Second, we identify the interactions among all the dimensions, not only between specific subgroups. Third, our analysis does not only categorise dimensions as causes or effects, but subdivides these into drivers, connectors, outcomes and independent elements. We thereby provide a detailed overall picture of how the different aspects of SoES are interrelated, allowing for a better understanding of the potential system-wide effects of intervening on one dimension.

This paper is organised as follows. We start in section two with a short review of the 12 dimensions proposed in Ref. [1]. Section 3 introduces the method we propose for analysing the interdependency 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 SoES

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” [15]. Building on this view, [1] 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.

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 [16]. It was designed to eliminate some disadvantages of the Delphi method, which ignores potential interdependencies between future events [17]. 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 [18], spread of HIV/AIDS [19] and barriers to investment in solar energy [20]. CIA identifies directional causal relationships between the relevant variables and helps to assess the strengths of these relationships [21]. One of its main advantages is its high flexibility; it is particularly well suited for discussions among stakeholders due to its transparent analytical logic [22]. Other approaches, such as fuzzy-based methods, aim to identify the causes and consequences among a set of variables. Our purpose is to develop a more comprehensive understanding among all the dimensions, which CIA enables us to do. In particular, it allows us to generate a wider classification (driver, connector, outcome or independent variable) and to identify the feedback loops in the system.

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