

## Durham Research Online

---

### Deposited in DRO:

12 June 2014

### Version of attached file:

Accepted Version

### Peer-review status of attached file:

Peer-reviewed

### Citation for published item:

Jamasb, T. and Nepal, R. (2013) 'Security of European electricity systems : conceptualizing the assessment criteria and core indicators.', *International journal of critical infrastructure protection.*, 6 (3-4). pp. 182-196.

### Further information on publisher's website:

<http://dx.doi.org/10.1016/j.ijcip.2013.07.001>

### Publisher's copyright statement:

NOTICE: this is the author's version of a work that was accepted for publication in *International Journal of Critical Infrastructure Protection*. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in *International Journal of Critical Infrastructure Protection*, 6, 3-4, 2013, 10.1016/j.ijcip.2013.07.001.

### Additional information:

## Use policy

---

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a [link](#) is made to the metadata record in DRO
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full DRO policy](#) for further details.

# **Security of the European Electricity Systems: Conceptualizing the Assessment Criteria and Core Indicators**

***Tooraj Jamasb\****

**Department of Economics, Heriot-Watt University**

**Rabindra Nepal\*\***

**Department of Economics, Heriot-Watt University**

The electricity systems have a central role to play in the transition towards a low carbon economy and integration of renewable energy sources in the European Union. However, the European electricity networks face a diverse set of existing and new risks that can hamper the energy security of the member countries. This paper aims to qualitatively and quantitatively assess these risks given the changing operating framework of the industry characterised by market liberalization and network interconnectedness in the EU. Within this context, we primarily focus on the risks from exceptional events and threats to the European electricity systems. A simple ex-ante risk assessment matrix is proposed to gauge the network risks and take prevention measures against them. Such assessment can be a useful approach for policymakers and practitioners amidst the existing ex-post reliability and quality of supply performance standards and indicators. Our analysis suggests that economic risks pose the most serious and challenging to the evolving European electricity system.

*Keywords: networks, risks, energy security, regulation*

*JEL Classifications: L94; L50; 030*

\* Heriot-Watt University, Department of Economics, Mary Burton Building, EH14 4AS, Edinburgh, UK, Phone: +44-(0)131 458 3844, Email: [t.jamasb@hw.ac.uk](mailto:t.jamasb@hw.ac.uk).

\*\*Corresponding author. Heriot-Watt University, Department of Economics, Mary Burton Building, EH144AS, Edinburgh, UK, Phone: +44-(0)131 4581 3622, Email: [rn71@hw.ac.uk](mailto:rn71@hw.ac.uk).

Acknowledgement: The authors acknowledge the financial support of the FP7- security project cofounded by the European Commission. The views expressed herein are those of the authors and can therefore in no way be taken to reflect the official position of the European Commission. We also acknowledge the comments from two anonymous reviewers in improving the paper.

## 1. Introduction

Electricity plays a vital role in the development of all economies because of its dual role in the economy. It is an indispensable intermediate input factor in production and a necessary final consumption good. Hence, the availability of electricity supply at an uninterrupted manner matters and remains a major energy policy goal of all economies. The economic, social, and political costs of electricity supply disruptions or fluctuations can be entrenched with adverse macroeconomic consequences. The adverse impacts arising from electricity supply fluctuations can only be mitigated by ensuring a secure supply across the potentially competitive segments (generation, retail) and the regulated natural monopoly segment (transmission and distribution networks) in a reliable and affordable manner.

Past debates on security of supply (or energy security hereafter) have heavily focussed on the availability of energy sources (Winzer, 2012; Jamasb and Pollitt, 2008). This implies that security of supply has traditionally come to be defined in terms of fuel availability or network reliability. However, there are also emerging concerns with regards to the security of the electrical systems (physical delivery of energy sources) and the integrity of its operation (robustness, reliability and resilience of networks) in the wake of several natural, accidental and human conceived external threats and events (Jamasb and Pollitt, 2008). These external events can be natural (such as natural calamities and severe weather conditions), accidental (such as explosions and nuclear accidents) or human-engineered malicious threats (such as terrorist attacks, sabotage and vandalism and coordinated cyber-attacks,).

These natural, accidental and malicious threats can be termed as 'low-frequency, high-impact' (LFHI) events. The LFHI events are characterised as having low probability of occurrence but with the potential to cause significant and long-term catastrophic damage to the bulk power system and the economy of many countries (NERC, 2010)<sup>1</sup>. As such, the risks from exceptional events can transcend other types of risks facing the electric sector due their magnitude of impact. For example, the vulnerability of electricity networks from LFHI threats was vividly exposed with widespread power outages or failures during the period 2002/03-2004/05

---

<sup>1</sup> This is to say that the LFHI events, in general, have low likelihood of occurrence and high magnitude of impacts although the measurements for each threat in terms of occurrence and impact vary within each category of the threats being natural, accidental or human-tailored.

across the UK, Italy, and North America (Bompard et al., 2011)<sup>2</sup>. In addition, the economic damages due to Japanese power failures in March 2011 in Fukushima in the wake of an earthquake and subsequent tsunami underscore the need for protecting the electrical systems and grids based on a thorough ex-ante risk assessment from inevitable natural calamities. However, the risks of damage from severe weather conditions are not likely to decrease in the foreseeable future. Long-term climate change and extreme weather conditions will continually challenge and test the reliability, resiliency and robustness (the 3 R's) of energy infrastructure in many European countries.

Likewise, the risks of national or international malicious attacks are another well-perceived LFHI threat. An attack on the substations or transmission networks can provide the possibility of engendering a major blackout and adversely impacting the functioning of other inter-dependent critical infrastructures and networks such as telecommunications, gas and waterworks. This is because electricity networks power much of the infrastructures in advanced economies and thereby creates a 'ripple effect' of economic, social and environmental damage post-attacks (Douglas, 2005). While the existing grids are in the process of being digitalized and getting 'smart' for efficiency improvement reasons; it also invites a new and increased risk of threat through isolated or coordinated 'cyber attacks' (Tritschler and Mackay, 2011).

The distribution networks stand rather vulnerable as they bear around 90 percent of power failures while around 10 percent of power failures are caused by failures in the transmission system (Hammond and Waldron, 2008). However, the rarity of the occurrence of these events complicates the process of making any probabilistic estimates in foreseeing the occurrence of likely threats and prepare against them accordingly. There also exists limited operational experience in handling the risks engendered by LFHI events while economic tools such as cost-benefit analysis (CBA) may not be adequate to internalise their impacts in long-term risk protection planning models.

Furthermore, the lack of clear conceptual frameworks concerning energy systems security can act as obstacles in designing proper security measures against external threats in energy networks. However, the aim of this paper is to identify the potential risks and threat indicators faced by the electricity networks in the light of on-going technological advancement and their existing energy policy goals. Identifying the risks arising from various natural, accidental and malicious threats

---

<sup>2</sup>Hurricane Katrina of the 2005 Atlantic hurricane season was the costliest natural disaster that completely halted the functioning of several critical infrastructures including the electricity systems. It is also one of the five deadliest hurricanes, in the history of the United States. There were at least 1,836 casualties in the hurricane and total property damage was estimated at \$81 billion (2005 USD) (Virginia, 2009).

to the European electricity networks in the context of increasing market liberalisation and integration through interconnectedness is a first step towards protecting against them. This is especially relevant from a policymaking perspective as the conventional literature on energy security has traditionally focussed on the security of fuel supply in the generation segment with the networks receiving little attention. This research aims to bridge such gap.

We proceed with the remainder of the paper as follows. Section 2 of the paper analytically discusses the concept, conventional measures and existing indicators of security of supply. Section 3 identifies a list of core set of security of supply indicators concerning electricity networks. These indicators are further quantitatively analysed and discussed in relation to some specific European economies in Section 4 while Section 5 concludes.

## **2. Security of Supply: A Conceptual Overview**

Security of supply (SES) is amply defined and used across the literature (Winzer, 2012). This is expected because energy security concerns many aspects that are vital to all economies while it lacks a well-defined idea which involves more than one scientific discipline (Loschel et al., 2010). The varying sources and nature of risks coupled with the difficulties in assessing the severity, certainty and scope of impacts can further blur and complicate the concepts and understanding of energy security issues. As such, it has no widely agreed upon definition for two major reasons. The primary reason is that security of energy supply is a multifaceted issue with rather varied, interrelated and often complex notion involving the diversity and difficult nature of the issues to be considered, and the requirement to consider them in a holistic manner (Bazilian and O'Leary, 2006). Hence, defining energy securities under stricter terms can become a complicated and controversial task. Secondly, the definitions of SES are often broad and not well-targeted while the security of the electricity system as a whole hinges upon the level of security across each segment in electricity sector. The aim of this paper is to conceptually address these concerns in understanding the security of supply in electricity networks and help policy making accounting for the risks from external threats.

In general, security of supply is commonly implied as the continued availability of energy relative to effective energy demand (Winzer, 2012). For example, the UK Department of Energy and Climate Change focuses the definition of energy security around the continuous availability of commodity supplies (DECC, 2009) while the European Union(EU) definition extend this concept to include welfare aspects such

as the impacts on the environment or the society in terms of sustainability (European Commission, 2000). Thus, energy security encompasses addressing the risks related to the scarcity and diversity of primary fuels (which is the production/generation aspects) and the operational reliability of energy systems (which includes the network aspects) to ensure that their services are delivered to end users in an affordable manner (Blyth and Leferre, 2004). Hence, it is inevitable that security of energy supply includes both issues of quantity, quality, and price of energy. Likewise, the risks and threats associated with each segment are related across the whole system while the integrity and operation of the system as a whole improves by abating the level of risks across different segments. However, past studies of energy security are primarily concerned with the physical availability and delivery of fuel supply in generation. This implies the availability of energy among the end consumers is unconditional upon the health of critical components of the electricity supply industry (ESI) such as the transmission and distribution networks.

Considerable emphasis is constantly placed on creating a diverse energy and electricity system amidst the growing confusion on what actually should be diversified (Grubb et al., 2006). It is generally believed that greater diversity enhances the robustness of an electricity system to fossil fuel supply shocks generating economic and security of supply benefits while also promoting network resilience (Bazilian and Roque, 2008). However, the diversity of an electricity system is wrongly interpreted both in qualitative and quantitative terms (Roques, 2003). Stirling (1994, 1998) argues that diversification is an investment allocation technique in modern electricity systems where uncertainty and ignorance rather than risk dominate the real electricity investment decisions.

As such, diversity can be understood from three necessary perspectives that include variety, balance and disparity (the nature and degree to which the options are different from each other) (Bazilian and Roques, 2008). Variety is the number of diverse categories of 'option' into which a system may be allocated while balance is a function of the allocation of the energy system across various identified options (Stirling, 1994). Disparity refers to the manner and degree in which energy options may be distinguished (Runnegar, 1987). Thus, *ceteris paribus*, system diversity increases with greater variety of distinct types of energy option; the more even the balance across energy options and the more disparate the energy options. The understanding of diversity based on such threefold classification places disparity at its heart while each of these property helps constitute the other two (Stirling, 1998). Although each of these aspects is necessary, they are insufficient properties of diversity. Table 1 shows that previous studies have used varying aspects of the threefold classification in order to understand diversity.

<b>Aspects of Diversity</b>	<b>Name/Reference</b>
Variety	Category count (MacArthur, 1965)
Balance	Shannon evenness (Pielou, 1969)
Variety/Balance	Shannon-Wiener (Shannon and Weaver, 1962), Herfindahl/Simpson (Simpson, 1949), Gini (1912), Hill (1973)
Disparity	Weitzman (1992), Solow and Polasky (1994)
Variety/balance/disparity	Junge (1994), Awerbuch(2006), Stirling (2007)

**Table 1: Aspects of diversity considered in prior studies**  
**Source: Stirling (2008)**

However, it is necessary to consider that diversity in itself is not a sufficient criterion to guarantee the security of the whole system. As such, diversification of energy sources is just one of the many security of supply strategies. It is important that critical infrastructure such as that for long transmission networks are continuously reviewed for properties of resilience in the face of several natural, accidental and malicious threats (JESS, 2004). Nonetheless, in the face of uncertainty and ignorance, an important insight to have emerged from a number of sciences is that diversity provides resilience to systems exposed to such incertitude (Grubb et al., 2006; Awerbuch, 2006). Alongside, it is important to acknowledge that there exist more energy security strategies apart from diversification even though diversification is often viewed as the dominant means to energy security (JESS, 2006).

Another widely used approach in conceptualizing security of supply primarily involves constructing indicators to assess the risks and associated costs in terms of fuel imports dependence, political instability and resource estimates. This is particularly important in the European context as energy imports and its transportation (for example, natural gas) can originate from politically unstable regions in the face of increasing energy demand. In addition, the creation of a common internal market for electricity exerts extra importance on the cross-border flow of electricity across countries. This will require more economic and political cooperation across economies along with an improvement in the overall quality of electricity networks considering the growing demand for electricity.

De Jong et al. (2007) measure the short-term responsiveness to an energy crisis with measures of security of internal energy supply and stability of the energy transport system as a measure of security of external supply in their index. This allows accounting for import risks which in reality is a component of overall security of supply index. Le Coq and Paltseva (2009) incorporate the concepts of risks and costs by constructing the risky external energy supply index (REES) and the contribution to EU risk exposure index (CERE). Likewise, Roller et al. (2007)

construct a general energy security index by dividing the net energy imports on the total energy consumption in which both the external energy supply and the internal energy supply are taken into account. Turton and Barreto (2006) incorporate the concept of long-term energy security by emphasizing the importance of the availability of the domestic energy sources.

Similarly, Loschel et al. (2010) construct ex-ante and ex-post set of energy security indicators by including the relevant risks and costs. Lesibrel (2004) and Bazilian and Roques (2008) have argued that the mean variance port-folio theory (MVP) can be applied to assess the trade-off between risks and costs in the generation mixes or to the wider energy system. However, MVP is an optimisation tool rather than an indicator for security of supply in itself. Jamasb and Pollitt (2008) suggest market mechanisms as an efficient tool for allocation of resources and balancing of supply and demand at times of scarcity.

The International Energy Agency (IEA) has developed two set of indicators incorporating the concepts of 'resource concentration' and 'stresses'. The IEA price component indicator shows the energy security implications of resource concentration while the physical availability component indicator incorporates the physical availability aspects of energy security. It is generally considered that the indicators established by IEA are the most influential set of indicators in measuring the security of energy supply (Loschel et al., 2010).

While these indicators primarily assess the SES in generation in terms 'quantity risks' and 'price risks'; the security of supply in the context of liberalized energy networks is unaddressed. The liberalisation of energy markets across the European Union and the subsequent energy policy objectives of creating an affordable, sustainable and reliable energy supply have placed greater challenges and pressures in the existing energy networks. The increase in international electricity trade coupled with the transition towards a greener economy exacts for considerable resources to be devoted in the design, maintenance and upgrade of existing networks for a secure energy supply. Interconnections of networks require extreme coordination among participating countries. The 6 blackouts that occurred in 2003 within 6 weeks impacting upon 112 million people in the US, UK, Denmark, Sweden and Italy demonstrate that increased cross-border trade of electricity resulting from the liberalisation of the electricity supply industry was not accounted for in the assessment of system security. Bailek (2004) states that the 2003 blackouts in the Western countries were primarily transmission-related and occurred due to the technical failure in the networks. These blackouts did not occur from generation inadequacy or shortages of primary fuels. Hence, it is generally believed that the frequency and scale of such blackouts is likely to intensify in the current context of liberalisation and privatisation due to increased

competition, scale of operation and cross-border trade of electricity (Thomas and Hall, 2003; Yu and Pollitt, 2009). Table 2 summaries the major transmission related blackouts that occurred in 2003 in terms of location, duration, population affected, economic costs and interrupted energy.

<b>Nature of Blackouts</b>	<b>North America</b>	<b>England</b>	<b>Croatia</b>	<b>Scandinavia</b>	<b>Italy</b>
<b>Date</b>	August 14, 2003	August 28, 2003	January 12, 2003	September 23, 2003	September 28, 2003
<b>Location</b>	USA and Canada	South London	Southern Croatia	Sweden and Denmark	Italy
<b>Population affected</b>	50 million	0.41million	N/A	4 million	55 million
<b>Duration</b>	2 days	30 minutes	N/A	8 hours	18-24 hours
<b>Economic costs</b>	4-10 billion US dollars	N/A	0.002375 billion US dollars	N/A	N/A
<b>Interrupted energy</b>	62000 MW	724 MW	1270 MWh	6550 MW	17 GWh

**Table 2: Major blackouts in 2003**  
**Source: Bompard et al. (2011)<sup>3</sup>**

While the causes of the blackouts affecting the transmission networks vary; the economic costs of security of supply interruptions are large. This justifies the need for attention that modern electricity networks require in delivering a secure supply of electricity. The case is especially true in Europe where it has become evident that the European electricity market is characterized by underinvestment in cross-border transmission capacity and by a reluctance to carry out costly upgrades of power technologies which can improve the service quality (Yu and Pollitt, 2009). These characteristics have coincided with the advent of liberalisation, unbundling, of the sector, privatization and new centralized and distributed energy technologies. However, changing climate and weather impacts also remain a major risk facing the electricity networks which needs to be accounted for in the evaluation of system security along with other threats (natural, accidental and malicious) and events.

A common and accepted way of accounting for various threats and events in evaluating the electricity system security is to assess the risks of security of supply. The risks assessment can be qualitative or quantitative while the sources of risks can be diverse. Qualitative risks can be quantified by assigning some clearly well-

---

<sup>3</sup> Please note that the data for interrupted energy is available with inconsistent units as reported in Table 2.

defined values. However, the value that a certain risk takes can vary across countries as the perception of risks arising from a particular threat or circumstances can vary significantly across them. We include four broad classifications of risks in this study, namely i) economic risks, ii) technical risks, iii) topographical risks, and iv) social risks facing the electricity networks. The valuation of these risks in either qualitative or quantitative terms allows us to construct a 'security of supply' indicator concerning the European electricity networks.

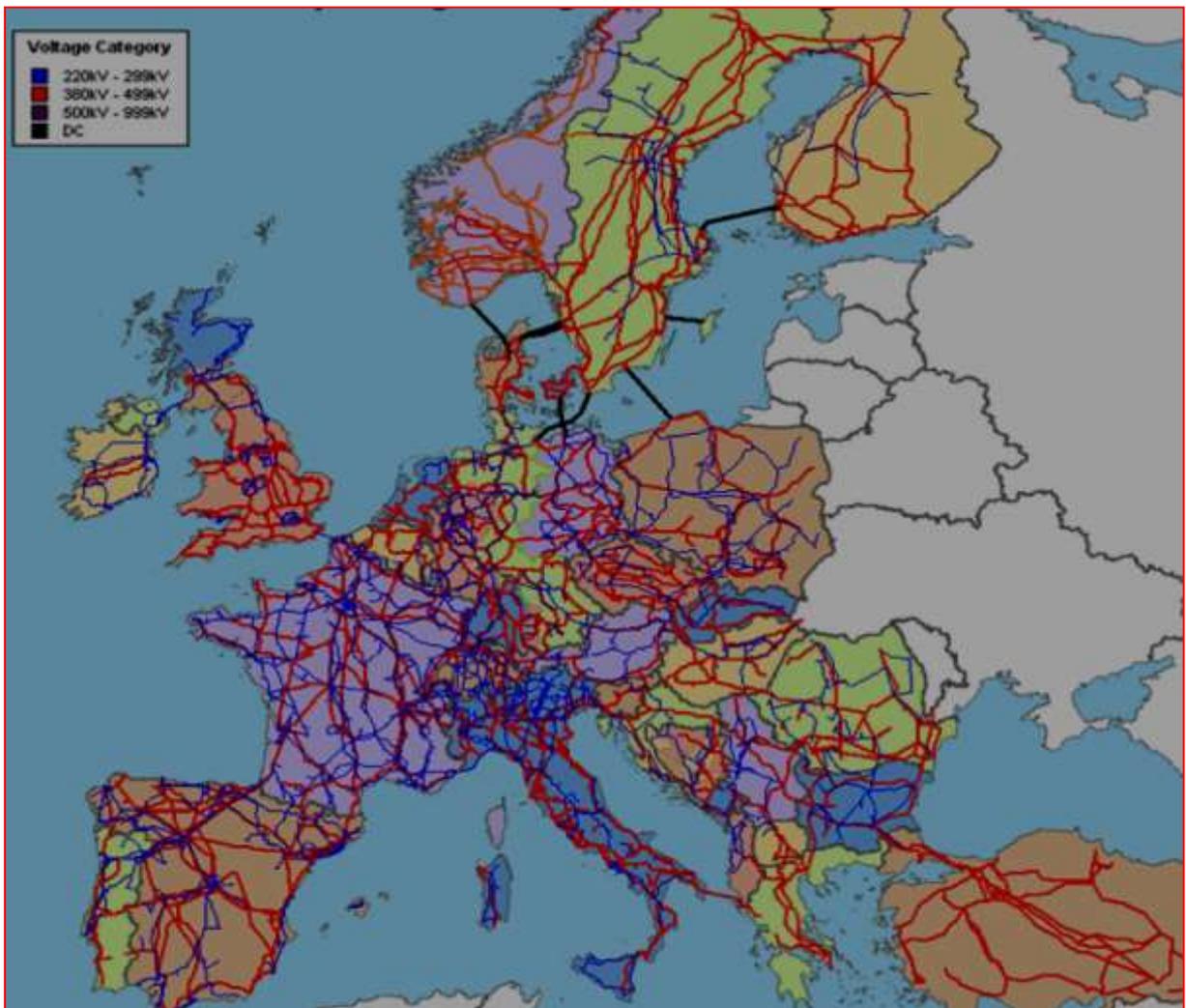
### **3. Identification and Assessment of Network Risks**

Energy security remains one of the topmost energy policy goals in the EU (see EU Directive 2009/73/EC). However, the transition towards a low carbon economy, the 2020 renewable targets and the need for cross-border interconnections in achieving a common internal market for electricity imply that energy security needs to be comprehended with these inter-related policy goals. The EU electricity market currently comprises of 41 transmission system operators (TSO's) from 34 countries covering about 300,000 km of transmission lines. Around 530 million people are served by these transmission lines across Europe. Figure 1 shows the map of high voltage transmission grid across Europe and the existing interconnectedness among member states. However, regional integration of wholesale electricity markets via increased interconnection, while promoting security of supply, also exposes the system to the threats of 'cascading failures' that can occur both within and among the interconnected networks.

The European electricity networks consist of a mixture of overhead lines and underground cables of varying voltages and include various system points and substations. The substations are responsible for voltage transformation and include the switching and control equipment. However, the long distance (mainly transmission) and short-distance (vastly distribution) electricity networks across Europe face many risks and challenges with the advent of liberalisation, ambitious climate change targets, increased distributed generation and digitalization of the grid. Most importantly, the risks arising from natural calamities, adverse weather conditions and social unrest cannot be over-looked. The risks to the existing electricity networks can be classified as (i) economic risks, (ii) technical risks, (iii) topographical risks and (iv) social risks depending upon the causes and sources where they originate from. An enhanced understanding and assessment of these risks is a useful 'qualitative indicator' to assess the system security which can nonetheless be quantified somehow.

### 3.1 Economic risks

Electricity networks (both transmission and distribution) are traditionally considered to be natural monopolies because their cost structure (high fixed costs relative to operating costs) implies that it is more cost efficient that the market is served by a single firm than many firms. Thus, they need to be regulated (Newbery, 1999). However, it is also the case that distribution networks while being regional monopolies in physical terms often have a ‘market’ for distribution services and activities (Saplacan, 2008). The networks being ‘natural monopolies’ are thus subject to economic regulation in terms of price, entry and service quality across Europe creating its own risks.



**Figure 1: Map of European high voltage transmission grid**  
**Source: Adapted from GENI (2011)**

### ***i) Lack of adequate investments***

It is observed that quality of service (QoS) is correlated with the amount of spending in general and investments in networks in particular (Joskow, 2008). Thus, QoS is an integral indicator of overall security of supply in the networks. Service quality in networks mainly involves two major aspects: continuity of supply and power quality. Continuity of supply is measured in terms of number and duration of planned and unplanned interruptions due to network failures. In the face of decaying and old electricity networks across Europe, the lack of investments can result in power losses, increase unplanned interruptions due to system breakdown and increased episodes of planned outages also increase due to frequent maintenance and upgrade. Power quality, on the other hand, requires the maintenance of constant voltage in the absence of which significant costs can be incurred due to damage to equipment.

The transformation from vertically integrated centralised electricity systems to liberalised and competitive electricity markets have led to the issue of investment inadequacy in electricity networks across Europe. The European Commission estimated in 2007 that the realisation of the European energy policy targets will require 750 billion euros to be invested in electricity infrastructure over the next three decades (Skoczkowski, 2007). This will involve around 90 billion to be invested in transmission networks and 300 billion in distribution networks. However, the desired level of investments has not been achieved. The inadequacy of investments in the electricity networks can be perceived as a regulatory and policy failure of the liberalized market structures across EU.

The lack of adequate investments in the networks implies that interconnection capacity between European member states is insufficient and bottlenecks exist within and between the countries in the fluid transmission of electricity. Likewise, the prevention of the grid against extreme weather conditions and other external threats coupled with the digitalization of the grid may require the adoption of sophisticated technologies which involves additional investments.

In centralised energy systems, the optimisation of investments can be achieved by coordination and command and control (Jamash and Pollitt, 2008). However, this is not the case among the European countries due to increasing liberalised and decentralised structure of the regulated electricity markets. Thus, the role of market design and regulatory framework can be crucial in addressing the investment adequacy issues in liberalised European electricity markets. This is discussed separately below.

### ***Role of regulation towards investments***

Liberalisation of the electricity markets has been on the agenda in the power sector of many European countries since 1990. Hence, the key features and operating environment of the sector has been changing. The industry no longer remains vertically integrated but rather unbundled (i.e. vertically separated) while the nature of vertical separation varies across countries in functional, legal and ownership terms. Competition has been introduced in the potentially competitive segments while the natural monopolistic network segments, in the absence of competition, remains economically regulated to mimic market mechanisms and promote efficiency improvements (Jamasb and Pollitt, 2007).

In particular, the primary goals of regulation in improving the security of supply in liberalised electricity markets is to attract adequate and timely investments, promote adequate maintenance and ensure efficient operation of existing network facilities and create sufficient incentives for innovation and technological progress (Jamasb and Pollitt, 2005). The electricity networks across the European countries are regulated by independent regulators. An independent regulator acts as the custodian of public interests (Armstrong et al., 1992). The regulators decide the amount of revenue to recover under regular time intervals (also called regulatory lag). Historically, cost-based regulatory approach was used by many regulators to regulate the network charges. It is argued that the cost-based regulation (also commonly known as the rate of return (ROR) regulation) is efficient for generating short-term investments but at the expense of long run efficiency. This is because the rate-of-return regulation deviates from cost-minimization (also termed as the Averch-Johnson effect) in the long-run (Averch and Johnson, 1962; Vogelsang, 2002). Likewise, the experience with price-based models suggests that price-based regulation is effective for short-term cost reductions and efficiency improvements but maybe less effective for long-term investments (Brunekreeft, 2009).

However, it is possible to encourage network investments with more market-based mechanisms and incentives mechanisms such as merchant electricity transmission networks (Joskow and Tirole, 2005). Such incentive laden price-based regulation is popularly known as 'incentive regulation'. The regulator has a pivotal role in ensuring adequate network investments while not letting the prices rise via the incentive regulation (Pollitt and Bialek, 2008). The network charges in many EU countries are now subject to incentive-based regulation. The incentive-based schemes encourage the network utilities to undertake cost savings. However, the striving for cost savings may result in lower service quality as maintaining or improving upon a given level of quality of service is costly and possible only at certain spending levels (see Ter-Martirosyan, 2003). A recent study by Jamasb et al. (2012) suggest that while the incentive schemes established

by the regulator to encourage utilities to reduce network energy losses leads to improvement in sector performance, they do not provide utilities with sufficient incentives to avoid power interruptions in the UK. However, the state of the current European electricity network suggests that not only the size but the timing of investments are crucial in ensuring a secure supply of electricity. The transition to the smart grids, likely adoption of electric vehicles and the likely widespread integration of distributed and renewable energy into the grid clearly heightens the importance of the size and timing of investments and the role that the regulator has to play.

In addition, it is also necessary that the appropriate incentives are incorporated in the regulatory mechanism to create additional support for the grid to be protected at times of extreme weather other external threats. The regulator faces a challenging task of designing an appropriate mechanism to allocate the costs of increased investments among different users in the regulated networks. As such the role of regulator is likely to increase in the context of liberalised EU electricity markets.

## **ii) *Growth in electricity demand***

Electricity demand is expected to increase in the European Union. It is estimated that the demand for electricity will range within 3530 TWh to 3795 TWh by 2020 than 2856 TWh in 2008 (Ruska and Simila, 2011). Germany, France and the UK were the largest electricity consuming countries in 2008 while combined electricity consumption totalled 356 TWh in the Nordic electricity market area comprising Denmark, Norway, Finland and Sweden. The transport sector is expected to play a major role in driving up the electricity demand in Europe. It is estimated that around 1.5 million electric cars (plug in hybrids and battery electric vehicles) will be running on the European roads by 2020 (Rankin, 2010). Thus, electric cars alone could increase the European electricity demand by 3% as compared to the 2006 levels. The adoption of the electric vehicles on a large scale can change the nature of the electricity demand as power demand can increase in select hours of the year. This trend can increase the ratio of system peak loads to average loads and falling capacity utilization leading to rising electricity costs. Such trend will exacerbate the need to build new generation plants and transmission lines in the face of rising average costs because of the need to pay for capital that is idle most of the time (MIT, 2011). Similarly, the increased use of air-conditioning (AC), computers and electric gadgets of varying shapes and sizes have catapulted electricity demand in the face of growing capacity constraints in generation.

The rising electricity demand is a major challenge and poses considerable risks to the already congested European electricity grid. Grid congestion leads to a deterioration in the quality of service due to frequent power outages. The 'price risks' also remain as congestion can drive the electricity price higher at peak times. In the light of market liberalisation, cross-border trade of electricity remains an undisputed option to satiate and balance national electricity demand across the European countries. Hence, whenever a large load is placed on the inter-connected network, the adverse effects can spread along a large area. Voltage fluctuations can occur as suppliers try to balance out demand or loads by reducing the voltage across the networks (Hammond and Waldron, 2008).

One of the factors of past blackouts across Europe and North America in the early 2000 was primarily caused by network failures due to high demand pressure in the grid. It is also likely that electricity demand will continue to rise for a foreseeable future. In addition, a study by Eskeland and Mideksa (2010) show that an increase in temperature has an impact on electricity consumption four times the size of the equivalent decreases in temperature in Europe. Thus, electricity consumption will be a crucial factor in the adaptation towards climate change effects in the wake of future temperature changes.

### **3.2 Technical risks**

Electricity is a non-storable product and requires the real-time balancing of demand and supply at all times. Electricity networks also need to accommodate a range of technologies such as distributed generation, electric vehicles, etc. and fuel. Hence, technological aspects remain central to the effective functioning of the network and hence the effective supply of electricity. In the light of technological developments involving the electricity networks, different risks can arise from such technological transitions as discussed below.

#### ***i) Distributed Generation***

Significant economies of scale and reliability are the major advantages of centralised electricity production. However, such system is also prone to environmental and security of supply issues justifying the adoption of distributed generation (DG). DG is predominantly site-specific in relation to energy resources and demand. It refers to the energy supply close to the point of use by way of 'distributed energy resources' (Hammond and Waldron, 2008). DG is slowly gaining pace across the EU member states as the liberalization of energy markets has created environment conducive for its promotion. One of the features of DG is

the flexibility that allows consumers to respond to changing market conditions because of their small size and shorter lead times in construction as opposed to centralised electricity systems. Devising and deploying mechanisms to provide incentives for investment in flexible generation and for operating flexibly within the system will become increasingly important as the penetrations of DG sources increase across the EU countries (MIT, 2011).

However, the adoption of DG to a wider network can pose certain risks to the existing distribution networks. This is because the existing networks are not designed for decentralized supply and thus can be technically challenging. High penetration of DG has the capability to complicate the design and the operation of the existing distribution systems. A major shock or disturbance anywhere in the network can instantly affect the power quality throughout the network and hence requires careful monitoring to keep it stable. DG connections are also likely to affect the system frequency. The absence of load-frequency control equipment implies that DG operators are likely to rely on the transmission network operator or the regulatory body to maintain system frequency. This can be risky and thereby the connection of DG to the network in the absence of suitable back-up arrangements needs to be cautiously assessed against such technical challenges.

## **ii) Diverse Generation Technologies**

Mitigating adverse impacts of climate change and improving the security of supply in generation require a significant switch towards low carbon energy sources in Europe. This has led to an increase in adoption of renewable energy generation across the EU member states. The EU countries in 2007 decided to meet 20% of the overall EU generation from renewable sources. Diversification of energy sources also adds to network resilience (Hammond and Waldron, 2008). However, major changes to the electricity network are needed to meet the European renewable targets while maintaining high service standards and reliability. This is because the growing use of renewable poses three major challenges across the EU involving i) the need to connect many new generators to the grids, ii) the need to upgrade the system to deal with intermittent electricity supply and iii) the need to connect small generating plants to the distribution network rather than the transmission grid (Hammond and Winnett, 2006).

The interruption in the supply of renewable energy sources can affect the stability and harmonics of the whole system in terms of fluctuating frequency and voltage. Hence, it can affect the way the electricity system operates with twin major impacts on balancing costs and the reliability costs. The balancing impacts relate to the rapid short-term adjustments needed in order to manage the variability in energy supply (energy fluctuations) over the time period. This can only be achieved in the presence of a flexible grid affecting the operation and economics of

electricity networks. In addition, the threats and risks resulting from the absence of needed changes in power system planning and risk management, distribution and transmission related planning, operations planning and interface between grid and diverse generation techniques cannot be undermined in the face of growing integration of diverse generation technologies in the grid (PSERC, 2010).

The reliability aspect relates to the extent to which generation will be available to meet peak demands. In the absence of adequate supply, the TSOs are obliged to ration the demand creating additional stress to the grid. Most importantly, the integration of renewables to the grid takes place with the help of power electronics converters that integrate the renewable sources to the grid in compliance with power quality standards. However, high frequency switching of inverters can inject major harmonics to the system creating severe power quality problems if not implemented properly (Khadem et al., 2010). Hence, efficiently increasing the penetration of grid-scale and diverse renewable generation while maintaining reliability require modifications to existing European power system design and operation. In addition, processes for planning transmission system expansion, allocating facility costs, and, particularly, siting cross-border transmission facilities will need to be reformed as interconnectedness increases in the EU (MIT, 2011).

While diversified generation technologies sources can add to network resiliency if connected to the grid, it can generate several security of supply risks in the absence of properly designed electricity networks to accommodate them in the face of growing intermittency of electricity supply. However, it can be expected that the adoption of smart grid will enable a larger integration of renewable sources and distributed generation across the European electricity systems.

### **iii) Smart Grid Technology**

Electricity networks across Europe are facing a major transformation as the need to integrate more renewable energy, improve energy efficiency and allow more consumer control over their energy consumption increases. The 'smart grid technologies' is expected to deliver these goals as smart grid planning is relatively at an advanced stage in Europe. The smart grid is expected to deliver three major benefits namely (i) facilitating the transition towards a greener economy with significant use of renewable energy, (ii) by creating an efficient grid that increases the surplus of the consumers through greater energy efficiency, and (iii) enabling technological innovation that creates jobs of the future and new opportunities (Chopra et al., 2011).

According to the European Network of Transmission system Operators (ENTSO-E), "smart grid" is the process "to transform the functionality of the present electricity

transmission and distribution grids so that they are able to provide a user-oriented service, enabling the achievement of the energy policy targets (2020 and beyond) and guaranteeing, in an electricity market environment, high security, quality and economic efficiency of electricity supply". Thus, smartness is not an objective in itself but rather a set of tools for achieving the 20/20/20 targets (Chaniotis, 2011). Nonetheless, the smart grid will create a power network that is more reliable, flexible, secure and efficient using smart devices and automation technologies.

However, the realisation of smart grid will require major investments in new technology and spending in research and development (R&D). This implies that the technology is fully prone to suffer from the economic risks of underinvestment. The increasing price of rare metals which form a critical component for a variety of smart-grid technologies because of a very limited global supply can deter the widespread adoption of those technologies across Europe and the US. As many new devices get connected to the grid, it also increases the threat surface with every new connection. As smart grid comes online, the increased risks of cyber-attacks will be among the main risk and challenge that the technology will face. This is because the technical threats related to cyber security such as malware, sensible information theft; traffic injection, etc. imply vulnerabilities of communication and information systems that are capable of shutting down the large areas of power generation plants in Europe (ENISA, 2012). Hence, there is a strong dependency between smart grid security and security of supply in the European electricity networks (Tritschler and Mackay, 2011).

While the future of the grid looks certainly smart, the risks and new challenges faced by these electricity networks to overcome will also become apparent. The cyber security risks and challenges associated with smart grid will require additional focus on data and information security requirements, large number of smart devices, legacy and secure communication protocols, synergies with other critical infrastructures such as utilities etc. implying several smart grid security challenges (ENISA, 2012). Moreover, it can be expected that smart grids can facilitate the transition towards a sustainable and secure electricity supply in Europe by overcoming the infrastructural and operational challenges evolving the European electricity system.

### **3.3 Topographical risks**

Topographical risks are those risks arising mostly due to the general location of the place and too little can be done towards their mitigation. For example, Italy is among the most seismically active countries in Europe as it lies directly above the Eurasian and African fault lines where the two tectonic plates meet. Factors such

as severe weather conditions and natural calamities also fall into this category. Table A in the Appendix reports that 1.1% of outages in the US are weather related while lightning also contributed to a mere 1.1% of outages. However, the main approach to mitigate the economic impacts from such risks in times of occurrence is by adapting to them through suitable prevention measures.

Weather remains a major challenge for the European electricity networks and the problem is likely to aggravate considering the growing climate change concerns. Immediate effects can be observed in terms of increases in temperature and precipitation with predicted increases in sea level rise and storm surge. For example, electricity transformers face new type of risks as temperature thresholds will be surpassed. More often, temperature rises can result in increased sag of transmission lines, increase in the number of underground fires and manhole explosions fuelling the outage frequency, extent (customers lost) and duration (Zimmerman and Faris, 2010). Long term changes in annual precipitation can also lead to the corroding of the network equipment. Likewise, increased rainfall can pose a significant threat to the substations and may also damage the underground cable systems. For example, it is reported that the power outage that occurred in the UK during 2007 affecting Yorkshire and Gloucester arose due to substation flooding when high water levels reached critical paths at some substations (ENA, 2011). Thus, in the wake of evolving climate change concerns, the EU electricity networks are required to adapt to the adverse impacts of climate change. Furthermore, the growth of weather dependent renewable and distributed electricity generation in the future will place major challenges across the EU electricity networks.

Overhead power lines are also particularly susceptible to severe weather conditions such as wind storms and lightning. The 2003 Italian blackout was caused by the severe weather storms that damaged the power lines from Italy to Switzerland (ENEL, 2011). Similarly, the vulnerability of the European power networks was also exposed when Scotland was affected by strong winds in the name of hurricane 'Bawbag' on December 5, 2011. The hurricane blasted several wind turbines and brought down several overhead power lines with 400 separate incidents disrupting the electricity network across Scotland. It is estimated that the economic losses from the power disruption amounted to about 100 million pounds (BBC, 2011).

Securing the infrastructures such as electricity networks against severe weather can be challenging. This is because it is difficult to make a probabilistic estimate on the likelihood of occurrence of these events as most of these events occur rarely. However, events such as extreme weather (high speed storms, heavy snowfalls,

etc.) and floods may be easy to predict using complex meteorological forecast as exists in many European countries. Adoption and innovation of sophisticated technologies can be crucial towards safeguarding the grids against external threats. For example, automated hydraulic wind power plants can be in windy areas like Scotland such that the plant responds to the speed of the wind by varying its height. However, this may require additional spending but also in research and development (R&D). Inadequate investments in-itself remains a larger economic risk facing the EU electricity networks aspiring to be modernized. The regulatory practice and regime will prove to be a significant factor to shape the future of European grids against several challenges in the light of investments inadequacy in electricity networks.

### **3.4 Social risks**

A social risk refers to those risks arising from unstable societal conditions. It includes aspects such as terrorist attacks (including cyber-attack), civil war and political instability. These events can largely affect the critical infrastructures of the nation such as electricity networks. This is because the critical infrastructures can be a prime target of the disgruntled masses to vent their dissatisfaction. Most importantly, certain equipment and components of the grid are crucial and installing them can be costly due to high sunk costs involved and greater time required. For example, high-voltage transformers are one of the unique assets in the grid. It can happen that unique assets are targeted by angry mobs which are very costly and can take one to two years to procure, build and install (POST, 2004).

Electricity powers much of the critical infrastructures of the industrialized nations such as EU from telecommunications to waterworks (Douglas, 2005). Hence, an attack on the networks can halt the functioning of major infrastructures such as transportation, communication, hospitals etc. However, the networks can also face the risk of domestic terrorism apart from or including international terrorism. Civil war and political unrest often become targeted and vandalised at times of these events although it happens quite rarely in Europe. Such acts of terrorism bear the potential of only causing short-term blackouts. It is proposed that decentralized generation can ensure increased security of the grid over a rather long-term implementation period because any single attack on the grid would have a lesser impact on the grid as a whole when a major proportion of distributed generation are installed (Hammond and Waldron, 2008). Nonetheless, the threats of international and domestic terrorism vary across countries.

The adoption of the smart grid implies that the growth of data flowing through the electricity grids is likely to exceed the growth of electricity flowing through them (in percentage terms) over the next two decades. In the future, the communication networks will become highly interconnected along with high physical interconnection of the EU electricity networks. Hence, the increasingly ICT reliant future grids are likely to expose its own set of vulnerabilities that may not be existent in today's grid. Millions of new communicating electronic devices such as automated meters to synchrophasors will introduce attack vectors (paths that attackers can use to gain access to computer systems or other communicating equipment) that increase the risk of intentional and accidental communications disruptions (MIT, 2011).

The threats from non-physical attack such as 'cyber attacks' and hacking to the grids is set to increase as the networks gets digitalized in the future. A successful 'cyber-attack' can allow the hackers to disable grid protective relays and gain control over the parts of the network (Douglas, 2005). As such, cyber-attack on the electric grid remains one of the serious short-term threats in the US today as reported by the American Broadcasting Corporation (ABC). A recent study by Galvin Energy Initiative (GEI) reports that most of the outages in the US that occurred at the distribution levels were caused by the acts of the public contributing to 1.2% of the total power outages (Rouse and Kelly, 2011). The problem is certainly set to spread and aggravate across the EU in the future.

Table 3 shows a simple risk assessment matrix based on the different risk dimensions identified in this paper. These risks can be assessed qualitatively using an ordinal approach such as low, moderate or high. However, one may also take a cardinal approach and quantify the risks accordingly. For example, low risks can take a score from 1-3, moderate risks can take a score from 4-7 and high risks can take a score from 8-10 in a scale of 1-10. For a single country case, the overall risk score will be the sum of the risks valued across all dimensions divided by the number of dimensions. Moreover, it is possible to assign weights to individual dimensions and take the weighted average for cross-country comparisons. This is necessary because the valuation and perception of the risks is different across countries at a given time as these risks are largely country-specific. For example, the threats to critical infrastructures from terrorist attacks are perceived to be higher in the US than Luxembourg.

On the other hand, risks can also be classified as short-term or long-term. Short-term risks engender short-term impacts while long-term risks produce lasting shocks to the system. For example, threats to the networks from civil unrest and political instability can short-term risks while threats from weather and natural

calamities can be a continued long-term risk. As such, the old risks associated with vertically integrated power systems are falling while new types of risks are emerging in the wake of a more liberalised and interconnected EU electricity markets.

<b>Risks</b>	<b>Aspects</b>	<b>LOW</b>	<b>MODERATE</b>	<b>HIGH</b>
Economic	Inadequate investments, demand factors			
Technical	Distributed generation, new technologies, smart grids			
Topographical	Weather, natural calamities			
Social	Terrorism, political instability, civil unrest			

**Table 3: Risk assessment matrix**  
**Source: Own compilation**

#### **4. Existing Indicators and Measures of SES in the European Electricity Networks**

A secure supply of electricity can only be possible in the presence of a robust, reliable and resilient grid. QoS is one of the important ex-post performance indicators to currently assess the security of supply of electricity networks among the EU member states. Quality of service encompasses three different quality dimensions: (i) voltage quality, (ii) commercial quality, and (iii) reliability (CEER, 2008). Voltage quality includes a variety of interruptions to the power system as already discussed above. Most of the network-related interruptions occur in the medium voltage (MV) and low voltage (LV) distribution networks (Keller and Franken, 2006). Commercial quality is associated with individual agreements between the consumers and the distribution companies while reliability includes network adequacy and security. Adequacy is the availability of sufficient network capacity to guarantee a continuous supply for electricity to the consumers in the longer run while security is the ability of the grid to withstand interruption (i.e. resiliency) in supply under adequate network capacity.

The most common quality of service indicators to assess system reliability in Europe across the distribution networks includes SAIFI, SAIDI and MAIFI. They are defined and understood as below:

- SAIFI stands for System Average Interruption Frequency Index. It is estimated by dividing the number of customer interruptions by total number of customers served and thereby measuring the number of outages experienced by users.
- SAIDI stands for System Average Interruption Duration Index. It is obtained by dividing the sum of long interruption duration (i.e. longer than 3 minutes) by the total number of customers. Hence, this measure is a proxy for the average amount of time that customers are interrupted.
- CAIDI stands for Customer Average Interruption Duration Index. It is expressed in minutes per interruption and can also be obtained as the ratio of SAIDI and SAIFI.

Other measures of reliability across the EU distribution networks include Momentary Average Interruption Frequency Index (MAIFI) which is conceptually similar to SAIFI, Average System Interruption Duration Index (ASIDI), Average System Interruption Frequency Index (ASIFI), Customer Average Interruption frequency Index (CAIFI), TIEPI and NIEPI.<sup>4</sup>

Likewise, reliability of the transmission grid is mostly assessed through Energy Not Supplied (ENS)<sup>5</sup> and Average Interruption Time (AIT). ENS is the total amount of energy that would have been supplied had there been no interruptions while AIT is the measure for the amount of time the supply is interrupted. Other indicators also include measures such as Average Interruption Frequency (AIF), Average Interruption Duration (AID), System Average Restoration Index (SARI) (see CEER, 2008). Table 4 shows the various reliability indicators used to assess the performance of the grid in selected European countries.

Country	Index
France	SAIFI, ENS, AIT
Germany	SAIDI, SAIFI
Italy	SAIDI, SAIFI, ENS, AIT
Netherlands	SAIDI, SAIFI, CAIDI
Hungary	SAIDI, SAIFI
Luxembourg	SAIDI, SAIFI, ENS
UK	CI, CML
Denmark	SAIDI, SAIFI, ENS

**Table 4: Network reliability indicators in selected EU countries**

**Source: CEER (2008)**

<sup>4</sup>In the UK, Customer Interruption (CI) is used instead of SAIFI which is calculated as 100\*SAIFI. Likewise, Customer Minuets Lost (CML) is a synonym for SAIDI in the UK.

<sup>5</sup> ENS is a synonym for END in Lithuania.

Table 5 reports the SAIFI and SAIDI reliability indicators for some European countries and the US accounting for major events. In the US, each customer is likely to encounter about more than 2 hours of interruption (on average) and is likely to face about 1.5 interruptions. These numbers are comparably larger than its European counterparts such as Denmark where each customer on average faces about 24 minutes of interruption with the chances of 0.5 outages. Similarly, each customer in Germany faces an average outage of 23 minutes as the country boasts of having the most reliable power grid in Europe. The average number of outages that a customer faces is highest in Spain and Italy (2.2 times). The length of interruptions that each customer is likely to face is also the highest in Spain with 104 minutes on average. Likewise, UK also faces a lengthy interruption with each customer likely to face about 90 minutes of outages on average.

Country	SAIDI (minutes)	SAIFI
USA	244	1.49
Austria	72	0.9
Denmark	24	0.5
France	62	1.0
Germany	23	0.5
Italy	58	2.2
Netherlands	33	0.3
Spain	104	2.2
UK	90	0.8

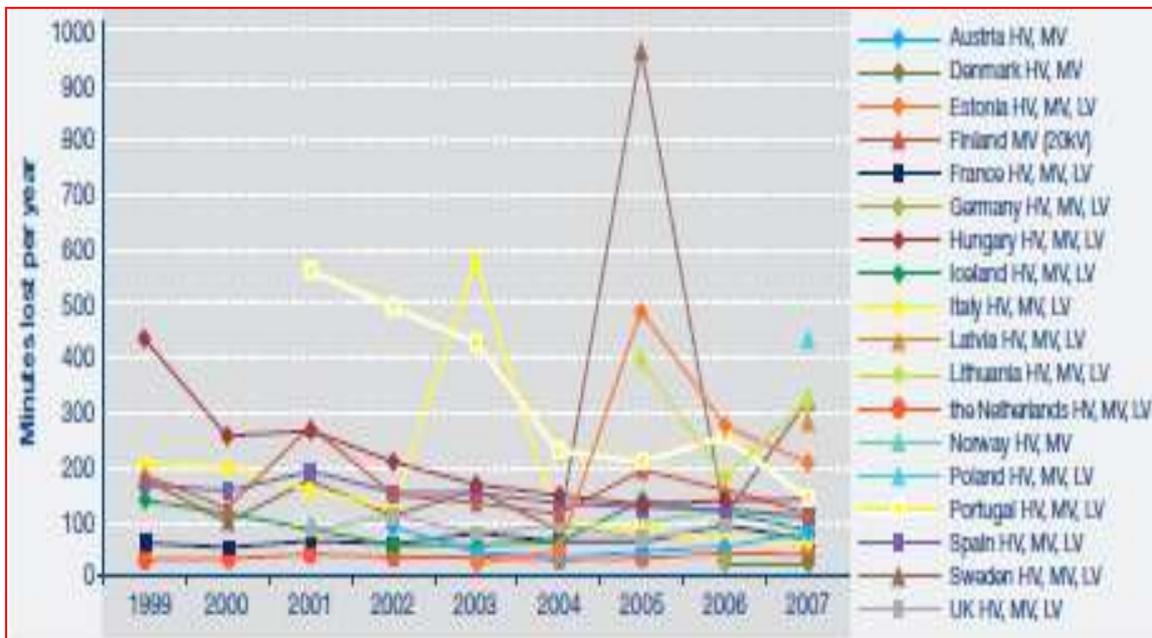
**Table 5: Reliability performance with major events**  
**Source: Rouse and Kelly (2011)**

Thus, we can infer that the reliability performances across the European countries are currently diverse and rather heterogeneous. The primary reason behind such heterogeneity is that the causes of interruptions (or risks of outages) largely vary across these countries. Weather can be a fundamental factor in countries like UK (Scotland in particular) and Spain while other topographical factors such as earthquakes can be influential in Italy which is prone to earthquakes. Most importantly, aging electricity infrastructure remains a central problem in many EU countries as the grid consists of aging power equipment, obsolete system layout, outdated engineering and old cultural values leading to old planning, engineering and operating of the system (Willis et al., 2001).

Thus, there exists a significant potential to improve the security of supply by enhancing the reliability statistics of the transmission and distribution networks in Europe. Figure A in the Appendix reports the time-series statistics on number of unplanned interruptions per year for selected European countries. Finland experienced more interruptions in 2001 where the number of interruptions is 3.5

more than in 2000 and 2002. Likewise, the number of interruptions for Italy in 2003 is one more than the interruptions occurred in 2004.

‘Exceptional events’ is the synonym for ‘major events’ in Europe. It includes exceptional weather conditions and other exceptional circumstances such as accidents and natural calamities that can affect the continuity of supply for long periods even if they occur rarely. Figure 2 is a time-series presentation of all unplanned interruptions that occurred among several European countries over a time period from 1997 to 2007 across the high voltage (HV), medium voltage (MV) and low voltage (LV) networks accounting for ‘exceptional events’. It can be seen that the blackout and load shedding of 2003 resulted in high minutes lost in Italy. Severe autumn storms contributed to high value of minutes lost in Finland and Hungary during 2001.



**Figure 2: Unplanned Interruption including all events (minutes lost per year)**  
**Source: CEER (2008)**

In addition, severe storm conditions in the southern parts of Sweden resulted in extremely long interruptions in Sweden during 2005. Excluding these exceptional events would mean that the average minutes lost in the countries considered due to unplanned interruption would range between 50 to 250 minutes per year as shown by the figure below. Furthermore, it is clear that annual variation for the number of interruptions is less than the annual variation for the minutes lost among the European countries. Hence, it is deducible that extreme events result in longer interruptions rather than more interruptions in the European context.

The regulatory approach in accounting for ‘exceptional events’ tends to vary across the European countries (CEER, 2008). In some, the concept does not exist as in Czech Republic and Finland. The different types of exceptional events in practice and their definition, the situations classified as exceptional events, whether exceptional events are visible in the interruption statistics and whether they are excluded from any compensation payment varies among the European countries.

Table 6 demonstrates the definition, classification and treatment of exceptional events in selected European countries. In most countries, exceptional events do not automatically qualify to receive compensation payments. Only the UK, Finland and Norway have some provisions of making companies eligible to receive compensation payments when exceptional events occur. Likewise, Slovenia, the Netherlands and Luxembourg do not explicitly report the interruption statistics due to exceptional events while Poland and Slovenia account for them in the statistics since 2009.

Country	Designation	Concept	Who classifies?	Included in interruption statistics	Eligible to receive compensation payments
France	Exceptional event	simultaneous interruption for more than 100,000 end users	TSO <sup>6</sup> and DSO	Yes	No
Finland		The concept of exceptional event does not exist			Yes, but interruptions longer than 12 hours are compensated
Germany	Force Majeure	Natural disasters, terrorist attacks and war, legal and official orders	Jurisdiction, National Regulatory Authority	Yes	No
Italy	Exceptional conditions periods	Based on statistical exploration and computational algorithm by NRA	DSO	Yes	No
Czech Republic		The concept does not exist			
Denmark	Exceptional event	Hurricanes and floods	Regulator	Yes	No
United Kingdom	Exceptional event	Weather and non-weather related	NRA	Yes	Yes, only in some situations

**Table 6: Definition and Treatment of exceptional events in some EU countries**

**Source: Adapted from CEER (2008)**

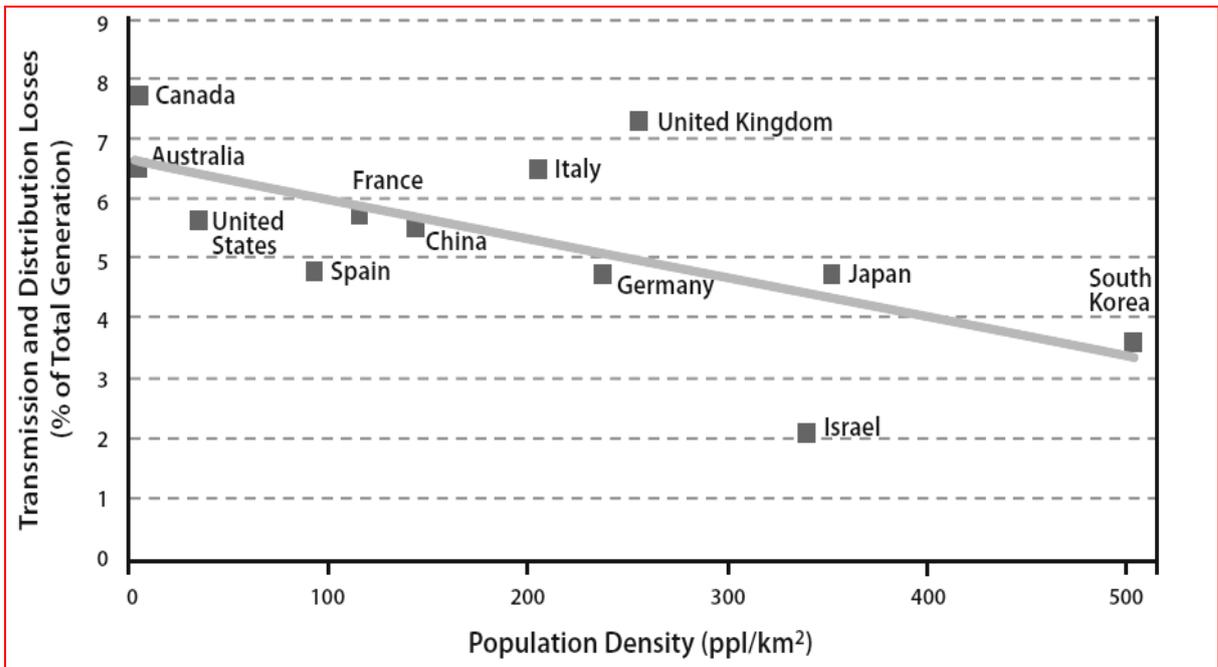
<sup>6</sup>TSO stands for Transmission System Operator while DSO stands for Distribution System Operator.

Similarly, the entities included under 'exceptional events' considerably vary across the EU members. Countries like Romania, Poland, the Netherlands, Hungary, Germany and Estonia explicitly include terrorist attacks and wars under exceptional events while Denmark and Austria only include natural disasters such as hurricanes and floods. For Sweden and Slovenia, the concepts of exceptional events are rather vague and broad. Sweden defines exceptional event as 'any events outside DSO's control' while Slovenia only considers 'more severe condition than the network requirements'. Thus, it is lucid that the regulatory approach in accounting for 'exceptional events' differ vastly between the European countries. In addition, it would be of interest to establish whether those countries explicitly regulating these events have performed better than the non-regulating ones.

Another set of ex-ante indicators to assess the performance of the transmission and distribution networks is the fraction of energy generated that is lost during the transmission and distribution process. Losses, in general, are measured as the difference between energy generated and energy delivered to customers. Hence, it does not include losses due to theft. However, theft is not considered to be important in the U.S. as well as in the wealthy EU countries today due to strong governance and (de)institutionalization towards theft. Moreover, in Europe losses consume between 4 to 16% of the electricity generated while the differences between the European countries in terms of average T&D losses are very high from 4.4% for Sweden to 16.1% for Romania (ERGEG, 2008). Most of the losses occur at the distribution grids than the transmission grids in Europe.

Figure 3 shows the transmission and distribution (T&D) losses of electricity including the US and selected EU nations as of 2008. The T&D loss remain high in the UK and is in line with Canada as compared to its European counterparts like Germany, Spain, France and Italy. This is mainly because of the relatively old grid in the UK than other countries. A significant proportion of the existing UK grid was constructed in the late 1950s and between the mid-1960s and the early 1970s (POST, 2007). Grid assets typically have a design life of about 40 years which implies that the UK grid have reached and surpassed their design lives. Older and decaying electricity network infrastructure can lead to higher system failure rates and losses implying increased maintenance and repair costs. It is expected that UK network companies will need to spend more on assets replacements over the next two decades to ensure an efficient management of the network (Hammond and Waldron, 2008). Moreover, the impacts of old network infrastructure on network losses are also high in other EU countries and remains to be adequately addressed. Furthermore, the figure further suggests that there might be a weak correlation between network losses and population density.

The treatment of losses across the regulated transmission and distribution network also explains the varying amount of losses in these countries. For example, Finland has no regulatory incentives or incentive mechanism to address losses while in France regulatory incentives only exists for theft at the distribution level. Explicit regulation of losses ex-ante can improve the performance of the grids by reducing network losses ex-post.



**Figure 3: T&D losses among some advanced economies**  
**Source: Adapted from MIT (2011)**

The above discussed set of indicators provides important insights on the performance of the electricity networks based on the quality of supply. However, these are ex-post indicators and their analysis is only useful after network failure and outages occur due to exceptional and normal events. In contrast, the primary objective of the European Commission (EC) is to design such energy policy measures that are conducive to minimizing the failures and power outages at a first place. This requires ex-ante risk assessment of the networks and designing appropriate prevention measures to counter these risks beforehand. In fact, such ex-ante risk analysis can be the first step towards creating a reliable, robust and resilient European grid. Hence, we apply the risk assessment matrix designed in Section 3 to assess the various risks that the electricity network currently faces in the UK and France as an example. Such matrix can be used to assess the network risks on other European countries lurching towards greater market liberalization and network interconnectedness.

#### 4.1 The UK Context

Economic risks to the networks are high in the UK due to lack of investment in new grid infrastructure and growth and variation in loads causing power quality risks. The topographical risks the UK network faces from severe weather conditions is moderately high. Likewise, the technical risks to the networks due to the adoption of new generation technologies and new technologies such as electric vehicles, smart grids can be considered to be weakly moderate. However, these risks are likely to increase in the future due to the wider adoption of new technologies and increased production of electricity from renewable energy sources. Similarly, UK is considered to face low network risks from terrorism and social riots currently. We assign a value to these risks based on a subjective assessment. The quantification of these risks is also supported by an earlier risk assessment study by Hammond and Waldron (2008).

Risks	Aspects	LOW (1-3)	MODERATE (4-7)	HIGH (8-10)
Economic	inadequate investments, demand factors			9
Technical	distributed generation, new technologies		4	
Topographical	weather, natural calamities		7	
Social	terrorism, political instability, civil unrest	3		

**Table 7: Risk assessment score for UK**

Therefore, overall networks risks for UK =  $(9+4+7+3)/4 = 5.75$

#### 4.2 The French Context

The modernization of the electricity networks remains a priority in France. Hence, the economic risks of under-investment are also high in France though not as high as in the UK. This is because the UK has one of the oldest grid infrastructures in Europe. Energy diversity is currently less of a concern in the French electricity supply system as the country relies on nuclear energy implying the dominance of one fuel, once technology and a small number of related designs (Bazilian and Roques, 2008). In such regards, the system is secure and robust to external political, technological and economic events although the system may be probe to generic technical faults. Hence, technical risk is low in France. The topographical risks from extreme weather can also be considered low in France. On the other hand, the risks of terrorist attacks on electricity networks can be high in France due to the heavy reliance on nuclear technology.

Risks	Aspects	LOW (1-3)	MODERATE (4-7)	HIGH (8-10)
Economic	inadequate investments, demand factors			8
Technical	distributed generation, new technologies	3		
Topographical	weather, natural calamities	3		
Social	terrorism, political instability, civil unrest		5	

**Table 8: Risk assessment score for France**

Therefore, overall network risks in France =  $(8+3+3+5)/4 = 3.8$

Does this imply that the French networks are more secure (reliable, robust and resilient) than the UK ones? The answer may be 'yes' considering the data on the minute lost per year, the number of interruptions and the T&D losses. Our network risks score also support the claim. However, a cross-country comparison becomes more authentic by reflecting country-specific characteristics into account. This can be done by ranking the country specific risks and assigning the weight accordingly in our case. Assuming that the first ranked risk is weighted 4, the second 3, the third 2 and last one 1, we obtain the following scores:

Weighted overall network risks for UK:

$$\{(4*9) + (3*7) + (2*4) + (1*3)\} / (4+3+2+1) = 6.8$$

Likewise, weighted overall network risks for France:

$$\{(4*8) + (3*5) + (2*5) + (1*5)\} / (4+3+2+1) = 6.2$$

The weighted score suggests that the French networks are relatively more secured than the UK networks by a small margin. Such an ex-ante risk assessment methodology can be an important starting point for policymakers in the face of uncertainty and scarcity of tools to assess security in networks. However, ex-ante risk assessment tends to rely on the availability of information while the survey methods can be costly as well. The accuracy of results is not guaranteed as some bias may exist. On the other hand, ex-post network security assessment (such as blackouts) can produce reasonable results with reasonable informational requirement. Nonetheless, the process can still be costly. It is also necessary that risk assessment should be done on a timely basis as risks are generally transient as market and conditions evolves. The risks tend to appear, disappear and reappear due to changes in market condition, technological developments and political environment as in the European context.

## 5. Conclusions

The quest for reliable, robust and resilient electricity networks remains a priority among the European Union members. The European networks are facing new risks in the face of rapid market liberalisation and growing market interconnections. As such, the paper does not consider market liberalisation and interconnections as sources of risk but rather a default conditions that the industry was destined to emerge through. The new risks are classified under economic risks, technical risks, topographical risks and social risks thereby allowing us to account for exceptional events in the European context. It also suggests that factors exogenous to the sector are creating new risks to the sector post 1990. We qualitatively and quantitatively analyse these risks using an ex-ante risk assessment methodology.

Our analysis suggests that economic risks of under-investment and rising electricity demand are one of the biggest risks facing the European electricity networks along with the risks of natural calamities and severe weather conditions. The transition towards smart grids and increasing digitalization of the grid imply new cyber security threats facing the European electricity networks. The protection of the networks against exceptional events and threats will require the adoption of sophisticated technologies and system design and planning which does not exist in many European grids. The obsolete system layout of power plants under centralised structures will require additional substation sites while the existing traditional tools of power delivery planning and engineering may not be effective in current problems of aged equipment, and modern deregulated loading levels. The high penetration of renewables in the grid will require detailed system planning coupled with accurate resource and load forecasting across Europe in the transition towards a low carbon economy.

Hence, the planning, engineering and operating system using concepts and methodologies that worked under vertically integrated market structure cannot be suitable under a deregulated and liberalised industry structure when most of the electricity networks remain vertically unbundled from the potentially competitive segments. More emphasis should be placed towards energy efficiency to manage the growing economic risks of increasing electricity demand in the European electricity markets. Our study also shows that an ex-ante risk assessment technique that takes country-specific risks into account can be a useful risk assessment tool to policymakers considering the uncertainty and paucity of risk assessment tools.

As electricity networks in Europe remain regulated natural monopolies, it is evident that the system relies on the regulatory framework in place to embrace the new risks from natural, accidental and malicious threats in the mechanism design and to stimulate innovation in power systems and electricity markets. Preventing against the risks arising from the integration of the different innovations such as smart grids, smart metering, electro mobility and storage is likely to be the hardest challenge for European regulators in the next future. Nonetheless, the coordination among network regulators of the EU countries is essential to prevent against the exceptional threats as these regulatory regimes have different priorities and focus. Hence, the future of the risks and threats facing the European electricity networks is vastly linked to the future of the network regulation in Europe.

## References

Armstrong, M., Cowan, S. and Vickers, J. (1994). *Regulatory Reform-Economic Analysis and UK Experience*, MIT Press, USA.

Averch, H. and Johnson, L.L. (1962). Behaviour of the firm under regulatory constraint, *American Economic Review*, Vol.52 (5), pp. 1052–1069.

Awerbuch, S. (2006). Portfolio based electricity generation planning: policy implications for renewable and energy security. *Mitigation and Adaptation Strategies for Global Change*, Vol. 11, pp. 693-710.

Bailek, J.W. (2004). Recent blackouts in the UK and Continental Europe: is liberalisation to blame? Cambridge Working Papers in economics, CWPE 0407/CMI Working Paper 34, Faculty of Economics, University of Cambridge.

Bazlilian, M. and O’Leary, F. (2006). Security of supply metrics. Energy Policy and Statistical Support Unit, Ireland.

Bazilian M. and Roque, F. (2008) eds. *Analytical Methods for Energy Diversity and Security: Analytical Approaches to Quantify and Value Fuel Mix Diversity*, Elsevier, the Netherlands.

BBC (2011). Scotland storm: Work to restore power to homes, British Broadcasting Corporation, London, December. Available at: <http://www.bbc.co.uk/news/uk-scotland-16102566>

Blyth, W. and Leferre, N. (2004). Energy security and climate change interactions, International Energy Agency (IEA), France.

Bompard, et al. (2011). Analysis of historic outages, Securing the European Electricity Supply Against Malicious and Accidental Threats (SESAME), Deliverable Number D1.1, Politecnico di Torino, Italy.

Brenan, V. (2009). *Natural disasters and public health: hurricanes Katrina, Rita, and Wilma*. Johns Hopkins University Press, Baltimore.

Brunekreeft, G. (2009). Regulation of network charges, in: Bausch, A. and Schwenker, B. (eds.), *Handbook of Utility Management*, pp. 435-456.

CEER (2008). Fourth benchmarking report on the quality of electricity supply, Council of European Energy Regulators, December, Brussels.

Chaniotis, D. (2011). Electricity Networks, European Network of Transmission System Operators (ENTSO-E), 30 March, Geneva.

Chopra, A., Kundra, V. and Weiser, P. (2011). A policy framework for the 21<sup>st</sup> century grid: Enabling Our Secure Energy Future, National science and technology Council, Executive Office of the President, Washington D.C, June.

Douglas, J (2005). Grid security in the 21<sup>st</sup> century, EPRIJ, Summer, pp. 26-33.

DECC (2009). Energy Markets Outlook, Department of Energy and Climate Change, London.

De Jong, J., Maters, H., Scheepers, M., and Seebregts, A (2007). EU standards for energy security of supply. ECN-E-07-004/CIEP.

ERGEG (2008). Treatment of losses by network operators: ERGEG Position Paper for Public Consultation, European Regulators Group for Gas and Electricity, July.

Eskeland, G.S. and Mideksa, T.K. (2010). Electricity demand in a changing climate, *Mitigation and Adaption Strategies for Climate Change*, Vol. 15(8), pp. 877-897.

European Commission (2000). Green Paper-Towards a European Strategy for Security of Energy Supply, Brussels.

European Commission (2009). Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC, Official Journal L 211 , pp. 0094 – 0136.

ENA (2011a). UK smart grid cyber security, Report, Energy Networks Association, June, London.

ENA (2011b). Energy networks climate change adaptation report, Engineering Report 1, Issue 1, Energy Networks Association, London.

ENEL (2011). Ente Nazionale per l'Energia e Lettrica, Rome, Italy. Available at: <http://www.enel.it/it-IT/>

ENISA (2012). Smart grid security, Annex II. Security of the Smart Grid, Deliverable-2012-04-25, European Network and Information Security Agency, April.

GENI (2011). National energy grid map index, Global Energy Network Initiative, San Diego, California.

Gini, C. (1912). Variabilita e mutabilita. *Studi Economics-Giuridici della R. Universita di Cagliari*, Vol. 3, pp. 3-159.

Grubb, M., Butler, L. and Twomey, P. (2006). Diversity and security in the UK electricity generation: the influence of low carbon objectives, *Energy Policy*, Vol. 34(18), pp. 4050-4062.

Hammond, G.P. and Waldron, R. (2008). Risk assessment of UK electricity supply in a rapidly evolving energy sector, Proc. IMechE Vol. 222 Part A: *Journal of Power and Energy*, pp. 623-641.

Hammond, G.P. and Winnett, A.B. (2006). Interdisciplinary perspectives on environmental appraisal and valuation techniques, *Proceedings of Institutions of Civil Engineers: Waste Manage*, Vol. 159(3), pp. 117-130.

Hill, M. (1973). Diversity and evenness: a unifying notation and its consequences. *Ecology*, Vol. 54, pp. 2.

Jamasb, T. and Pollitt, M. (2005). Electricity market reform in the European Union: review of progress toward liberalization and integration, *The Energy Journal*, Vol. 26, pp. 11-42.

Jamasb, T. and Pollitt, M. (2007). Incentive regulation of electricity distribution networks: lessons of experience from Britain, *Energy Policy*, Vol. 35(12), pp. 6163-6187.

Jamasb, T. and Pollit, M. (2008). Security of supply and regulation of energy networks, *Energy Policy*, Vol. 36, pp. 4584-4589.

Jamasb, T., Orea, L. and Pollitt, M. (2012). Estimating marginal cost of quality improvements: the case of electricity distribution companies, *Energy Economics*, Vol. 34 (5), pp. 1498-1506.

JESS (2004). Fifth report, Joint security of supply working group, November, Department of Trade and Industry, London.

JESS (2006). Long-Term security of energy supply-December 2006 Report. Joint Security of Supply Working Group, Department of Trade and industry, London.

Joskow, P. (2008). Incentive regulation in theory and practice: electricity distribution and transmission networks. In Rose, N. (Ed.), *Economic Regulation and its Reform: what have we learned?* University of Chicago Press.

Joskow, P. and Tirole, J. (2005). Merchant transmission investment, *Journal of Industrial Economics*, Vol. 53(2), pp. 233-264.

Junge, K. (1994). Diversity of ideas about diversity measurement, *Scandinavian Journal of Psychology*, Vol. 35, pp. 16-26.

Keller, K. and Franken, B.F.C. (2006). Quality of supply and market regulation, survey within Europe, KEMA Consulting, December, the Netherlands.

Khadem, S.K., Basu, M. and Conlon, M.F. (2010). Power quality in grid connected renewable energy systems: role of custom power devices, International Conference on Renewable Energies and Power Quality, 23-25 March, Granada, Spain.

Le Coq, C and Paltseva, E. (2009). Measuring the security of external energy supply in the European Union, *Energy Policy*, Vol. 37, pp. 4474-7781.

Lesbirel, S.H. (2004). Diversification and energy security risks; the Japanese case, *Japanese Journal of Political Science*, pp. 5-1.

Loschel, A., Moslener, U. and Rubbelke, D. T.G (2010). Indicators of energy security in industrialised countries, *Energy Policy*, Vol. 38, pp. 1665-1671.

MacArthur, R. (1965). Patterns of species diversity, *Biological Review*, Vol. 40, pp. 510-533.

MIT (2011). The future of electric grid, MIT Energy Initiative, Massachusetts Institute of Technology, MIT Press, Cambridge, USA.

NERC (2010). High-impact, low - frequency event risk to the North American bulk power system, North American Electricity Reliability Corporation, June, United States.

Newbery, D. (1999). Privatisation, restructuring and regulation of network utilities, MIT Press, Cambridge, MA.

POST (2004), Terrorist attacks on nuclear facilities, Parliamentary Office of Science and Technology, Potstone no. 222, London.

Pileou, E. (1969). An Introduction to Mathematical Ecology. Wiley, New York.

Pollit, M. and Bialek, J.W. (2008). Electricity network investment and regulation for a low carbon future. In *Delivering a Low Carbon Electricity System Technologies, Economics and Policy*. Grubb, M., Jamasb, T. and Pollitt, M. G. Cambridge: Cambridge University Press.

PSERC (2010). Challenges in integrating renewable technologies into an electric power system, Power Systems Engineering Research Center, White Paper, April.

Rankin, J. (2010). Driving up demand for electricity, Europeanvoice.com. Available at: <http://www.europeanvoice.com/article/imported/driving-up-demand-for-electricity/68017.aspx>.

Roller, L.H., Delgado, J., Friederiszick, H.W. (2007). Energy: choices for Europe, Bruegel Blueprint Series.

Roques, F. (2003). Security of electricity supplies, UK Parliamentary Office of Science and Technology Report and Postnote 203, September.

Rouse, G. and Kelly, J. (2011). Electricity reliability: problems, progress and policy situations, February, Galvin Energy Initiative (GEI), US.

Runnegar, B. (1987). Rates and modes of evolution in the Mollusca. In Campbell, M. and May, R. (Eds), Rates of Evolution. London: Allen and Unwin.

Ruska, M. and Simila, L. (2011). Electricity markets in Europe: business environment for smart grids, VTT Research notes 2590.

Saplacan, R. (2008). Competition in electricity distribution, *Utilities Policy*, Vol. 16(4), pp. 231-237.

SESAME (2011). Analysis of historic outages, Securing the European Electricity Supply Against Malicious and Accidental Threats (SESAME), Deliverable Number D1.1, Politecnico di Torino, Italy.

Shannon, C. and Weaver, W. (1962). The mathematical theory of communication, Urbana, IL: University of Illinois Press.

Simpson, E. (1949). Measurement of diversity. *Nature*, Vol. 163. pp.41-48.

Skoczkowski, T. (2007). Energy efficiency policy in the European Union, Leonardo Energy: The Global Community for sustainable energy professionals. Available at: <http://www.leonardo-energy.org/>

Solow, A. and Polasky, S. (1994). Measuring biological diversity, *Environmental and Ecological Statistics*, vol. 1, pp. 95-107.

Stirling, A. (1994). Diversity and ignorance in electricity supply investment: addressing the solution rather than the problem, *Energy Policy*, Vol.22, pp. 195-216.

Stirling, A. (1998). On the economics and analysis of diversity, SPRU Electronic Working Paper 28, October, University of Sussex.

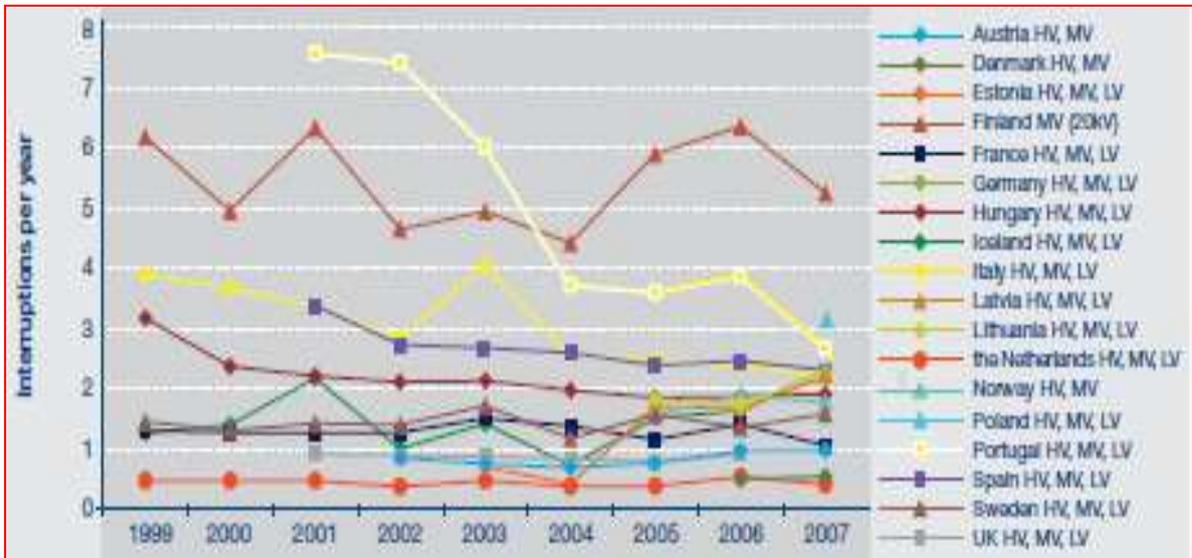
Stirling, A. (2007). A general framework for analysing diversity in science, technology and society, *Journal of the Royal Society Interface*, Vol. 4(15), pp. 707-719.

- Striling, A. (2008). Framing, lock-in and diversity in social choice of energy futures. In Dorfman, P. (Ed.), *Nuclear Consultation: Public Trust in Government*. Coventry: Nuclear Consulting Working Group, University of Warwick.
- Ter-Martirosyan, A. (2003). The effects of incentive regulation on quality of service in electricity markets, Working paper, George Washington University.
- Thomas S. and Hall D. (2003). Blackouts: Do liberalisation and privatisation increase the risk? Public Services International research Unit (PSIRU), University of Greenwich, London.
- Tritschler, M. and Mackay, W. (2011). UK smart grid cyber security, Energy Networks Association, London, June.
- Turton, H and Barreto, L. (2006). Long-term security of energy supply and climate change. *Energy Policy*, Vol. (34), pp. 2232–2250.
- Vogelsang, I. (2002). Incentive regulation and competition in public utility markets: a 20-year perspective, *Journal of Regulatory Economics*, Vol. 22(1), pp. 5-27.
- Wietzman, M. (1992). On diversity, *Quarterly Journal of Economics*, Vol. (107), pp. 363-405.
- Willis, H. L., Welch, G. V., and Schrieber, R. R. (2001). Aging power delivery infrastructures. Marcel Dekker, Inc., New York.
- Winzer, C. (2021). Conceptualizing energy security, *Energy Policy*, Vol. 40, July, pp. 36-48.
- Yu, W. and Pollitt, M. (2009). Does liberalisation cause more electricity blackouts? evidence from global study of newspaper reports, Cambridge Working Papers in economics 0911/ EPRG Working Paper 0902, University of Cambridge.
- Zimmerman, R. and Faris, C. (2010). Infrastructure impacts and adaptation challenges, *Annals of New York Academy of Sciences*, 1196(2010), pp. 63-85.

**Appendix:**

<b>Causes of outages</b>	<b>Impact Percentage</b>
Major events	80.6%
Trees	5.6%
Distribution equipment failures	4.0%
Other	2.6%
Planned interruptions	1.3%
Acts of public	1.2%
Weather related	1.1%
Transmission outages	1.1%
Lightning	1.1%
Substation outages	0.9%
Animals	0.5%
Generation Outages	0.0%

**Table A: Causes and percentage of outages in the US**  
**Source: Adapted from (Rouse and Kelly, 2011)**



**Figure A: Number of unplanned Interruption including all events (interruptions per year)**  
**Source: Adapted from CEER (2008)**