POLITECNICO DI TORINO

ENERGY DEPARTMENT

DOCTORAL SCHOOL

Doctorate in Electrical Engineering – XXVIII CYCLE

Thesis title:

ELECTRICITY SECURITY: MODELS AND METHODS FOR SUPPORTING THE POLICY DECISION MAKING IN THE EUROPEAN UNION

Supervisors	**PhD Candidate**
Prof. Francesco Profumo, Prof. Ettore Bompard	Ing. Gianluca Fulli

April 2016

FOREWORD AND DISCLAIMER

This doctoral research was carried out in the context of the cooperation between Politecnico di Torino and the European Commission's Joint Research Centre, Institute for Energy and Transport.

"The universal utilization of water power and its long-distance transmission will supply every household with cheap power and will dispense with the necessity of burning fuel.
The struggle for existence being lessened, there should be development along ideal rather than material lines."

Nikola Tesla, electrical engineer and futurist

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

Firstly I want to thank my PhD supervisors at Politecnico di Torino, Prof. Francesco Profumo and Prof. Ettore Bompard, for their scientific support, their incessant encouragement and their patience. Secondly but not less important, I am particularly grateful to the JRC-IET Director Dr. Giovanni De Santi and my Head of Unit Mr. Marcelo Masera for their scientific advice and for having continuously fostered my professional and educational development in the power system area, which is indeed a central topic of this doctoral research.

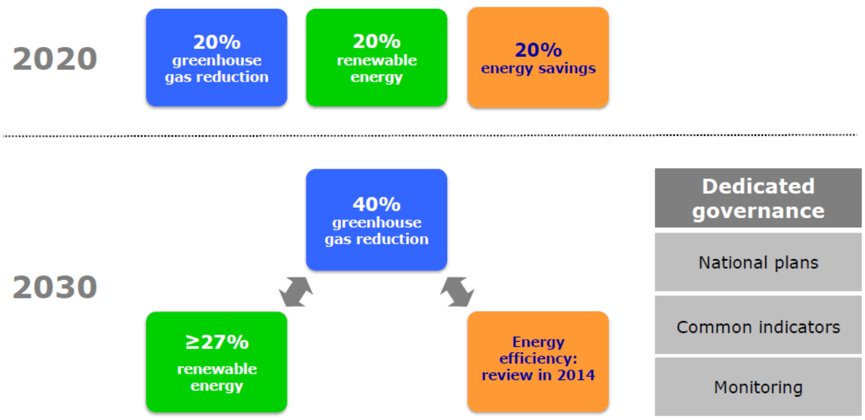
I wish also to thank the knowledgeable members of my defence committee, Prof. Gianfranco Chicco (Politecnico di Torino), Prof. Nouredine Hadjsaid (Grenoble INP Institute of Technology), Prof. Giuseppe Parise (Università La Sapienza), for their participation and valuable comments. Furthermore, I am highly indebted to Dr. Tao Huang (PoliTO), Dr. Felix-Catalin Covrig (JRC), Dr. Mircea Ardelean (JRC), Dr. Angelo L'Abbate (RSE), Dr. Carlo Brancucci (NREL) and Dr. Francesco Gracceva (ENEA) for their contributions and critical reviews.

Several other colleagues at DG JRC and DG ENER, directly and indirectly, helped me greatly at different stages of drafting this work: Dr. Ricardo Bolado, Dr. Burcin Cakir, Dr. Stamatios Chondrogiannis, Dr. Tilemahos Efthimiadis, Ms. Anna Kostecka, Dr. Fabio Monforti-Ferrario, Dr. Marta Poncela Blanco, Dr. Pavel Praks, Dr. Giuseppe Prettico, Dr. Arturs Purvins, Ms. Amanda Spisto, Dr. Matti Supponen.

Several Professors, assistants and staff members at Politecnico di Torino, including Prof. Mario Chiampi, Prof. Alberto Tenconi, Prof. Maurizio Repetto, Prof. Enrico Carpaneto, Prof. Evasio Lavagno, Prof. Radu Iustin Bojoi, Dr. Enrico Pons, Dr. Abouzar Estebsari, Mr. Ren Jian Pi, Ms. Mariapia Martino, as well as several other staff members at the Energy department and the SCUDO secretariat, deserve my gratitude for having promoted and supported my PhD research.

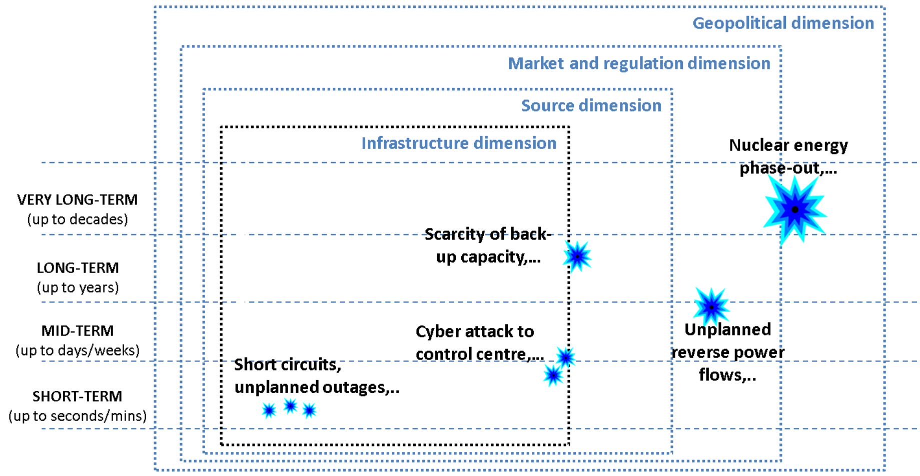
Last, I really want to thank my family for having assisted and indeed borne me during these interesting though challenging times (…often: nights) of doctoral studies. You are the smile in my life.

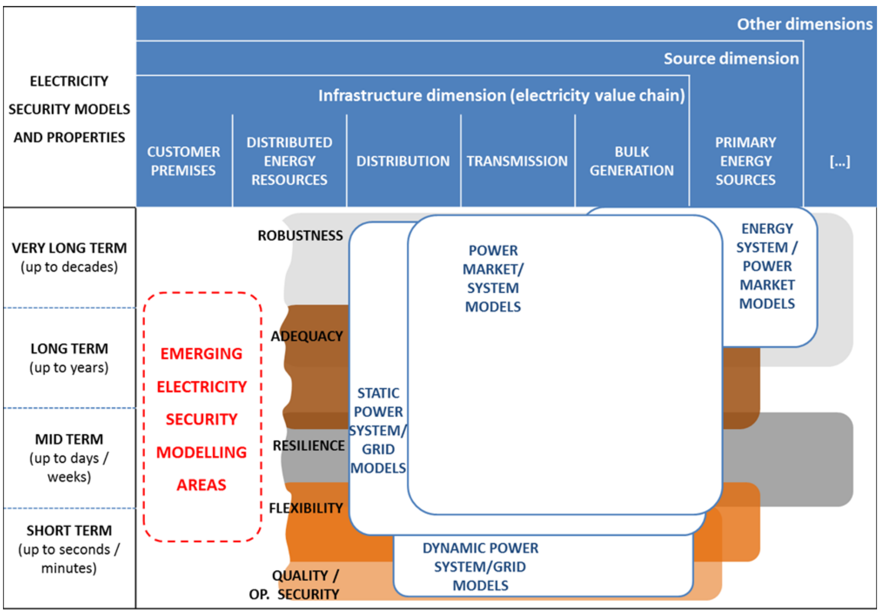
VISUAL ABSTRACT



The EU energy system experiences unprecedented trends and challenges in correlation with internal energy and climate change policies and geopolitical dynamics

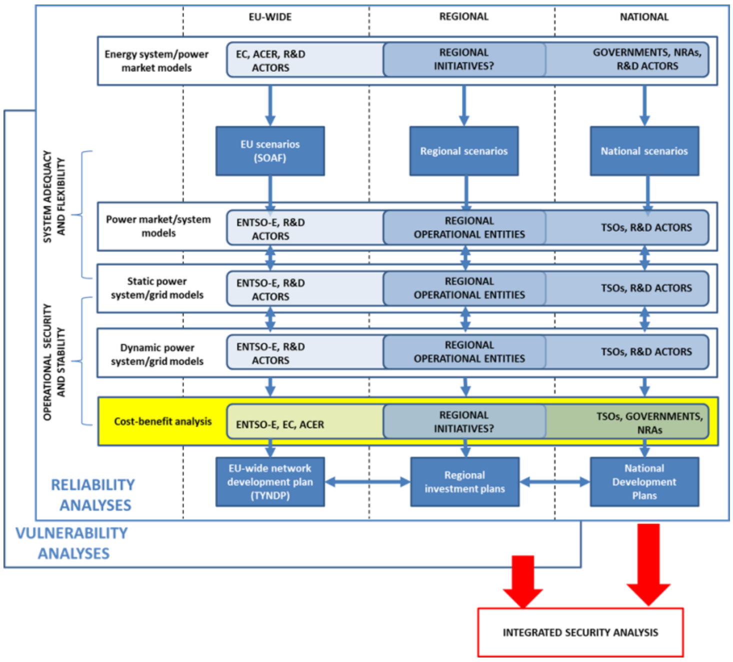
Within the energy system, the power system faces several security threats - natural, accidental, malicious, as well as linked with emerging low-carbon systemic changes

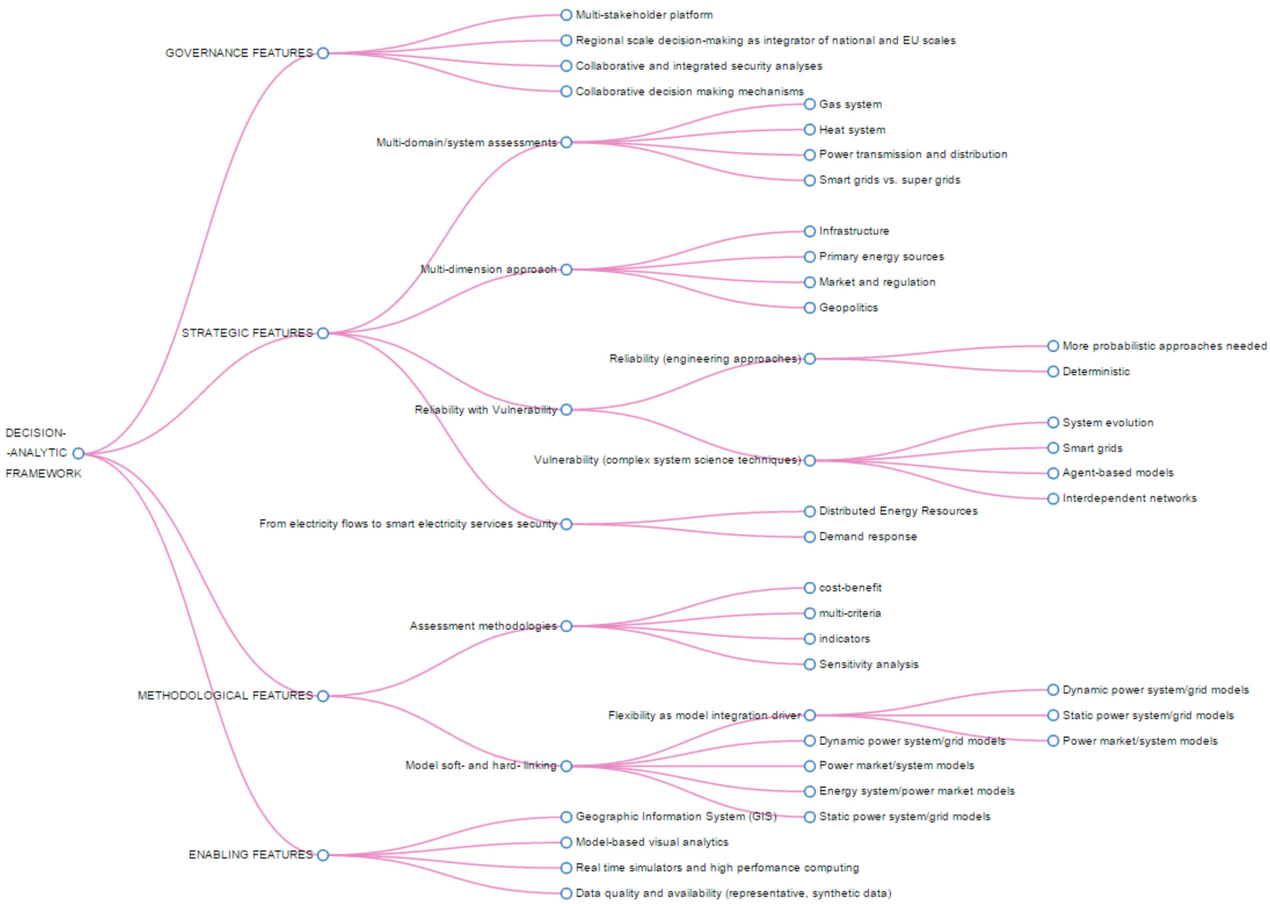


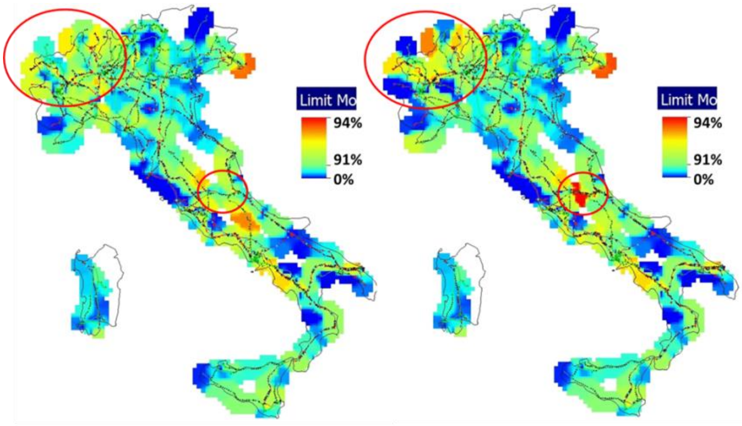


A taxonomy between science and policy is derived for electricity security properties, and electricity security models and approaches are critically reviewed and contrasted

A novel conceptual framework for electricity security analyses - encompassing multiple actors, dimensions and models - is afterward proposed and contextualised in the Energy Union's initiatives



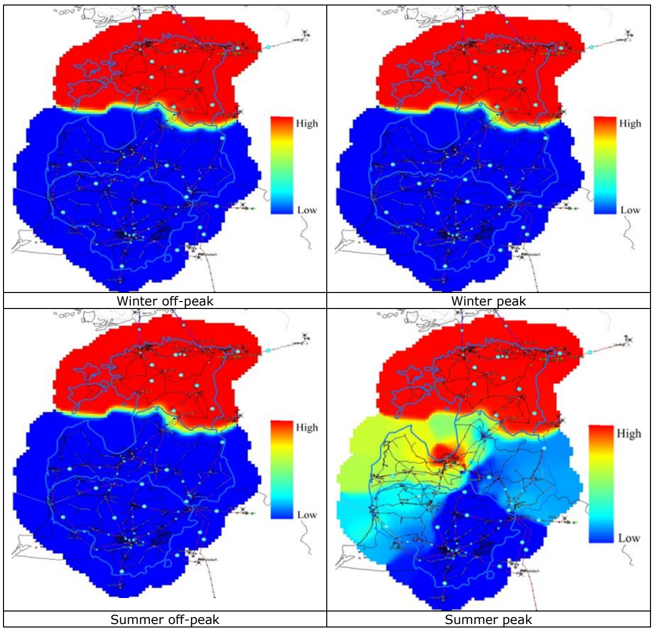


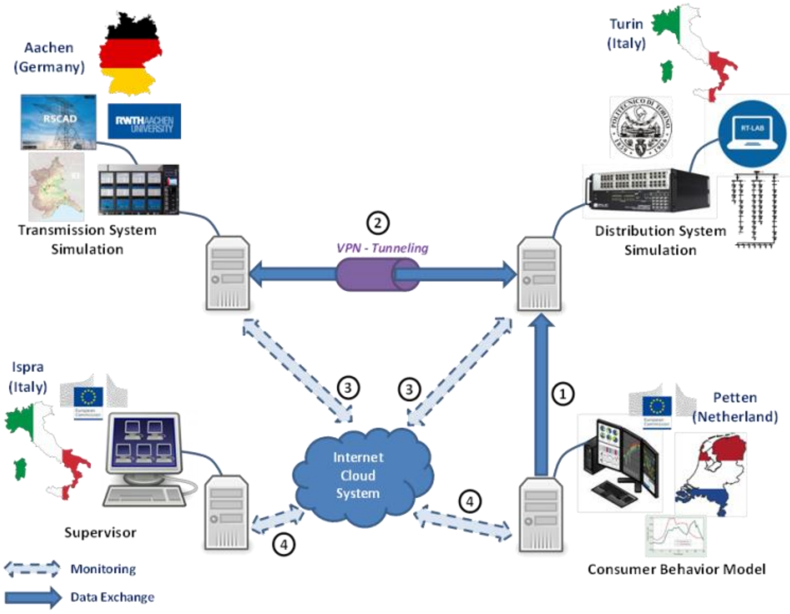


a) before line tripping b) after line tripping

Within the conceptual framework, first an operational security analysis on the Italian transmission grid vulnerability (fully georeferenced model) is presented

Then an integrated adequacy and operational security analysis for the Baltic power system is illustrated, highlighting links with the geopolitical context and the policy decision making process





Finally a proof-of-concept for a multi-actor, real-time simulation platform to perform integrated security analyses is shown and discussed

EXECUTIVE SUMMARY

Energy is crucial for the mankind and is central to nearly every major European and world's challenge, be it related to security, climate change, food, welfare or employment. Energy must be provided when and where individuals and societies require it, in the amount needed and according to certain minimum criteria and standards. Failing to do so would result in serious hazards to the European society and economy.

For these reasons, energy security - which regards the capability to deliver energy to the users - represents a crucial concern for policy decision making at all geographical levels.

The European Union (EU), with an estimated 1,626 Mtoe gross inland consumption, is the fourth world's more energy consuming region, after China (3,036 Mtoe), the United States (2,188 Mtoe) and Asia (without China) (1,655 Mtoe). However, differently from the other world economies, the EU largely relies on foreign energy production: over the last decade, roundabout half of EU's energy needs were covered by imports, bringing the EU energy import bill to the daunting amount of 400 b€/year. The energy price gap between the EU and major economic partners has widened and electricity and gas prices have been rising especially for households.

Against this background, the EU conceived and is implementing energy policies driven by three overarching objectives: energy security, energy competiveness or affordability, energy sustainability.

Looking at the key energy policy action areas and initiatives put in place by the EU, one can note how energy security occupies a prominent place in several of them:

- The EU's Energy Union strategy is made up of five mutually reinforcing dimensions: Supply security (based on: energy diversification and more efficient use); Energy market integration (via better use/faster build-up of energy interconnectors and better alignment of wholesale and retail markets); Energy efficiency; Emissions reduction; Research and innovation.
- The proposal for a European Energy Security Strategy includes short and long-term energy security measures targeting critical energy infrastructure.
- The EU internal energy market is expected to be integrated and resilient.
- The promotion of energy efficiency and domestic energy production (including from renewable energy sources), would foster the reduction of energy import dependency.

To pursue the above introduced policy objectives within a coherent long-term strategy, the EU has agreed specific 2020-2030 targets and proposed a roadmap for 2050:

- 2020. The EU is not far from reaching its 20-20-20 targets, namely reducing its greenhouse gas emissions by 20% below 1990 levels, increasing the renewable share in energy consumption to 20%, and achieving energy savings of 20%. Additionally, a 10% electricity interconnection capacity by 2020 was agreed by the EU (with a few Member States not having reached it yet).
- 2030. The EU aims to reduce its domestic greenhouse gas emissions by at least 40%, to raise the renewable share in energy consumption to at least 27% and to improve energy efficiency of at least 27%. Furthermore, a new target for a 15% electricity interconnection capacity by 2030 was put forward by the European Commission.

- 2050. The EU aims to achieve an 80% reduction in greenhouse gasses compared to 1990 levels by 2050. The Energy Roadmap 2050 analyses scenarios to meet this target. Most of the decarbonisation scenarios anticipate RES might cover at least 55% of gross final energy consumption in 2050.

Over €1 trillion needs to be invested into the EU energy sector by 2020 alone, with €400 billion (thus equalling the yearly EU energy import bill) allocated to electricity and gas distribution grids and €200 billion for electricity transmission grids and gas pipelines.

In this context, more and more shares of EU's energy are expected to be converted into electricity, particularly in the transport, heating and services demand sectors. Depending on the scenarios, the electricity in the EU's final energy consumptions - which roughly represented one fifth in 2012 - is anticipated to grow from one fourth in 2030 to one third or above in 2050. Furthermore, the target of a 20% share of renewable energy in final EU energy consumption corresponds to a 35% share of renewable energy sources in electricity consumption by 2020 (compared with just 21% in 2010), whereas the 27% RES target by 2030 corresponds to some 50% RES share covering electricity consumption in 2030.

The EU energy and electricity systems record an evolution - generally defined as transition - especially source-wise (RES increase), infrastructure-wise (smart grid, super grid), and market-wise (different models/schemes and incentives). The future electricity system is expected to include both local smart distribution grids (characterised by numerous independent participants like prosumers, retailers, distributed generators, energy storage, electric vehicles as well as technologies still to be conceived) and transnational super grids (e.g. networks connecting large-scale time-varying renewable sources to national power grids and markets). One of the main characteristics of these interacting and integrated systems is the bidirectional communication and power exchange between suppliers and consumers/prosumers, from households to small and medium sized enterprises, as well as larger companies. The grid modernisation will demand and enable new market structures, new services, and new social processes.

Against this background, the following research question was formulated:

Given the strategic role of electricity and considering the multitude of threats electricity delivery faces in the European Union's socio-economic and the global geo-political context, how shall power system modelling and assessment methodologies evolve to adequately support the policy decision making on electricity security at EU, regional and national scale?

The research question was broken down in the following sub-questions:

1. How shall electricity security properties be defined in the current socio-political, economic and energy transition context?
2. What models and methodologies are currently available and/or deployed to assess electricity security levels in Europe and worldwide?
3. What strengths, weaknesses and synergies can be identified in the scientific and technical analyses in support of the electricity security policy decision making at national, regional and EU level?
4. What modelling, methodological and stakeholder-interaction features should be introduced to improve the policy decision making on electricity security in the European Union?

The research carried out to address the identified sub-questions is described in the following. In this work, we generally: discuss modelling and methodological features relevant to electricity security analysis, hence

not scrutinising aspects specifically linked to e.g. market and/or sustainability analyses; focus on the bulk power system security aspects, thus analysing transmission (more than distribution) system issues.

1. How shall electricity security properties be defined in the current socio-political, economic and energy transition context?

To address the first research sub-question, an intense literature review - at the cross-roads of science and policy making - was carried out to come up with a revised taxonomy for electricity security, based upon a reasoned combination of the relevant EU legislative and regulatory references and the EU and international scientific/technical sources.

Energy can be indeed considered from two different viewpoints, one more linked to the priorities set out by the policy making (e.g. long-run energy availability, energy cost-effectiveness and affordability, and desired quality and security levels) and the other one more associated to the intrinsic techno-economic features of the energy system and energy delivery (like flexibility, stability, resilience etc), instrumental to achieving the aforementioned objectives.

The threats potentially affecting electricity security can be characterised in terms of impact areas, time duration, internal or external provenance, intrinsic nature (natural, accidental, malicious and systemic).

Four overall dimensions of electricity security were identified, which can be visualised as the physical or virtual corridors across which the electricity commodity/service has to travel to reach the users:

- In the **infrastructure dimension**, electricity security is assessed in terms of the power system (i.e. the electricity value chain) capability to supply end users with minimum service standards/criteria.
- In the **source dimension**, electricity security is assessed in terms of the energy system capability to ensure the accessibility, in the various timeframes, to primary sources to be converted in the power plants to meet the required total demand of electricity.
- In the **regulation and market dimension**, electricity security is assessed in terms of the power system and market capability to adequately fulfil their electricity delivery mission with a set of laws, rules, market arrangements and price schemes.
- In the **geopolitical dimension**, electricity security is assessed in terms of the energy/power system capability to assure the availability of primary sources and/or cross-border electricity exchanges in case of economic or geopolitical constraints/stresses (e.g. unilateral primary energy cut by international players outside the considered region).

Electricity security was defined as the power system's capability to withstand disturbances - i.e. events or incidents producing abnormal system conditions -, or contingencies - i.e. failures or outages of system components - with minimum acceptable service disruption.

Electricity security was then characterised, with reference to its inherent features, via the following five properties:

- **Operational security** is the ability of the power system to maintain or to regain an acceptable state of operational condition after disturbances. It covers dynamic issues and real-time network management issues.

- **Flexibility** is the capability of the power system to cope with the short/mid-term variability of generation (like renewable energy) and demand so that the system is kept in balance.
- **Adequacy** is the ability of the power system to supply the aggregate electrical demand at all times under normal operating conditions. It generally includes: generation/storage adequacy, transmission network/import adequacy, distribution network and the end user adequacy (demand response), market adequacy.
- **Resilience** is the mid-term capability of the power system to absorb the effects of a disruption and recover a certain performance level.
- **Robustness** is the long-term capability of the power system to cope with constraints/stresses originating outside the infrastructure dimension.

The term reliability - referring to how the power system should work - was adopted to combine the operational security, flexibility and adequacy properties, whereas the term vulnerability - referring to how the power system might fail - was used to indicate the absence of robustness and resilience.

2. What models and methodologies are currently available and/or deployed to assess electricity security levels in Europe and worldwide?

To address the second research sub-question, a further dedicated literature review was conducted to classify the electricity security models and assessment methodologies and map them to the electricity security properties previously introduced.

For the purposes of our research, we first clustered the models, primarily according to the domains of the electricity value chain they target, into:

- **Dynamic power system/grid models**. They provide a detailed short-term description of the power system, grid and protection components. They mainly target the infrastructure dimension of electricity security, i.e. they model as endogenous factors and variables included in the electricity value chain. The typical time horizon is up to seconds (minutes) and the time steps are in the order of milliseconds or even microseconds. The dynamic power system/grid models necessarily embed a static model of the power system/grid.
- **Static power system/grid models**. They offer detailed representations of the power grid (component by component). The static power system/grid models mainly target as endogenous the infrastructure-related electricity security dimension (some elements of the primary energy sources dimension might be included). The typical time horizon is one or several years. The time steps largely vary depending on the very different models within this cluster (power flow, topological, graph-based, etc): they might not even be specified (when studying system snapshots or topological features) or they could typically be hours or fractions of hours.
- **The power market/system models** generally represent the demand-supply equilibrium, and might use simplified assumptions for describing the grid ("single node" or more detailed representations). They mainly consider as endogenous factors within the infrastructure and the primary energy source dimensions of electricity security, as well as some aspects of the market and regulation dimension. The typical time horizon is up to one year (or several years) and the typical time steps are hours/weeks (or weeks/months).

- **The energy system/power market models** represent the whole energy system and selected portions of the power system/market. They target the source and the market and regulation dimensions of electricity security (the latter, as well as the geopolitical dimension, may be exogenous to the model). The typical time horizon is up to years or decades and the typical time steps (named also time slices) are weeks/months (i.e. a few tens per year).

Afterward, electricity security assessment approaches - tackling operational security, flexibility, adequacy, resilience and robustness - were assessed and mapped to the model clusters. Mirroring the definitions and grouping of the electricity security properties, two main electricity security assessment approaches were identified:

- **Reliability approaches** (addressing operational security, flexibility and adequacy), focusing on the ability of the system to perform its intended function.
- **Vulnerability approaches** (addressing the lack of resilience and robustness), focusing on the inability of the system to withstand strains and on the effects of the consequent failures.

Solutions for **integrated analyses**, like those based upon cost-benefit analyses, multi-criteria analyses and indicators, were also analysed.

3. What strengths, weaknesses and synergies can be identified in the scientific and technical analyses in support of the electricity security policy decision making at national, regional and EU level?

To address the third research sub-question, results obtained from the previous research tasks - i.e. about reviewing definitions, models and methodologies - were matched, having in mind that the provision of electricity depends on the decisions of various players (policy decision makers, regulators and their associations, system operators and their associations, etc.) in different fields (economic, technical, strategic, etc.) at multiple time and spatial scales:

- At **national level,** the main electricity security actors are the TSOs, partly flanked by governmental/regulatory bodies. The TSOs have very detailed and complete dynamic and static models of the national transmission system under their responsibility and they are considered as the official owners of the related datasets. The further electricity modelling moves from grids towards market/energy systems, the larger the number of actors, including market operators, having a stake (in terms of data ownership) and playing a role (in terms of assessment perspectives). Electricity security models are used for supporting decision making across all the electricity security actions - operation, operational planning and scheduling, system planning, strategic energy planning. R&D actors frequently contribute to electricity security analyses and propose methodological improvements but they lack reliable data for their models. The whole range of electricity security analyses is conducted, both on reliability (operational security, flexibility, adequacy) aspects and vulnerability (resilience and robustness) aspects. Electricity models, from the time frame viewpoint, tend to be more and more combined or at least soft linked; probabilistic approaches (vs deterministic ones) are increasingly used - but their results are not necessarily embedded in the decision making process - for reliability analyses, whereas vulnerability analyses rely upon the most diversified (not always sophisticated) approaches. Areas for improvement at national scale include: following the best practices (e.g. UK) for model interlinking, including domains/subsystems/systems like: the electricity distribution grid, the gas system, the heat system etc; encouraging utilities to fully incorporate innovative approaches - as e.g.

those based on advanced probabilistic/complex system techniques, generally proposed by the R&D community -, in the decision making process.

- At **regional (cross-national) level,** there are emerging actors - even though not fully formalised yet - performing electricity security analyses: particularly CORESO, the Pentalateral Energy Forum and other nascent regional operational initiatives. R&D actors are less active than at national and EU level as the regional scale represents a rather recent EU development. Electricity models are quite detailed and (compared to the national scale) better capture the cross-border aspects of the region under study. The electricity security models are used for supporting some of the electricity security actions: the focus is more on operational planning and scheduling actions and system planning actions (since operational actions and strategic energy planning actions are beyond the current remit of these regional bodies). As for the electricity security analyses, operational security, flexibility and adequacy analyses seem to have priority on resilience and robustness analyses. Time-wise, selected electricity security models are better linked and probabilistic approaches (vs deterministic ones) begin to be used for reliability analyses. Areas for improvement at regional scale include: better defining roles and responsibilities of the actors (so that the even accurate and innovative analyses can be used to support the decision making process), expanding security analyses in the vulnerability area and in modelling the interfaces with other energy systems.
- At **EU level**, the main actors are ENTSO-E, ACER and the European Commission. ENTSO-E is tasked to perform EU-wide analysis and coordinate national/regional studies. ENTSO-E is progressing well in combining primarily static power system/grid models with power market/system models. Like explained above for the regional scale, the electricity security models are used for supporting decision making (especially) on operational planning and scheduling actions and system planning actions, (rather than) operational actions and strategic energy planning actions. In the scientific area, several R&D (FP7/H2020) projects are producing advanced models however with partially reliable datasets (if no formal agreement with the TSOs/ENTSO-E is in place). Probabilistic approaches (vs deterministic ones) begin to be proposed in the reliability assessment area, particularly for power system adequacy and flexibility. At this level, the visibility/observability of dynamics/issues occurring at regional/local level is however limited. Areas for improvement at EU level include a deeper assessment of issues occurring at the transmission-distribution interface, whereas first trials for interlinking gas and electricity models are ongoing, streamlining the modelling interactions and the assessment processes between the EU-wide and the regional scale, advancing the dynamic representation of the whole transmission system (e.g. via real-time simulation), targeting the emerging smart/super electricity systems challenges and tensions.

Additionally, a crucial, overarching issue regards the interaction between science and policy in the electricity security sphere. As seen, specific electricity security models and analysis are pervasively embedded in the decision making process of power system industry, particularly in the operational and planning phases. The same, despite society heavily depends on electricity service provision, does not generally hold for the connections between scientific/technical electricity security analysis and the policy decision making process. There are several reasons for this disconnection: the political and scientific/engineering communities speak different languages; policy making is a mixture of politics, facts and values, whereas science primarily contributes to one of these, namely facts; technical results are often too complex to interpret and grasp, etc. However, as a paradox, even if politicians' risk aversion can be generally considered high, not being aware or informed of the security implications of some policy decision may lead to security of supply deterioration rather than safeguard.

4. What modelling, methodological and stakeholder-interaction features should be introduced to improve the decision making on electricity security in the European Union?

To address the fourth and final research sub-question, a novel decision-analytic framework was defined featuring the following elements and recommendations grouped in four macro-categories:

GOVERNANCE FEATURES

- **Multi-stakeholder platforms**, with proper governance and structured interaction mechanisms, should be further developed at all spatial scales - **national, regional and pan-European -** to perform joint assessments and carry out harmonised actions in the electricity security field.
- The **regional scale of decision making** should be fostered and streamlined. In the current geopolitical context, the regional scale appears as a strategic playing field where identifying synergies and reaching compromises between the EU and the Member States energy policy orientations. The current regional pilots offer valuable experience and lessons learned; still, harmonising the geographical/physical boundaries of the regions, considering the wealth and the variable geometry of the initiatives currently in place, is a prerequisite.
- Truly **collaborative and integrated security analyses** - again at wider geographical scale (than the traditional national one) **-** should be used to combine different aspects of security and include as many electricity security properties as feasible. They should take into account the different perspectives/interests of the electricity system stakeholders. By using a common framework and consistent evaluation methodologies, stakeholders can better compare studies and strategies and they can make the results understandable and replicable. Additionally, given the interdependence of the main energy policy objectives - security, affordability and sustainability - these integrated security analyses, even if focused on electricity security, should be framed in a wider energy and economic context.
- **Cooperative decision making mechanisms**, steering the coordinated implementation of concerted actions stemming from the integrated security analyses, should be established. This would improve the overall electricity security performances, thanks to the stronger synergies and complementarities of balancing resources ranging from interconnectors, conventional/renewable generation capacity, storage and demand response. Even if the best spatial scale would be the EU-wide or continental one, since addressing security issues does not just entail solving technical problems but also letting several actors and decision makers interact effectively, it may turn out as more feasible - and less complex - to implement regional (cross-national) electricity security analyses-actions, also considering the evolving EU policy framework.

STRATEGIC FEATURES

- **All the electricity security dimensions** should be covered by the security assessment approaches: **infrastructure, sources, market and regulation, and geopolitics.** The electricity security assessment methodologies should be able to better observe and interpret the interactions of the electricity value chain system with the wider energy system and all the other surrounding dimensions.

- **Smart/super grid and multi-energy carrier systems assessments should be intensified**. Given the growing interdependences within the electricity domains (e.g. transmission and distribution) and between different energy systems (gas, heat, etc), electricity security aspects related to these interdependencies shall be studied. The modelling efforts in emerging areas - like distributed energy resources, end user's demand response - shall be boosted with the aim to integrate these aspects in wider national/regional models. On the same note, the modelling efforts and the electricity security analysis on super grids shall be interlinked with the modelling efforts on smart grids since major tensions are expected to develop at the interface between these emerging transmission and distribution systems.
- **Electricity security analyses should move from assessing flow security to assessing services security**. Smart grids promise to radically change the way power system is operated, designed and planned. Studying security of supply of smart grids is not only about interlinking transmission and distribution, but changing the prospective from electricity supply to electricity services. This shift could help identifying different means and pathways to achieve/safeguard security and identify different opportunities throughout the supply chain (e.g. linked to demand response).
- Emerging **vulnerability assessment** approaches - which observe how the system might fail and are increasingly **based on complex network science** - should be promoted, also at the regional scale, to complement reliability assessment approaches - which instead focus more on how the system should work. As a matter of fact, vulnerability analyses could systematically explore the effects of failures and stresses in order to identify system weaknesses that may be exploited by, perhaps unknown, threats or hazards.
- Since both **complex network and engineering approaches** have their distinguishing features and might be instrumental to assessing different aspects of electricity security, a **deeper interplay** between the two disciplines is recommended. Some of the most promising areas where complexity concepts applied to power systems have potential for developing sound scientific evidence are: power system evolution scenarios, smart grids, agent-based modelling and interdependent networks.

METHODOLOGICAL FEATURES

- Policy makers and other stakeholders should propose and agree upon **common definitions** of crucial electricity security properties - particularly: **flexibility, resilience and robustness** - which (differently from other attributes like operational security and adequacy) are not consented at the EU level.
- **Cost-benefit analyses** should be preferred **to multi-criteria analyses** whenever viable. As all energy systems deliver some level of security, the primary objective for supply security policy is to strike the balance between the costs of improving security and the benefits from it. One of the main ambitions of the decision maker is to monetise and assess every aspect through cost-benefit analysis. However this approach can hardly be used when there is no thorough knowledge of the features (e.g. magnitude and probability) of the security threat, the outcome of the impact (e.g. severity) and options for a prevention policy. If this information is not available other methods may be used, such as indices or multi-criteria analyses, to support decision making under uncertainty. Multi-criteria analysis can be used to analyse both qualitative and quantitative aspects. If only quantitative data is evaluated, the ranking weights can be used to construct a complex indicator.

- **Indicators should be used with care**. Composite indicators, aggregating data - coming from model outputs and/or expert opinions - over time and/or space, are generally easier to communicate to and grasp for policy decision makers. However the aggregation might conceal and/or underestimate specific security properties - like the vulnerability of certain users, components or subsystems - and a single value makes it hard to grasp all the implications for security. Additionally, the aggregation rules largely consider threats and other electricity security features as static.
- **Sensitivity analyses** should continuously **support security analyses**. Sensitivity analyses can help in understanding the impact of factors that are important for electricity security but assumed to be exogenous. Also crucial for validation, sensitivity analyses are needed in order to understand how initial assumptions and boundary conditions (e.g. on meteorological data, renewable energies development, etc.) influence the results of the models.
- Energy system/power market **models**, Power market/system models, Static power system/grid models and Dynamic power system/grid models would need to be utilised - and, depending on cases, **soft or hard linked** - in so far as they address complementary electricity security aspects and properties. Using the models separately and independently may lead to conflicting assumptions and/or solutions on how to increase the level of security.
- **Flexibility** should be increasingly used as **driver for modelling integration** in the reliability analysis area. Since flexibility can be time-wise positioned between operational security and adequacy, its study not only requires a finer evaluation of adequacy aspects but is also bound to steer the integration of stability/operational security studies into the decision making/planning process.
- **Probabilistic approaches** should complement and - in specific areas (e.g. flexibility and adequacy of power systems with high penetration of renewable energy sources in particular) - completely supplant the deterministic approaches **when assessing reliability** aspects of the electricity security problem. Reliability analyses - encompassing operational security and flexibility/adequacy analyses - provide crucial input to decision makers although they do not cover the whole spectrum of security events/aspects (even when based on probabilistic techniques).

ENABLING FEATURES

- Advanced model-based and **Geographic Information System** (GIS)-based **visual analytics** should be extensively adopted to support the interactions with the policy makers while presenting, analysing and interpreting electricity security scenarios/results.
- Decision makers and analysts should take advantage of **supercomputers, real time simulators and parallel processing** to develop detailed, full-scale models of the power grids, and possibly make the high performance computing (HPC) technology available for real-time daily operations. These technologies would allow for more detailed and accurate system simulation and speed up the response to adverse situations, thus reducing the inability to prevent failures and enabling the integration of dynamic analysis into real-time grid operations. These technologies would be especially effective when combined to visual analytics.
- **Reliable, representative datasets** should be **made available** to analysts. Although most of the data generated in the electricity sector is viewed as proprietary, both because it includes sensitive industrial information about company operations and because it might be used for malicious

purposes, producing and sharing representative, synthetic data that is sufficient to mirror real operations/performances could be the right compromise to consider (preliminary initiatives are already in place).

The proposed decision-analytic framework was then contextualised in the Energy Union's power system planning process, in order to show how it could better support the policy decision making on electricity security; reliability analyses and vulnerability analyses might be conducted, fundamentally by the same actors, on two different layers and combined through an integrated assessment approach. Looking deeper into the reliability analyses, additional assessment blocks and models were introduced compared to the traditional framework. As for the models deployed, along with the energy system/power market models, power market/system models and static power system/grid models already featuring in the traditional framework, also dynamic power system/grid models were proposed for integrated reliability studies. The key point here is the integration of flexibility studies, which requires going closer to real time to assess the system performances.

Lastly, again to address the fourth sub-question, selected elements and features of the decision-analytic framework were studied and demonstrated in the following test cases and proof of concept:

- a **national application,** mainly targeting the infrastructure dimension of electricity security and assessing operational security and robustness features of the Italian transmission grid. The national application features a fully georeferenced model and advanced visualisation tools capable to present in a graphically impacting and effective manner the electricity security simulation outputs.
- a **regional application,** targeting several dimensions of electricity security - infrastructure, source, geopolitical - and testing operational security and adequacy features of the integrated Baltic system power system. The regional application presents an independent extra high voltage/high voltage model of the Baltic power system introducing also preliminary market aspects.
- a proof-of-concept for a potentially **EU-wide** real time simulation **platform** to perform multi-dimension and multi-property integrated security analyses. The prototype EU-wide platform is based on real-time remote interconnection of high-performance computing, data infrastructure and hardware/software components through a dedicated Virtual Private Network.

As far as the two test cases and the proof of concept are concerned, more details and key results are eventually reported below:

- **The Italian national application helped to show how the decision makers (the system operator in particular), via Geographic Information System and other visualisation tools, could gain quicker awareness of potentially critical system conditions and this would more speedily allow them to react.**

  Starting from commercial, publicly available and in-house databases, a fully georeferenced model of the Italian transmission system (380 and 220 kV) was developed with 4 typical power/demand snapshots for the year 2014, namely: winter peak, winter off-peak, summer peak and summer off-peak.

  In order to demonstrate the use of georeferenced model for natural threats analysis, we assessed the potential effects of extreme events, including a severe winter storm in the Alps, between Italy and Switzerland. The study was performed resorting to steady state contingency analysis and the impacts of the adverse natural events were assessed through a set of metrics including percentage of

line/transformer overloading, number of violations, number of isolated busses, amount of load shed and generation disconnected.

The extreme weather condition may be occurring in exceptionally cold winter days in the Alps when the temperature can go as low as - 45°C. The transmission corridor hosting the two 220 kV lines, connecting Switzerland and Italy, crosses the Alps at an average altitude of some 3500m. The highest recorded snowfall in the Alps, 11.5m high, was assumed in this case. The towers of the two 220 KV lines were considered to be overwhelmed by snow and ice and, consequently, the two lines across this corridor with Switzerland got interrupted.

The contingency analysis showed that - even if there were no isolated buses, disconnected loads or generators - an additional loss of lines could trigger system violations with high potentials to develop a system wide disturbance. As an example, after tripping a 380 KV line in Central Italy, the highest line flow reached 210.9% of the line rated capacity. Besides the above reported severe contingencies which can directly cause serious violations, other potential risks for the transmission tower collapse in the same area, due to the same winter storm, were identified. After the disconnection of the two considered tie-lines, the recorded power flow decrease over the lines in the same area would in turn further hinder the capability of melting the ice over the transmission lines. Then the accumulated ice could cause the collapse of the towers of those lines. Performing the contingency analysis is the first step to understand and then improve power system’s response to natural threats, since operators and decision makers in general can devise other actions to mitigate the damage caused by adverse natural events. For example, emergency plans shall be designed and implemented in order to: reduce the disturbance probability, rapidly respond to natural threats and recover a normal operation status after the events occurred.

- **The Baltic regional test case helped to demonstrate how coordinated security analyses can be conducted across Member States, targeting multiple security properties and how the electricity security models can be used to make decisions going well beyond the techno-economic aspects and including the geopolitical dimension.**

The energy policy of the Baltic States is integrated in the energy strategy of the European Union and aims at pursuing its three major objectives: affordability, sustainability and security. The power systems of Estonia, Latvia and Lithuania (Baltic Integrated Power System) are currently operated - as a synchronous grid - in parallel with the Integrated/Unified Power System (IPS/UPS) of Russia and Belarus. The Baltic power systems still lack adequate electricity connections, both between themselves and to other parts of the EU. However, the situation is improving: recently, the Estlink 1 and 2 connections between Estonia and Finland, the LitPol Link connection between Lithuania and Poland and the Nordbalt connection between Sweden and Lithuania have considerably raised the transfer capacity between the Baltic and the EU electricity markets.

A power system model of the Baltic States was developed with the purpose of assessing comparative options for a reliable and secure operation/development of the region's electricity system. The model covers the 330 kV, 220 kV and 110 kV network and it includes four scenarios: winter peak, winter off-peak, summer peak, summer off-peak.

First, the generation adequacy for the three Baltic States was assessed based on the deterministic approach and the best available public data. Individually, Estonia displayed the highest potential for export, while Lithuania turned out as the most vulnerable in terms of generation adequacy, as an effect

of the Ignalina Nuclear Power Plant decommissioning and locally higher generation prices. While wind generation in Lithuania could supply 15% of peak demand, the volatility of renewable generation and the risk of icing at winter peak call for further assessment of generation adequacy based on stochastic methodologies.

Although Latvia is a net exporter to Lithuania, it still has considerable dependence on power imports especially from Estonia and partly from Russia.

Techno-economic and security analyses of the Baltic power systems were conducted with the objective to understand the competitiveness of the single country in the Baltic electricity market, while considering the network infrastructure constraints. The system marginal cost for electricity for each Baltic country was given in terms of locational marginal cost, so that possible zonal splitting was identified. Further, contingency analysis was performed on the basis of the four reference models to check the system operational security. The results were used to identify the criticalities of the system under different generation and load conditions. These were ranked by a set of metrics such as maximum overload percentage, maximum voltage violation percentage, number of violations, islanded generation and load, etc.

In all current and future scenarios, the marginal cost in Estonia was higher than in the other two countries (where the marginal costs were pretty much aligned), due to the Estonian resort to expensive shale oil. For the summer peak case, the locational marginal costs varied from region to region in Latvia and Lithuania. Marginal costs in Latvia's Riga area were driven up to the same level as Estonia by frequent congestion occurrences in that region, whose effects were experienced as far as in parts of Lithuania.

Based on the operational points calculated in the four reference models, contingency sets containing each single transmission line, transformer and generator in the models were applied for the steady state security analysis. In the winter off-peak scenario, a specific contingency on the 330 kV network turned out as particularly critical and provoked a system-wide disturbance; additionally, in most of the scenarios another contingency resulted in several system overloads.

This study represented a first building block contributing to the process of scientific support to policy decision making within the BEMIP platform. The preliminary techno-economic analyses in the current study pave the ground for more detailed market analyses, expected to be conducted with tailored market/power dispatch tools to support electricity system development policies and initiatives in the Baltic States. As an example, re-dispatch actions could be considered after each congestion event to assess the costs of such security actions on the integrated power system under study.

The final ideal target would be to deploy an integrated modelling approach by combining static power system/grid models with dynamic power system/grid models and power market/system models, as called for by the Baltic stakeholders, hence addressing more electricity security properties - from stability to adequacy - in support of the policy decision making.

Different geo-political options and scenarios for higher security of energy supply and energy independence are in the process of being defined and assessed with the relevant actors, particularly in the BEMIP context.

- **The cross-EU proof of concept helped to show how a real-time simulation platform can overcome computational power and data confidentiality constraints towards accurate and detailed cross-national and cross-regional real time security analyses.**

Performing much needed security analyses with increased time/spatial granularity and ideally closer to real time, poses several challenges: the computational resources required are remarkable, operators cannot risk putting the real system in danger to test what-if options, and realistic models cannot be built without sharing high-quality confidential data. The time hence seems ripe for taking advantage of real time simulators and co-simulation arrangements to address these challenges: sharing parallel, distributed resources through co-simulation can dramatically increase the computational capability, allowing developing detailed, full-scale models of the power grids; real time simulators could be coupled to real time operations providing a safe test-bed where mimicking real system conditions; sensitive models/data could be stored in geographically distributed and protected servers and only input/output data for the modelling interfaces would be shared.

As demonstration case, four laboratories in Germany (RWTH Aachen), Italy (PoliTO, Torino and JRC, Ispra) and the Netherlands (JRC, Petten) were interconnected to develop a multi-site real time co-simulation platform for power system analysis. As a test case, the multi-site real-time lab performed a co-simulation of an interconnected transmission and distribution system: the transmission system was simulated in a first lab (Aachen, Germany) and the Medium Voltage distribution grid in a second lab (Turin, Italy). The behaviour of the prosumers on the distribution grid was captured by a dedicated consumer/prosumer model in a third lab (Petten, Netherlands). In addition, a monitoring system hosted by a fourth lab (Ispra, Italy), analysed the data and simulation results through a cloud system.

A power system scenario with high penetration of distributed generation was under study. The system was assessed during a summer day around 5 pm, with high demand, most people returned home from work and a large number of electric vehicles plugged in for charging. At the same time, local generation from PV panels abruptly drastically drops due to a sudden change from sunny to cloudy weather. Consequent voltage drops in the distribution system and frequency perturbations in the transmission grid were observed when performing the co-simulation.

The specific scenario designed for the demo was an interconnected transmission and distribution grid; however, alternative scenarios (e.g. the interconnection of several transmission systems over a regional or a pan-European scale) can be envisaged and implemented. This collaboration demonstrated the potentials of a federation of laboratories located in different member states and sharing capabilities and resources across the EU.

THESIS STRUCTURE

This thesis is organised as follows (see also Figure 1):

- In Chapter 1, first the main historical patterns and the current status of the EU's and global energy consumption and production are analysed. Then the current role and challenges for renewable energies and for the electricity sector are described. Next projections scenarios for the whole energy system are illustrated, eventually focusing on the perspective role of renewable energy and electricity.
- In Chapter 2, first the main energy policy objectives and action areas are described. Then EU policy initiatives on the power system are illustrated, highlighting the special role of the regional dimension and initiatives. Finally, the interaction of security-driven actions and other energy policy actions are discussed, identifying implications for the transitioning energy system.
- In Chapter 3, first the energy system and energy supply in general are characterised. Subsequently a taxonomy for energy and electricity security, at the cross-roads of science and policy, is proposed. Then the main techno-economic challenges to power system security are discussed. Finally the main threats, the related adverse events and their potential effects on electricity security are described.
- In Chapter 4, building upon the electricity security dimensions and properties introduced in Chapter 3, first a classification of the models for electricity security analysis is proposed. Afterward the main electricity security methodologies and approaches are described and then strengths, weaknesses and synergies of the different models and methodologies in support of electricity security decision making are discussed.
- In Chapter 5, after having provided a conceptual synthesis of the electricity security problem and grouped the issues faced by assessment approaches against the different spatial scales, a conceptual framework for electricity security analyses is discussed. Possible applications within the new framework, and in the context of the Energy Union's initiatives, are eventually introduced.
- In Chapter 6, test cases and a proof-of-concept fitting in the conceptual framework defined in Chapter 5 are discussed. First the performances of an Italian geo-referenced transmission model, subjected to extreme natural events, are assessed. Then operational security and adequacy analyses on an integrated Baltic power system model are illustrated. Thirdly, a proof-of-concept for a multi-scale and multi-stakeholder platform for real time simulation is demonstrated.
- In Chapter 7 conclusions are drawn and final considerations shared.

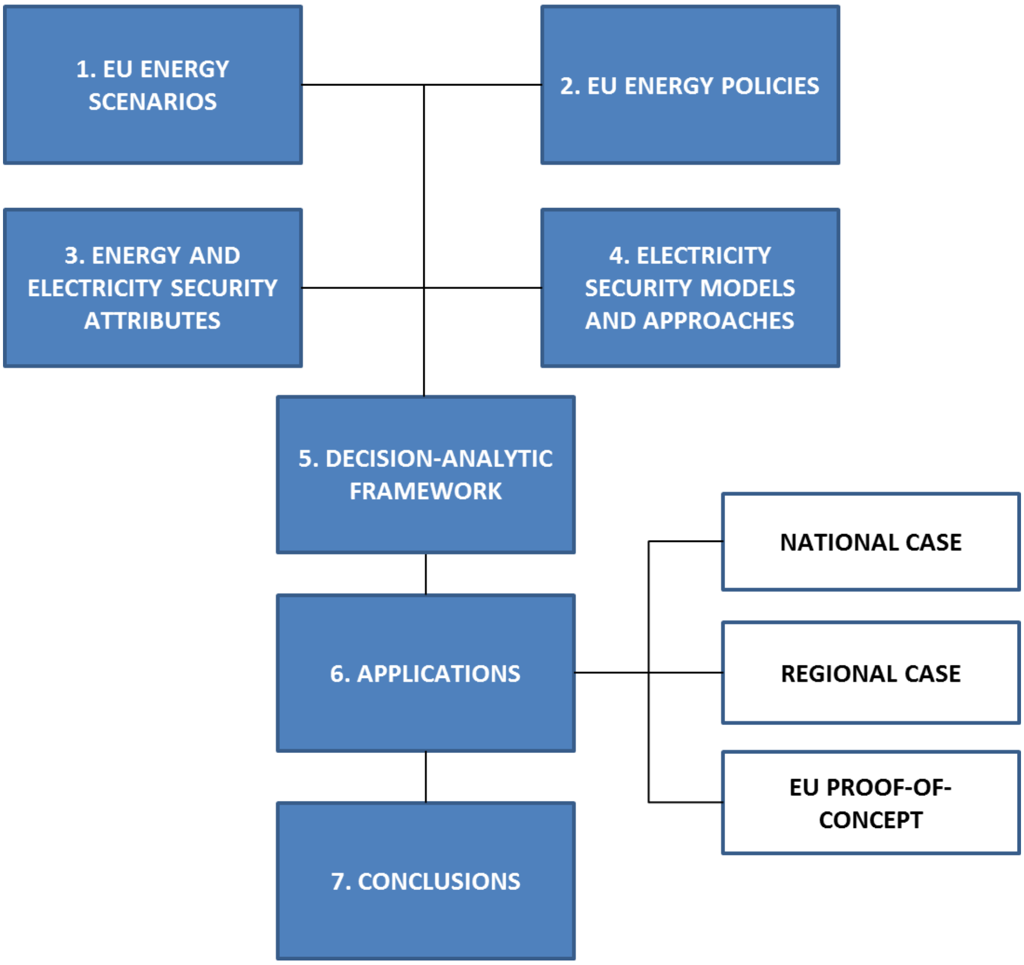


Figure 1 - PhD thesis structure

1. EU ENERGY SCENARIOS IN THE GLOBAL CONTEXT

"Energy is the golden thread that connects economic growth, social equity, and environmental sustainability."

Ban Ki-moon, UN Secretary-General

In this Chapter, first the main historical patterns and the current status of the EU's and global energy consumption and production are analysed. Then the current role and challenges for renewable energies and for the electricity sector are described. Next projections scenarios for the whole energy system are illustrated, eventually focusing on the perspective role of renewable energy and electricity.

1.1. HISTORICAL PATTERNS AND CURRENT STATUS

Energy is crucial for the mankind and is central to nearly every major European and world's challenge, be it related to security, climate change, food, welfare or employment. Energy scarcity, poverty or disruption can result in serious hazards to economies, ecosystems and social equity [1][2].

The European Union's energy system is facing big challenges: over the past decade there has been a decisive shift in the centre of gravity of global energy demand towards emerging economies, particularly China and India. At the same time, some new recorded trends and policy initiatives - primarily linked to decarbonisation, liberalisation and energy consumption "electrification" - exert their direct and indirect impacts particularly on the power market and system [3][4].

1.1.1. ENERGY CONSUMPTION AND PRODUCTION

Between 1990 and 2013, world primary energy demand increased by 55%. The EU, with an estimated 1,626 Mtoe gross inland consumption[1], is the fourth world's more energy consuming region (see Figure 2), after China (3,036 Mtoe), the United States (2,188 Mtoe) and Asia (without China) (1,655 Mtoe). Over the last two decades, gross inland energy consumption in the EU, which stood at 1,645 Mtoe in 1995, peaked at 1830 Mtoe in 2006 and then decreased steadily. Between 2005 and 2013, gross inland energy consumption in the EU has fallen by 9%, mainly due to the combined action of a hard-hitting economic-financial crisis and targeted energy efficiency measures [5][6][7].

From the energy production side (see Figure 3), despite the decarbonisation efforts, the share of fossil fuels in the world energy mix has changed little over the last thirty years (81% in 2013), while coal (the most carbon-intensive fossil fuel) has attained, in 2013, its highest share of the energy mix for at least 40 years [5][6][7].

---

[1] The gross inland energy consumption covers: consumption by the energy sector itself; distribution and transformation losses; final energy consumption by end users; statistical differences. It is the indicator commonly employed to represent the total energy demand of a country/region.

Year	1995	2000	2005	2010	2013
Rest of the World	2199	2408	2629	2838	2883
China	1055	1174	1788	2483	3036
United States	2067	2273	2319	2215	2188
Middle East	307	356	471	628	689
Asia (w/o China)	868	1039	1239	1523	1655
Russia	637	619	652	690	731
Africa	442	494	596	691	747
EU-28	1645	1692	1787	1721	1626
Total World	9220	10055	11481	12789	13555

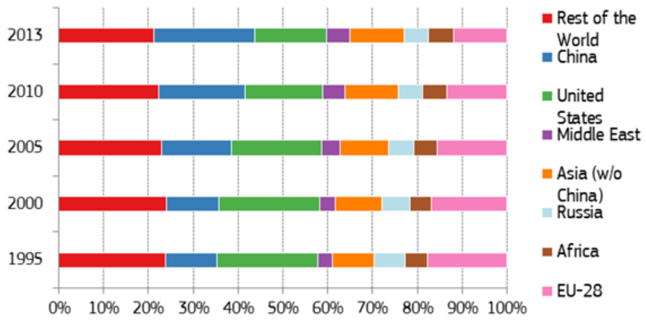


Figure 2 - World Gross Inland energy consumption by region [Mtoe] [5]

Year	1995	2000	2005	2010	2013
Petroleum and products	3395	3703	4046	4077	4216
Solid Fuels	2220	2279	2989	3546	4006
Gas	1812	2060	2363	2715	2909
Renewables	1206	1289	1428	1663	1828
Nuclear	608	676	722	719	646
Other	17	21	22	32	37
Total	9258	10007	11548	12720	13605

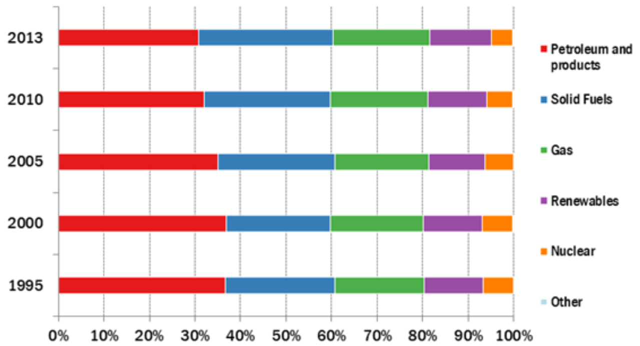


Figure 3 - World energy production by fuel [Mtoe] [5]

In the European Union, as depicted in Figure 4, the situation is changing as the combined share of petroleum products and solid fuels fell from 65.1% of gross inland consumption in 1990 to 50.6% in 2013. The share from nuclear energy - which was 13.6% in 2013 - remained overall stable. By contrast, renewable energy sources grew closer to nuclear since they reached 11.8% in 2013, almost three times higher than the Renewable Energy Source (RES) share (4.3%) in 1990. The relative importance of natural gas also increased quickly in the 1990s and more slowly thereafter, to peak at 25.4% in 2010; the natural gas share fell during the following three years and reached 23.2% in 2013, a share that was relatively close to that observed 10 years earlier [5][6][7].

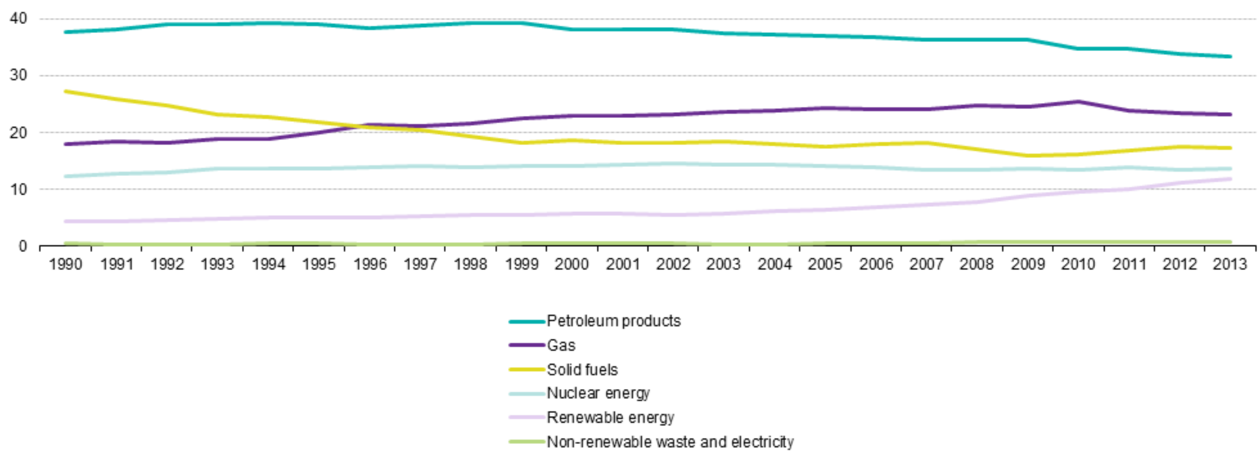


Figure 4 - Fuels covering the EU's gross inland energy consumption in 1990-2013 [7]

Renewable energy sources accounted for more than one third of gross inland consumption of energy in Latvia (36.1%) and Sweden (34.8%) in 2013, and their share was over one quarter of the total in Austria (29.6%) and Finland (29.2%). The fastest expansion between 1990 and 2013 in the share of renewable energy sources in energy consumption was recorded in Latvia, rising by 22.9%; increases in excess of 10.0% were also recorded in Denmark, Lithuania, Romania, Italy, Estonia, Sweden and Finland [6][7].

Also when it comes to final energy consumption[2], the EU ranks fourth (Figure 5) after China, United States and Asia (without China) [6][7].

Year	1995	2000	2005	2010	2013
Rest of the World	1623	1761	1920	2048	2101
China	797	825	1171	1534	1823
United States	1378	1546	1561	1501	1495
Middle East	202	243	315	415	452
Asia (w/o China)	643	746	878	1067	1174
Russia	458	418	412	446	434
Africa	325	370	436	508	555
EU-28	1127	1176	1235	1203	1139
Total World	6553	7085	7928	8722	9173

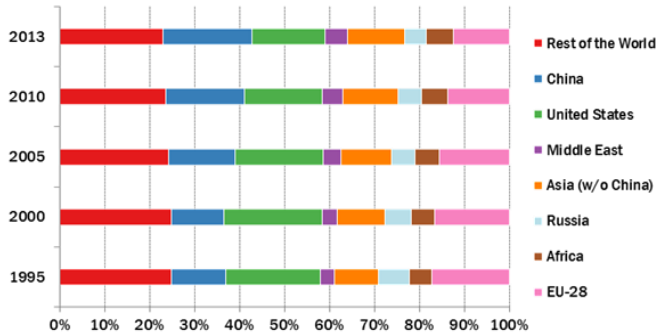


Figure 5 - World final energy consumption by region [Mtoe] [5]

Despite the sizeable energy needs, the EU ranks last - compared to the other big world's economies - in terms of primary energy production[3]. As one can see from Figure 6, only 793 Mtoe of the 1,626 Mtoe of energy needs were covered by means of inland resources. The *domestic* production of primary energy in 2013 was mainly covered by low-carbon energy technologies such as nuclear energy (28.1%) and renewables (23.9%), followed by solid fuels (19.5%), gas (16.4%) and oil (10.6%) (however, all fossil fuels together accounted for a 46.5% share) [5][7].

Year	1995	2000	2005	2010	2013
EU-28	965	949	905	836	793
China	1065	1129	1701	2204	2614
United States	1659	1667	1631	1723	1881
Middle East	1138	1327	1516	1629	1791
Asia (w/o China)	816	924	1107	1343	1473
Russia	968	978	1203	1279	1340
Africa	772	884	1083	1171	1129
Rest of the World	1875	2170	2422	2566	2620
Total World	9258	10028	11568	12751	13641

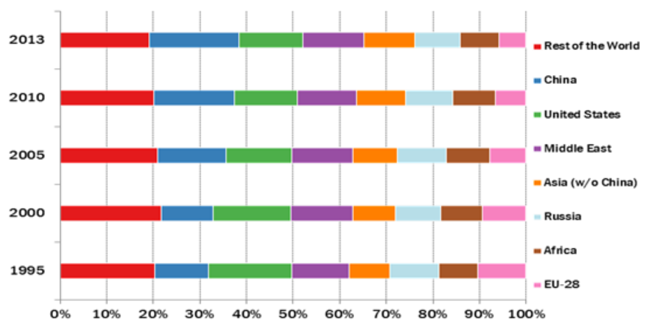


Figure 6 - World energy production by region [Mtoe] [5]

The EU indeed highly relies on foreign energy production: over the last decade, roundabout half of EU's energy needs were covered by imports. Over the 2006-2012 period, energy import in the EU was on average (stable) at 51%; comparatively, over the same period, China imported 8.1% (with an upward trend: it

[2] *Final energy consumption is the total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself.*

[3] *Primary energy production is any extraction of energy products in a useable form from natural sources*

reached 12.7% in 2012) and the United States 22.9% (with a downward trend: it went down to 15.6% in 2012) of their energy [6][7][8].

Figure 7 shows the EU's energy import dependency, broken down per fuel: in 2013, 53.2% of energy consumed in the EU (gross inland consumption plus bunkers) came from imports, significantly higher than a decade earlier - it was 48.8% in 2003. Energy import dependency greatly relates to petroleum and products (almost 88.1%), to natural gas (65.3%), and to a lesser extent to solid fuels (44.2%) [6][7].

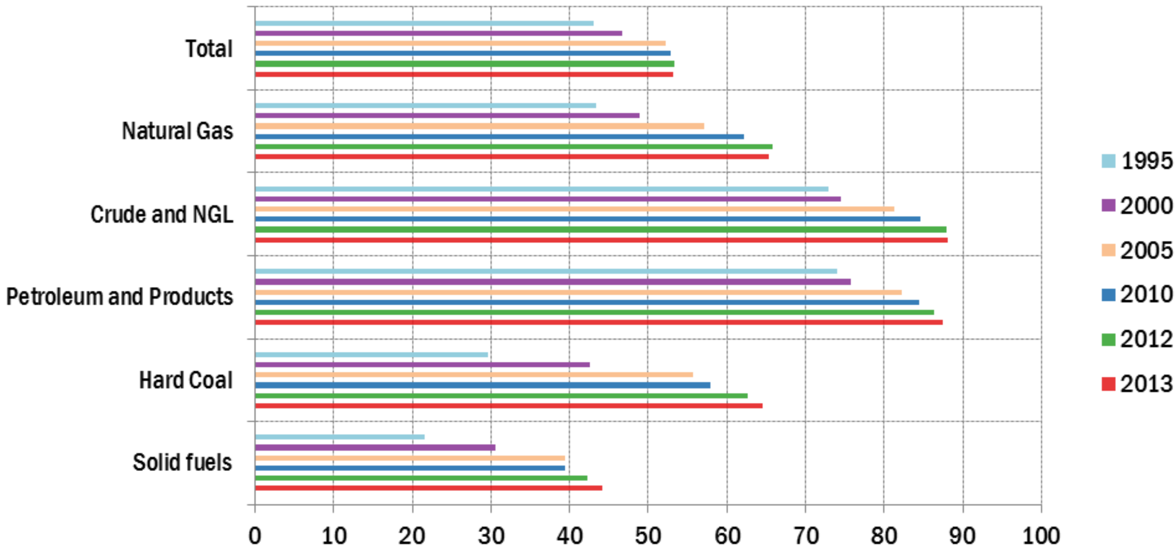


Figure 7 - EU28 energy import dependency [%] [5]

Not only the EU is the largest energy importer in the world but it strongly depends from a few external suppliers. This is particularly true for gas, where six Member States depend from Russia as single external supplier for their entire gas imports. In 2013 energy supplies from Russia accounted for 39% of EU natural gas imports or 27% of EU gas consumption; Russia exported 71% of its gas to Europe with the largest volumes to Germany and Italy [9][10].

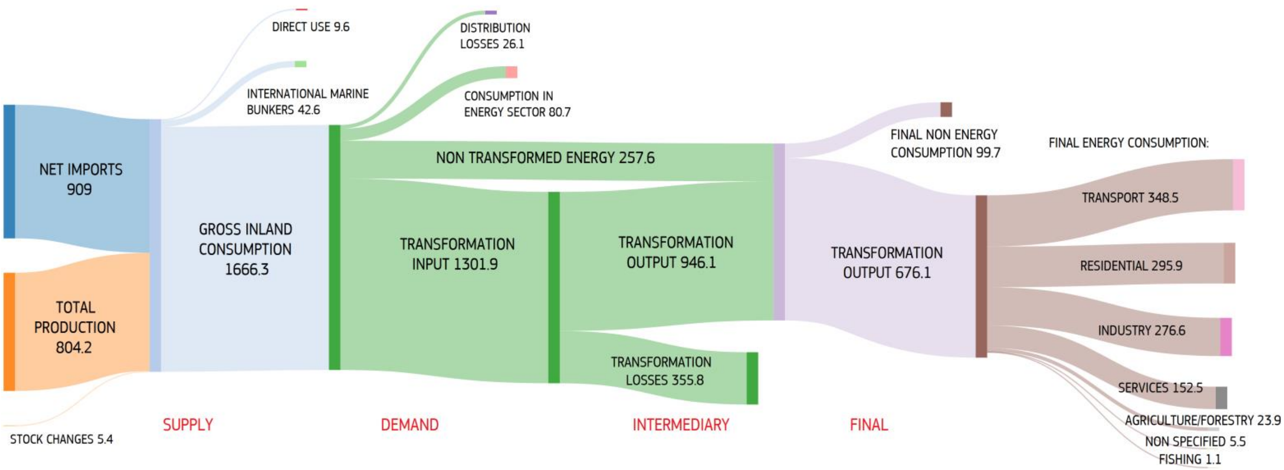


Figure 8 - EU energy flow 2013 [Mtoe] [5]

As also illustrated in Figure 8, in 2013 the most demanding EU final energy consumption sectors were the transport sector (31.6%), the residential sector (26.8%), the industrial sector (25.1%) and the service sector (13.8%), followed by agriculture/forestry/fishery/other sectors (2.8%). In terms of fuels, the final energy consumption was mainly covered by petroleum and products (38.5%), gases (23.5%), electricity (21.6%), renewables (7.4%), plus others (derived heat, solid fuels, wastes, non-renewables, adding up to 8.9%) [5][7][11].

Overall, final energy consumption decreased by 7% between 2005 and 2013, a bit less than primary energy consumption in the same period, and preliminary estimates show a continuation of this declining trend [12].

The heating and cooling consumption, a cross-cutting class encompassing different final energy consumption sectors, deserves a special mention as in 2012 it accounted for half (546 Mtoe) of the EU's energy consumption (1,102 Mtoe). More in detail, heating and cooling are consumed in three main sectors, namely residential, tertiary and industry, with the residential (mainly households buildings) representing the highest share. The residential sector accounted for 45% (248 Mtoe) of final energy heating and cooling consumption in 2012, followed by industry's share of 37% (202 Mtoe) and services' of 18% (96 Mtoe). Cooling - compared to heating - represented a fairly small fraction of total final energy use, but it is steadily increasing [13].

The EU external energy bill represents more than €1 billion per day (around €400 billion in 2013) and more than a fifth of total EU imports. The EU imports more than €300 billion of crude oil and oil products, of which one third from Russia [9]. EU's households and industrial users are increasingly concerned by rising energy prices and price differentials with many of the Union's trading partners, most notably the United States. The internal energy market has developed but new risks for fragmentation have emerged [3]. The energy price gap between the EU and major economic partners has widened: household and industrial retail electricity and gas prices kept rising over the last years; in contrast, wholesale electricity prices declined (with no clear trend recorded on wholesale gas) [14].

The widening gap between EU and US gas prices (caused inter alia by the cheap American shale gas exploitation) and the sharp fall of the carbon allowance price within the European Emissions Trading Scheme recently instigated a sharp drop in EU coal import prices and a massive shift of EU power production from gas to coal. The energy sector is the main contributor to CO_2 emission since fuel combustion and fugitive emissions from fuels (excluding transport[4]) were responsible for 57.2% of EU greenhouse gas emissions in 2013 (in 1990 this source sector was even more dominant) [11].

1.1.2. ROLE OF RENEWABLE ENERGY

Worldwide, renewables secured their position as the second-largest source of electricity in 2014, behind coal. Compared to 2013, renewables accounted for 85% of the increase in total generation. Supportive policies led to the installation of a record-high 130 GW of renewables capacity in 2014. Over the last decade, 318 GW of hydropower were built, more than any other form of renewables, followed by wind power (304 GW) and solar PV (173 GW). During that time, hydropower output in China increased by two-thirds more than gas-fired generation in the United States [5].

While the European Union still meets the largest fraction of its energy needs with fossil fuel based (65.1%) and nuclear energy (13.6%), renewable energy was the only type of primary energy to increase

[4] *Fuel combustion for transport (including international aviation) is the second most important source sector with 22.2 % in 2013.*

systematically over the past years: the quantity of renewable energy produced within the EU increased overall by 84.4% between 2003 and 2013, equivalent to an average increase of 6.3% per year [2][7].

In 2013, the renewable energy production to gross inland energy consumption ratio stood at 11.8%, with Sweden (34.8%) and Latvia (36.1%) in the lead and Austria (29.6%), Finland (29.2%) closely following [7][11].

The renewable energy production to final energy consumption ratio in 2013 reached 15.0%; the highest share again was recorded in Sweden (52.0%), with three other member states exceeding a 30.0% share: Latvia (37.1%), Finland (36.7%) and Austria (32.3%). As detailed in Chapter 2, this ratio is particularly relevant as chosen as indicator to track the EU's progress against its 2020, 2030 and longer term renewable energy integration targets [7][11].

Renewable energy and the electricity sector are tightly intertwined. As a matter of fact, the electricity sector, along with the heating and cooling sector and the transport sector, are those targeted by key EU's policy initiatives aimed at fostering renewable energy penetration, with the following mixed results recorded as of 2014 [15]:

- In the electricity sector, 26.0% of the EU's power was generated from renewables (out of which, about 10% sourced from variable renewable electricity, such as wind and solar).
- In the heating and cooling sector, the renewable energy share reached 16.6%. Renewable heating is increasingly replacing fossil fuels in district heating and at local level.
- In the transport sector, renewable energy covered only 5.7% of energy consumption.

1.1.3. PRESENT ELECTRICITY SYSTEM STATUS

For decades, economic growth has been accompanied by growing electricity demand. From 1990 to 2013, global Gross Domestic Product (GDP) and electricity demand both roughly doubled and so, too, did coal and gas demand in the power sector and related carbon-dioxide (CO_2) emissions. In 2013, the power sector accounted for over 60% of coal demand, 40% of gas demand, 55% of the use of renewables and 42% of global energy-related CO_2 emissions [5].

The total net electricity generation in the EU was 3.10 GWh in 2013, thus recording the third consecutive drop (- 0.9% in 2013, - 0.1% in 2012 and - 2.2% in 2011). As such, the level of net electricity generation in 2013 remained 3.6% below its peak level of 2008 (3.22 million GWh). Germany had the highest level of net electricity generation in 2013, accounting for 19.2% of the EU total, just ahead of France (17.7%); the United Kingdom was the only other Member State with a double-digit share (11.0%) [7].

More than one quarter of the net electricity generated in the EU in 2013 came from nuclear power (26.8%), while almost twice this share (49.8%) came from fossil fuels (natural gas, coal and oil). Among the renewable energy sources, the highest share went to hydro (12.8%), followed by wind (7.5%) and solar (2.7%) [7].

The relative weight of renewable electricity sources grew between 2003 and 2013 from 12.6% to 23.2%, while both fossil fuel-based power (from 56.4% to 49.8%) and nuclear power (from 30.9% to 26.8%) slightly shrank. Although hydropower remained the single largest source for renewable electricity generation in the EU in 2013, the amount of electricity generated in this way in 2013 was relatively similar to that recorded a decade earlier. By contrast, the fraction of net electricity generated from solar, wind and biomass increased significantly: from 0.01% in 2003 to 2.7% in 2013 for solar and from 1.4% in 2003 to 7.5% in 2013 for wind [7].

The installed electrical capacity increased by 70% in the period from 1990 to 2013, with fossil fuels keeping the lion's share and renewable surpassing nuclear. In 1990 and 2000 fossil fuels (57%-58%), nuclear (21-20%) and hydro (21-20%) covered pretty much the same relative fractions whereas wind started appearing (2%) in 2000. In 2013 the installed capacity of fossil fuel (50%), hydro (16%) and nuclear (13%) all went down while wind increased to 12% and solar reached 9% [7]. Figure 9 provides an overview of the power plants by age [16]. On the generation side, almost a fifth of the EU'S total coal capacity is to be retired by 2020 [4].

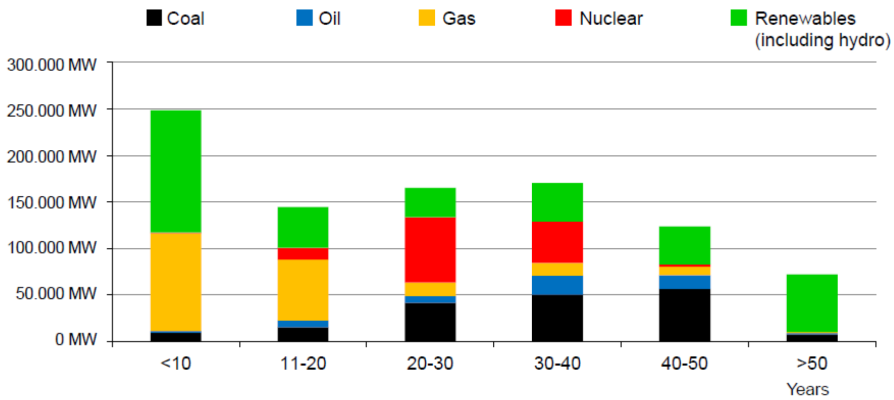


Figure 9 - Age of power generating capacities in the EU in 2013 [16]

Electricity trade shows an increasing trend over the last two decades since 1993 with small oscillations in between. Since 1990, the EU has been a net electricity importer, with two exceptions in 1996 and 2004, when exports exceeded imports of electricity. The quantity of electricity imported from non-EU countries in 2013 was close to 350 TWh, while 336 TWh were exported. Taking into account the EU total gross electricity generation of more than 3,000 TWh, EU net imports are of negligible magnitude (less than 1%). In 2013 the biggest net importers of electricity were Italy, the Netherlands and Finland, while France, Germany and the Czech Republic were the biggest net exporters of electricity [7].

EU industrial retail electricity prices over the past years have been estimated as more than twice those in the US and Russia, and 20% more than China's [14]. Since 2008, household electricity prices in the EU have increased by more than 30% and household gas prices have increased by 35%. Compared to the year before, EU prices for electricity and gas for household consumers increased on average by 4.4% and 2.7%, respectively. In 2013, prices for electricity industrial consumers increased by 2.0% compared to 2012, while prices for gas industrial consumers decreased by 1.2% [7][17][18].

In contrast to the retail developments, in the period 2008-2013 wholesale electricity prices converged downward declining by more than 30% on several European wholesale electricity benchmarks. This can be explained by the increasing penetration of renewables (driven by the national support schemes), combined with the availability of cheap coal on international markets. During the period from 2004, the main integration initiative in the electricity market has been the implementation of market coupling. The very large majority of EU Member States have their electricity markets coupled with at least one other Member State. In Central West Europe, electricity markets are deeply connected through price coupling, a practice expected to expand throughout the Union in the short term. Coupled markets imply that power flows out of a market when prices in a neighbouring market are higher. Inversely, power is imported when domestic prices are higher. The traded volumes can constitute a multiple of the interconnection capacity available but physical flows will be limited to the available capacity on the given interconnectors. Some benefit - linked to

short term arbitrage in energy trading - is appearing, especially in the large electricity markets of North-West Europe and the Nordic region, where market coupling is already operational [17].

The lower levels of electricity wholesale prices in Europe since 2009 have impacted gas-fired power plants in particular: their marginal cost has exceeded day-ahead prices during an increasing number of hours, pushing them out of the electricity dispatch merit order [17]. Due to low energy demand and increasing renewable electricity production, some 65 GW of gas and coal power plant projects have been postponed or cancelled in the last three years [4]. Over the course of 2012-13 ten major EU utilities announced the mothballing or closure of over 22 GW of combined cycle gas-fired power plants capacity in response to persistently low or negative clean spark spreads; 8.8 GW of this was either built or acquired within the last ten years [19].

Figure 10 - Synchronous areas and cross-border interconnectors in the European transmission grid [4]

An indicator adopted to sense the level of wholesale market integration is the price convergence. For instance, the Czech, Hungarian and Slovakian price significantly converged following the extension of market coupling from the Czech Republic and Slovakia to Hungary in September 2012. However, there is room for improvement in the EU. In 2013, the Central-West Europe region recorded the most significant decrease in price convergence (down by 32% compared with 2012). This is explained by other important factors, for example, RES penetration and cheap coal in the international markets drove German prices down more than elsewhere in the region, due to the relatively high proportion of RES and coal-fired generation in Germany [17].

Unscheduled flows constitute an important barrier to market integration and to secure grid operation. The increasing problems relating to these unplanned flows include, among other things, reduced availability of

cross-border capacity on some borders and associated social welfare losses. The high volatility and limited predictability of loop flows are a challenge for the operation of the network [17].

Currently, 300 thousand km of transmission lines are managed by the European Transmission System Operators (TSOs) [20] and 10 million km of power lines are managed by the European Distribution System Operators (DSOs) [21]. Figure 10 depicts the current status of the European electricity transmission infrastructure, highlighting synchronous zones and cross-border interconnectors.

Energy security of supply concerns every Member State, even if some are more vulnerable than others. This is valid in particular for less integrated and connected regions such as the Baltic and Eastern Europe. Three Member States (Estonia, Latvia and Lithuania) are dependent on one external operator for the operation and balancing of their electricity network [22].

Cross-border capacity is traded and allocated in different timeframes, depending on the market design and the different needs of market participants. The day before delivery, long term and day-ahead trades are expressed in day-ahead commercial schedules (also known as day-ahead nominations or day-ahead exchange programmes). Further, cross-border trade takes place within the day (resulting in intraday nominations) or closer to real time, via e.g. exchange of balancing.

Figure 11 shows the relatively low utilisation levels of intraday EU cross-border capacity compared to the day-ahead timeframe between 2010 and 2013. Figure 12 shows instead the cross-border physical exchanges among ENTSO-E members in 2010-2014, where a moderate upward trend can be appreciated [23].

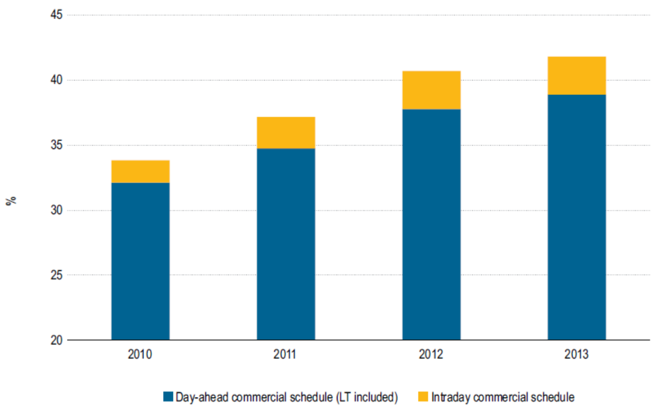


Figure 11 - Commercial use of interconnectors as % of Net Transfer Capacity in the EU [17]

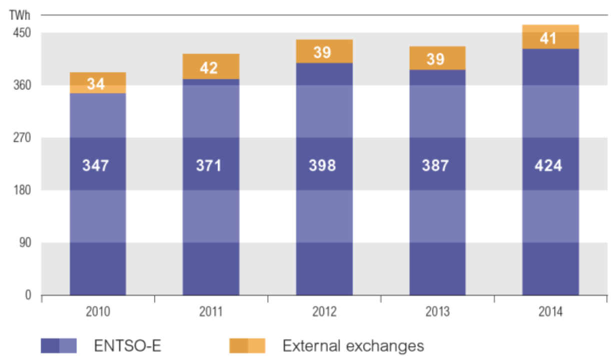


Figure 12 - Overall cross-border exchanges among ENTSO-E members in 2010-2014 [23]

1.2. FUTURE SCENARIOS

The data and scenarios presented in the following are mainly based on the EU's climate change and energy strategy (further explained in Chapter 2) and on projections and analyses from the IEA. More in detail:

- The EU energy trends to 2030 [24] discusses two scenarios - the Baseline and the Reference scenario for 2030 - whereas the EU energy, transport and GHG emissions trends to 2050 [25] develops the Reference scenario further up to 2050. Other scenario analyses are included in the Energy Roadmap 2050 and related annexes [26][27][28]. All these studies have been mainly conducted with the PRIMES model [29].
- The IEA World Energy Outlook 2015 presents three core scenarios spanning till 2040, which differ in their assumptions about the evolution of energy-related government policies: the New Policies Scenario; the Current Policies Scenario; and the 450 Scenario [5]. The World Energy Model (WEM) is the principal tool used to produce these projections [30].

1.2.1. ENERGY CONSUMPTION AND PRODUCTION

The IEA projects the world primary energy demand (see Table 1) to grow by a 45% to 2040 (reaching 17,934 Mtoe) in the Current Policies Scenario, 32% (19,642 Mtoe) in the New Policies Scenario and 12% in the 450 Scenario (reaching 15,196 Mtoe), compared to the 2013 levels. In all scenarios, fossil fuels remain the dominant source of energy supply to 2040, but their share in the energy mix falls; renewables increase significantly, especially in the 450 Scenario [5].

Table 1 - World's energy demand projections [5]

WORLD PRIMARY ENERGY DEMAND	2020				2030				2040			
	CPS		NPS	450	CPS		NPS	450	CPS		NPS	450
	Mtoe	%	%	%	Mtoe	%	%	%	Mtoe	%	%	%
Coal	**4 228**	**28**	27	26	**4 941**	**28**	26	20	**5 618**	**29**	25	16
Oil	**4 539**	**30**	30	30	**4 942**	**28**	28	27	**5 348**	**27**	26	22
Gas	**3 233**	**21**	22	22	**3 878**	**22**	23	23	**4 610**	**23**	24	22
Nuclear	**827**	**6**	6	6	**959**	**6**	6	9	**1 036**	**5**	7	11
Hydro	**380**	**3**	3	3	**449**	**3**	3	3	**507**	**3**	3	4
Bioenergy	**1 537**	**10**	10	11	**1 702**	**10**	11	13	**1 830**	**9**	10	15
Other renewables	**296**	**2**	2	2	**474**	**3**	4	6	**693**	**4**	5	10
TOTAL	15 041	100	100% (14743 Mtoe)	100% (14308 Mtoe)	17 345	100	100% (16349 Mtoe)	100% (14673 Mtoe)	19 643	100	100% (17934 Mtoe)	100% (15197 Mtoe)

Comparatively (see Table 2), the European Union's primary energy demand is expected to remain below the 2020 levels, more precisely between 1,246 and 1,530 Mtoe, depending on the effectiveness in the implementation of energy efficiency policies. Compared to the global framework, the fossil fuel fraction is considerably lower and the share of low-carbon technologies (nuclear and renewables) significantly larger [5].

According to IEA, Europe's gas import dependency will continue to increase by almost one-third between 2014 and 2020 and Russia will remain the main supplier (even if cheap LNG supplies will increasingly reach the European shores) [31].

For what concerns energy efficiency, the EU agreed energy saving targets and a long-term roadmap as detailed below:

- **By 2020** the EU agreed to achieve **energy savings of 20%** compared to the projected energy consumption trends. The 20% energy efficiency objective may still be short of a few percentage points (measures recently adopted by the EU Member States lead to a 17.6% primary energy saving projection by 2020) [12][32][33][34].
- **By 2030** the EU agreed to attain **27% energy savings** relative to the projected consumption trends [3][22].
- **In the 2050** Energy Roadmap, all the scenarios contemplate a **32-41%** reduction in energy consumption (compared with the 2005–2006 values) [25]-[28].

Table 2 - EU's energy demand projections [5]

EU PRIMARY ENERGY DEMAND	2020				2030				2040			
	CPS		NPS	450	CPS		NPS	450	CPS		NPS	450
	Mtoe	%	%	%	Mtoe	%	%	%	Mtoe	%	%	%
Coal	**256**	**16**	16	15	**209**	**13**	11	8	**168**	**11**	7	6
Oil	**475**	**30**	30	30	**419**	**27**	26	23	**372**	**24**	23	16
Gas	**386**	**24**	24	24	**445**	**29**	27	26	**478**	**31**	28	22
Nuclear	**225**	**14**	14	15	**181**	**12**	14	17	**171**	**11**	15	19
Hydro	**33**	**2**	2	2	**34**	**2**	2	3	**35**	**2**	3	3
Bioenergy	**162**	**10**	11	11	**182**	**12**	13	16	**200**	**13**	15	20
Other renewables	**59**	**4**	4	4	**83**	**5**	7	8	**107**	**7**	9	14
TOTAL	1595	100	100% (1563 Mtoe)	100 (1527 Mtoe)	1 554	100	100% (1455 Mtoe)	100% (1359 Mtoe)	1 530	100	100% (1377 Mtoe)	100% (1246 Mtoe)

1.2.2. Role of Renewable Energy

Global capacity additions of renewables total 3,600 GW over 2015-2040, more than all other power plants together. China is the largest market for renewables, adding 1 out of every 4 GW in the world to 2040, followed by the European Union, India and the United States. These regions account for two-thirds of global renewables capacity added to 2040. Global investment in renewables capacity totals $7 trillion to 2040, about 60% of total power plant investment [5].

In the New Policies Scenario, continued government support (estimated at $135 billion in 2014) and declining costs drive greater use of renewables, raising their share in total primary energy demand from 14% in 2014 (the current level in the EU is 12%) to almost 19% in 2040 (in the EU it may reach 22%). In 2040, renewables account for one-third of total electricity generation, one-sixth of the energy consumed to provide heat and 8% of road transport fuels [5].

Promotion of renewable energy is seen as one of the instruments to increase EU's energy security by lowering its energy dependency. Renewables are also expected to substantially contribute to the economic growth: European renewable energy businesses have a combined annual turnover of €129 billion, employing over 1 million people [5].

At EU level, the targets for renewable energy penetration in final energy consumption are as follows:

- **By 2020** the EU agreed to increase renewable energy[5] to cover **20%** final energy consumption. The EU is on track to meet the renewable targets (a 15.3% share was recorded in 2014) [32][15].
- **By 2030** the EU agreed to raise the renewable share in final energy consumption to at least a **27%** [3].
- **In the 2050** Energy Roadmap the share of renewables in energy is projected to grow, covering more than **40%** of final energy consumption [26][25].

Confirming that renewable energy and the electricity futures are tightly interlinked, Table 3 shows the projections for renewable energy penetration in the electricity sector (in terms of generated electricity and installed capacity). The EU is anticipated to continue playing a prominent role, with RES covering up to 49% of generated electricity by 2030 and up to 60% by 2040 (in 2013 it was 26%).

Table 3 - IEA renewable energy penetration projections in the electricity sector [5]

	RES SHARE IN GENERATED (TWh) ELECTRICITY [%]		
	2020	**2030**	**2040**
WORLD	25-28	26-41	27-53
CHINA	25-29	25-39	24-48
UNITED STATES	16-18	18-32	20-43
EU	33-36	38-49	41-60
	RES SHARE IN INSTALLED (GW) ELECTRICITY GENERATION [%]		
	2020	**2030**	**2040**
WORLD	33-36	36-49	37-58
CHINA	36-40	36-52	37-60
UNITED STATES	22-25	26-39	29-48
EU	46-47	50-57	53-63

1.2.3. Electricity system developments

The electricity sector is becoming more and more the playing field where conceiving and implementing low-carbon energy policies. At global level, electricity demand increases by more than 70% over 2013-2040 in the New Policies Scenario, with non-OECD[6] countries responsible for 7 out of every 8 additional units of global

[5] *In the transport sector, the target for 2020 is to achieve 10% share of renewable energy, the bulk of which is still anticipated to come from biofuels. However, in 2014 just a 5.7% share was achieved [15][15].*

[6] *The OECD's origins date back to 1960, when 18 European countries plus the United States and Canada joined forces to create an organisation dedicated to economic development. Today, OECD includes 34 Member countries spanning the globe, from North and South America to Europe and Asia-Pacific.*

electricity demand. Electricity demand sees the fastest growth among the final energy sources, raising its share in final energy use from 18% to 24% by 2040 [5].

Electricity already covers a fair share - some 20% - of final energy consumptions in Europe and it is anticipated to play an even more important role as consumers switch to electricity from other energy sources (and increase self-consumption as well): the EU's scenarios show electricity growing above 30% in 2030 and almost doubling to shares close to 40% in 2050, whereas in China ambitious studies analyse scenarios of electricity covering over 60% of end-use in 2050 [25][26][35].

At global level, Installed power generation capacity reaches 10,570 GW in 2040, an increase of some 4,400 GW over the level in 2014 and one-third more than the increase in the previous 25 years. To keep pace with strong electricity demand growth, installed capacity more than doubles in non-OECD countries, led by China (where capacity doubles) and India (where capacity almost quadruples) [5].

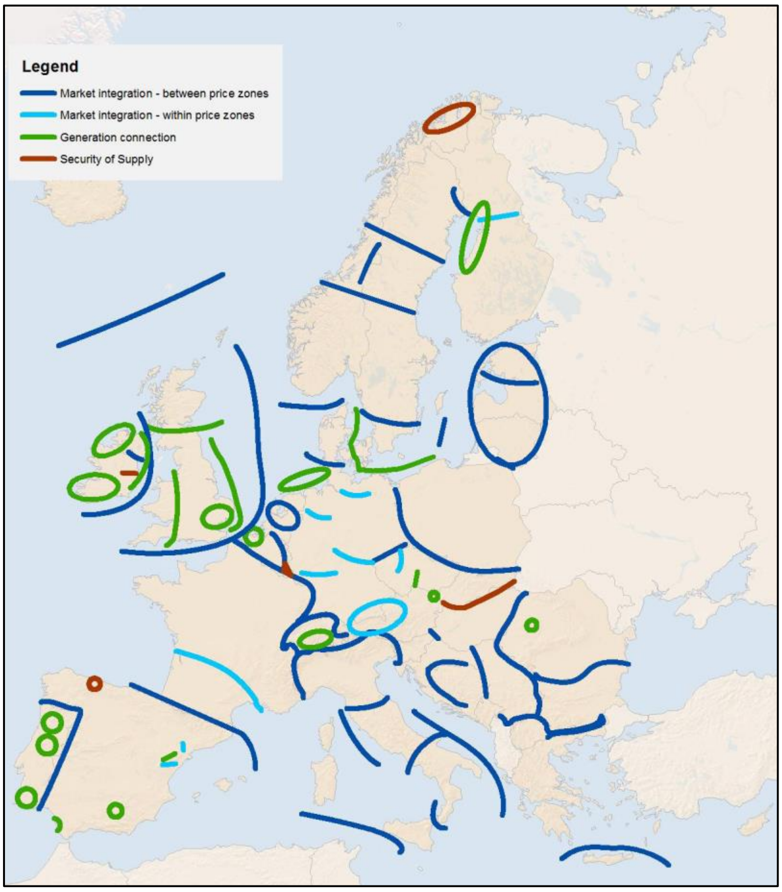


Figure 13 - Map of main bottlenecks in the ENTSO-E grid [78]

While in 2013 23.2% of the electricity production originated from renewables, reaching the European Union 2030 energy and climate objectives means the share of renewables is likely to cover up to 45-50% of electricity produced [3][7][24]. This is pretty much in line with the IEA's projections presented in Table 3.

The evolution of the power grid in the medium to long term depends greatly on which scenarios are adopted for renewable energy deployment, extension of the European electricity network towards neighbouring power grids, and penetration of distributed energy sources driving smarter system developments. RES development requires also investment in the electricity grid to transport and balance electricity generated

from renewable sources. A significant share of generation capacities will be concentrated in locations further away from the major centres of consumption or storage. The decentralised power generation share (% of small scale power plants connected to low/medium voltage grid over total net power generation) could grow from 6-7% in 2020 to 9-17% in 2030 up to 10-31% in 2050 according to some - conservative - estimates [27][28].

It has been estimated that the total investment required in the EU in energy generation, transmission, and distribution infrastructure through 2020 is in the order of €1 trillion. As far as the power transmission grid is concerned, the new investment needed (including storage facilities) is foreseen to amount to about €200 billion through 2020 [4].

For 2020, a political target of at least 10% electricity interconnection capacity (to the installed generation capacity) was agreed by the EU Member States. Currently eight Member States remain below the 10% threshold, which should be achieved primarily through Projects of Common Interest (see definition in Chapter 2) [32][36][37][38].

For 2030, the priorities for transmission infrastructure development are again those included in the Projects of Common Interest. Additionally, a new target for a 15% electricity interconnection capacity by 2030 was put forward by the European Commission.

As a result of the market and network study process, about 100 bottlenecks have been identified by ENTSO-E for the European electricity system in the coming decade. Figure 13 shows the affected grid sections, classified according to three criteria: security of supply, direct connection of (both thermal and renewable) generation, market integration [39].

Most of the transmission grid projects agreed by network stakeholders and supported by EU legislative and financial instruments fall into the following four regional clusters [4]:

- **Baltic power system**. The Baltic Energy Market Interconnection Plan (BEMIP)'s main priority is strengthening the interconnections between the Baltic States and the other EU countries. The Baltic States are still synchronously connected with the power systems of the Republic of Belarus and the Russian Federation (IPS/UPS[7]); asynchronous interconnections with Finland, Sweden and Poland have recently been put in operation. Additional internal reinforcements, especially in Latvia and Lithuania, as well as cross-border interconnections are planned in the short and medium term. In the mid-term a strategic objective is to operate the Baltic system synchronously to the European continental one and to achieve stronger market integration [40].
- **North Sea Offshore Grid**. The North Seas Countries Offshore Grid initiative (NSCOGI) launched in 2009 by ten nations (Belgium, Denmark, France, Germany, Ireland, Luxemburg, The Netherlands, Sweden, Norway and UK) aims to exploit the huge wind power potential of the North Sea via an offshore transmission network connected to the mainland grid. A total wind generation capacity of between 120 and 180 GW - out of which 40 to 60 GW offshore - may be connected by 2030. From a grid design standpoint, several topological solutions are being studied, with a preference for the meshed multi terminal networks. On top of the already existing interconnectors, other tie lines are planned to link Germany, the Netherlands, Norway, and the United Kingdom [41].

[7] *The IPS/UPS (Integrated Power System/Unified Power System) is a wide area synchronous transmission grid of the following countries (former Soviet Republics): Azerbaijan, Belarus, Estonia, Georgia, Kyrgyzstan, Kazakhstan, Latvia, Lithuania, Moldova, Mongolia, Russia, Tadzhikistan, Ukraine, Uzbekistan.*

- **South-western Europe and the Mediterranean Sea**. Planned reinforcements in this area include the cross-border link between Italy and France. Other short- and medium-term plans in the region call for reinforcements and new interconnections at the Portugal-Spain border as well as connecting islands with the continental grid. Furthermore, the south-western European systems play a key role in connecting Europe to North Africa, where conventional, solar, and wind energy are all available. Two main groups of grid developments in the Mediterranean area are planned. The first consists of projects needed to complete a Mediterranean ring (Medring) that will interconnect most of the power systems of the countries around the Mediterranean. The second is the cross-Mediterranean undersea interconnection of selected power systems on the northern and southern shores of the Mediterranean. Many factors - technical, regulatory, financial, market, socio-environmental, and political - are delaying the implementation of such projects [42].
- **Central and Eastern Europe**. In central and eastern Europe several grid upgrades are needed, especially in Czech Republic and Poland and at the interfaces with eastern and north-eastern Germany, as well in the grids of Austria, Hungary, and Slovakia. At the same time, considering that generation capacity in Germany is concentrated in the northeast while load is increasing mostly in the south, considerable north-south transfer capacities should be planned. In the medium and long term, there is the need for additional generation connection and interconnection capacities within and between the south-eastern European countries and also for increasing transfer capacity with central Europe. Other axes to be expanded are the east-west corridor between the Adriatic and Black Sea countries as well as the corridors at the borders of Italy with Austria and Slovenia. As far as interconnections with non-EU countries are concerned, the most ambitious plan concerns the potential coupling of the European continental zone with the IPS/UPS system in the former Soviet countries.

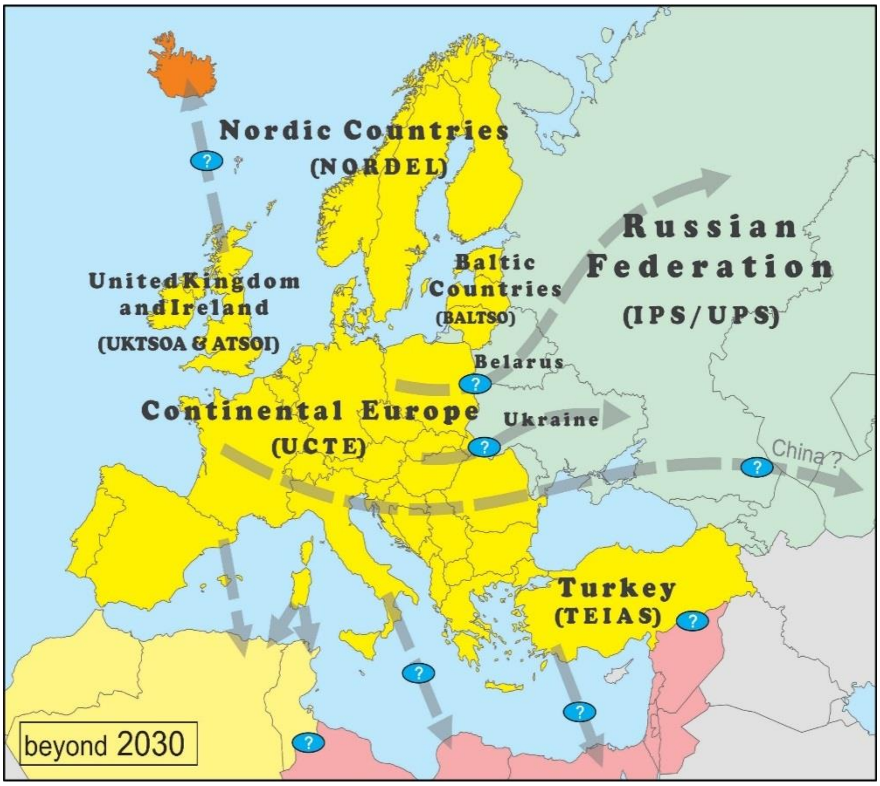


Figure 14 - Evolution of the European transmission grid beyond 2030 [4]

Moving beyond 2030 (see Figure 14), a prospective pan-European super grid may in the long run include an enlarged High Voltage Alternating Current (HVAC) continental network that synchronously interconnects with the Baltic countries, Moldova, Turkey, and possibly Ukraine and further asynchronously links up with the British isles and Scandinavia, along with the presence of a closed Mediterranean ring and interconnections between the north and south shores of the Mediterranean. In this system, islands like Cyprus and Iceland (via potential HVDC links) would be electrically linked; Belarus and Russia would be asynchronously interconnected as well. According to some analysts, the overall grid expansion till 2050 would require to triple interregional transmission capacity compared to current levels: in some corridors, the expansion would be even greater, such as at Spanish-French border, where transfer capacity would reach 15-30 GW. Further extension of the interconnected power system to remote electricity grids (such as that of China) could represent a very long-range option to explore beyond 2030 [4][43].

In summary, a pan-European super grid can be envisioned as an electricity grid infrastructure based on mixed HVAC and HVDC onshore and offshore backbones (highways) interconnecting renewable energy sources and storage technologies and transporting bulk power to load centres across the whole European continent and beyond. At the transmission level, the implementation of a pan-European super grid requires addressing and solving several technological, regulatory, market, and socio-environmental issues [4].

In parallel, the electrical energy system is currently undergoing a paradigm change towards a more decentralized system, in which the participants change their roles dynamically and interact cooperatively.

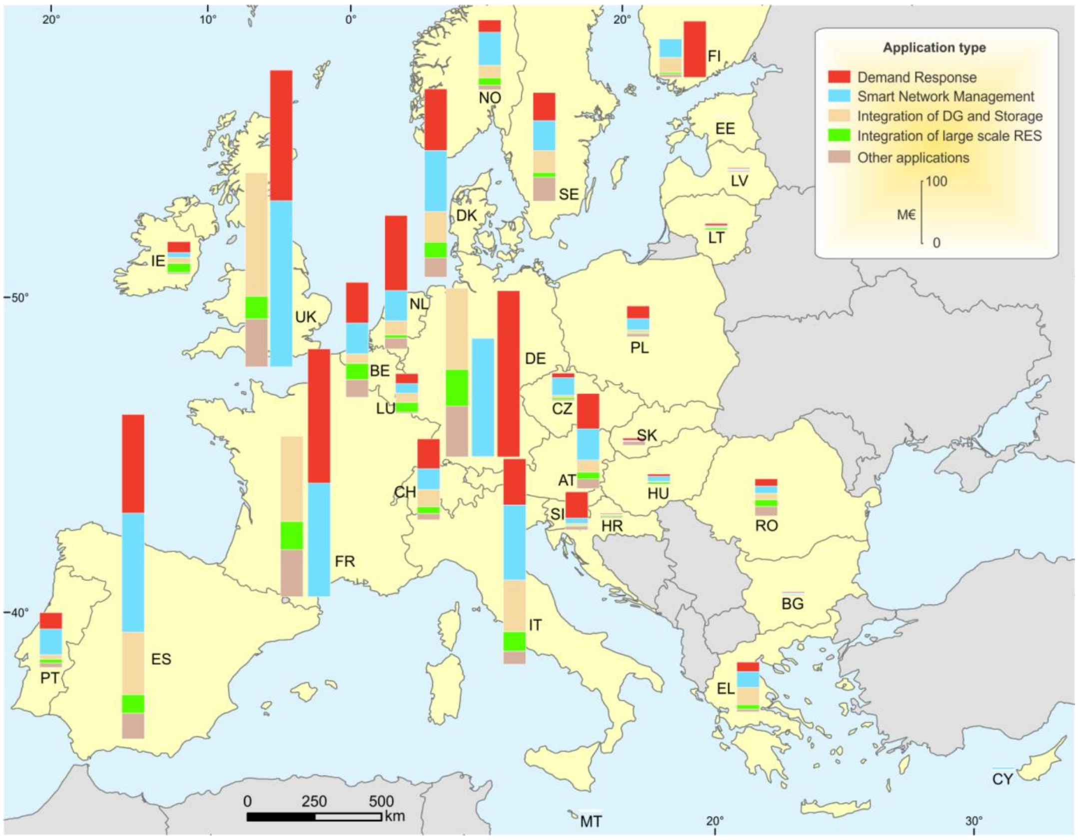


Figure 15 - Smart Grid research & demonstration projects in Europe ([44], JRC analysis)

Figure 15 depicts the Smart Grid research and demonstration projects in Europe: up until 2014, the JRC Smart Grid Project Outlook mapped and analysed 459 smart grid projects (implemented in 578 sites),

totalling 3.15 b€ investment. Smart grid project budgets have been growing steadily over the last decade: after a first phase with some sporadic activity (2002-05), smart grid projects multiplied swiftly from 2006 onward, but the real boom was recorded after 2009. The smart grid projects are also getting larger: the share of projects with budgets over €20 million grew from 27% in 2006 to 61% in 2012 [44].

Even with the advent of more decentralised power technologies and systems, it is expected that the transmission grid will still have a crucial role in wheeling power over long distances and serving as a backup to local distribution grids. It is probable that neither of the different and, to a certain extent, conflicting architectures - supercentralised transmission and smart and decentralised distribution - will prevail over the other, but they will need to be integrated and combined [45][46].

The range of legal and regulatory arrangements in Europe might present significant barriers to the replicability of smart grid project results in different areas and to the scalability of projects to larger regions. Targeted analyses are necessary to understand the impact of the current wholesale and retail market schemes (and the related electricity prices and tariffs structures) on smart grid deployment opportunities. Uncertainty persists in several countries over: roles and responsibilities in new smart grid applications, sharing of costs and benefits and consequently new business models. Finally, a high degree of consumer resistance to participating in trials continues to be recorded throughout the EU [44].

2. EU ENERGY POLICIES AND ELECTRICITY SECURITY CHALLENGES

"Smart grids could become Europe's shale gas."

Maroš Šefčovič, European Commission Vice President

In this Chapter, first the main energy policy objectives and action areas are described. Then EU policy initiatives on the power system are illustrated, highlighting the special role of the regional dimension and initiatives. Finally, the interaction of security-driven actions and other energy policy actions are discussed, identifying implications for the transitioning energy system.

2.1. EU ENERGY AND CLIMATE CHANGE POLICIES

2.1.1. EU POLICY OBJECTIVES AND ACTION AREAS

The Lisbon Treaty [47], ratified in 2009, introduced a remarkable change in European Union's primary law with the inclusion of energy and trans-European networks among the areas of shared competence between the European Union and the Member States. Prior to that, the European Union institutions had to rely upon different, fragmented articles and references within the Treaties - not necessarily primarily addressing energy (but e.g. competition) subjects - to justify policy initiatives and actions centred on energy.

More specifically, the Lisbon Treaty identifies four main aims for the EU's energy policy making mission:

- to ensure the functioning of the energy market;
- to ensure the security of supply in the Union;
- to promote energy efficiency and energy saving, and develop new and renewable forms of energy; and
- to promote the interconnection of energy networks.

In general terms, the measures put forward by the European Union "shall not affect a Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply". However, the Treaty also stipulates that "the Council, on a proposal from the Commission, may decide, in a spirit of solidarity between the Member States, upon measures appropriate to the economic situation, in particular if severe difficulties arise in the supply of certain products, notably in the area of energy" [47].

Against this background, over the last few years, the European Commission started developing a strategy for a resilient Energy Union, with correlated climate policy actions. The stated goal is to give EU consumers - households and businesses - secure, sustainable, competitive and affordable energy. Achieving this goal will require a fundamental transformation of Europe's energy system [2].

Particularly, the political challenges over the last years have confirmed that diversification of energy sources, suppliers and routes is crucial for ensuring secure and resilient energy supplies to European citizens and companies, who however expect access to affordable energy [2].

The European Union's energy policies are driven by three main objectives, mirroring the aims introduced by the Lisbon Treaty (the energy network interconnection promotion may be largely considered as cutting across the other aims) [2]:

- **Energy affordability:** ensuring that energy providers operate in a competitive environment that guarantees affordable prices for homes, businesses, and industries.
- **Energy security:** ensuring the reliable provision of energy whenever and wherever needed.
- **Energy sustainability:** rendering energy consumption sustainable, by lowering greenhouse gas emissions, pollution, and fossil fuel dependence.

To pursue its energy and climate change goals within a coherent long-term strategy (see Figure 16), the EU agreed specific 2020-2030 targets - and outlined a roadmap for 2050 - for renewable energy and energy efficiency (as already discussed in Chapter 1) and for greenhouse gas emissions.

The greenhouse gas emission target seems to emerge as the overarching driver shaping the EU's internal/external energy and climate change policies, as also confirmed in the 2015 Paris climate conference (COP21), where 195 countries adopted a legally binding climate deal. The agreement, due to enter into force in 2020, sets out a global action plan to limit global warming to well below 2°C [48].

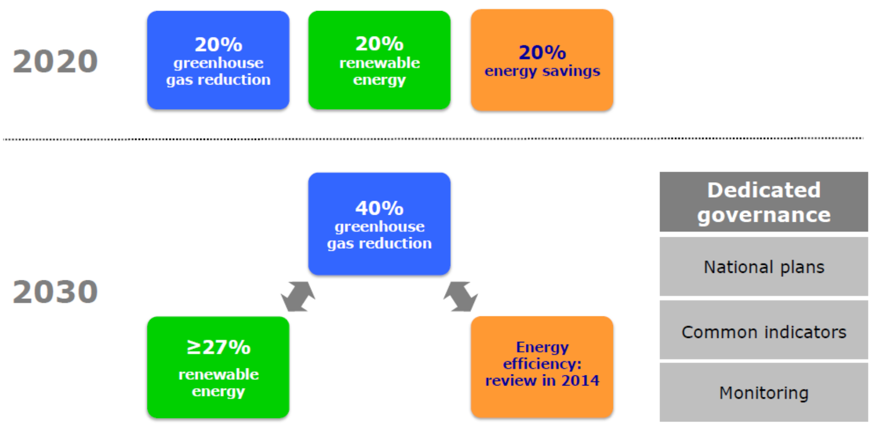


Figure 16 - EU's energy policy targets [16]

The EU's greenhouse gas emissions are expected to decrease as follows:

- **by 2020:** The EU agreed to reduce domestic greenhouse gas emissions **by 20%** below 1990 levels. The EU overshot this target since a 23% reduction was already achieved in 2014 [32].
- **by 2030:** The EU agreed to reduce domestic greenhouse gas emissions **by at least 40%** [3][22].
- **by 2050:** All scenarios defined by the EU assume a greenhouse gas emission reduction **of at least 80%** [25][26].

Looking at the key action areas and initiatives on energy put in place by the EU, one can note how energy security occupies a prominent place in several of them [9][22]:

- The implementation of a **European Energy Union** that will ensure secure, affordable and climate-friendly energy for EU citizens and businesses. The EU's Energy Union strategy is made up of five mutually reinforcing dimensions: Supply security (based on: energy diversification and more efficient

use); Energy market integration (via better use/faster build-up of energy interconnectors and better alignment of wholesale and retail markets); Energy efficiency; Emissions reduction; Research and innovation.

- The proposal for a **European Energy Security Strategy** with short and long-term measures. The short-term measures include energy stress tests and preparedness/action plans to cope with short run supply security issues. The long-term measures cover most of the Energy Union strategic dimensions, along with speaking with one voice in external energy policy, strengthening emergency and solidarity energy supply mechanisms and protecting critical infrastructure.
- The realisation of an integrated and resilient energy market across the EU.
- The promotion of **energy efficiency and domestic production of energy**, including renewable energy sources.

Particularly, to meet the 2030 policies targets, the European Commission has proposed [3]:

- **A reformed EU emissions trading scheme (ETS)**. The reform includes a Market Stability Reserve which aims to neutralise the negative impacts of the existing allowance surplus and to improve the system's resilience to future shocks. Furthermore the EC intends to reduce the overall number of allowances also by better targeting the free allowance distribution (among others through the updating of benchmarks to reflect technological progress, more targeted carbon leakage groups, and a better alignment of the amount of free allocation with production levels) [32].
- **New governance system based on national plans** for competitive, secure, and sustainable energy. These plans will follow a common EU approach in order to ensure investor certainty, transparency, policy coherence and coordination across the EU.
- **New indicators for the competitiveness and security** of the energy system, such as price differences with major trading partners, diversification of supply, and interconnection capacity between EU countries.

2.1.2. EU POLICY INITIATIVES ON THE POWER SYSTEM AND MARKET

Several energy and climate change policy initiatives launched in the last decade targeted the EU's power system and market. The most important recent ones are described below:

- **Large combustion plant Directive.**

  Directive 2001/80/EC [49] sets emission standards for all emission from EU's power plants with an installed capacity greater than 50 megawatts. Power plants not meeting the specified emission standards must retrofit appropriate pollution control equipment, phase out their production or shut down.

- **Security of electricity supply and infrastructure investment.**

  The Directive 2005/89/EC on measures to safeguard security of electricity supply and infrastructure investment [50] aims to guarantee an adequate level of generation capacity, ensure an adequate balance between supply and demand and achieve an appropriate level of interconnection between EU countries.

For operational network security, the Directive specifies that the countries must ensure that the transmission system operators set minimum operational rules and obligations on network security. In turn, the distribution system operators are expected to comply with these rules. In particular, the countries shall ensure that interconnected transmission and distribution system operators exchange information relating to their networks operation.

As far as generation adequacy is concerned, the EU countries must encourage the establishment of a wholesale market framework that provides suitable price signals for generation and consumption and require transmission system operators to ensure that an appropriate level of generation reserve capacity is available for balancing purposes and/or to adopt equivalent market based measures. EU member states must regularly undertake an objective, facts based, assessment of the generation adequacy situation in their country fully taking account of developments at regional and Union level.

The Directive states that the countries may take additional measures to: facilitate new generation capacity and the entry of new generation companies to the market; remove barriers that prevent the use of interruptible contracts; remove barriers that prevent the conclusion of contracts of varying lengths for both producers and customers; adopt real-time demand management technologies such as advanced metering systems and energy conservation measures.

Regarding network investment, the Directive calls for the EU countries to establish a regulatory framework that provides transmission and distribution system investment signals in order to meet foreseeable demand and facilitate network maintenance/reinforcement. Third Party (named also merchant) interconnection schemes are introduced, provided that a close co-operation with the relevant transmission system operators is guaranteed.

The provisions relating to security of electricity supply are currently under review in the framework of the new Energy Union's strategy on energy security [9][10].

- **Critical Infrastructure Protection.**

  Directive 2008/114/EC concerns the identification and designation of European critical infrastructures and the assessment of the need to improve their protection [51]. In the context of the European Programme for Critical Infrastructure Protection (EPCIP) for energy, besides funding relevant projects and promoting international cooperation, the EU defined a procedure to identify and assess Europe's critical infrastructures and proposed measures to aid protection [51][52]. In 2013, EPCIP started a new phase and launched a pilot project analysing possible threats to EU's electricity and gas transmission grids (and other categories of infrastructures) [53].

- **Renewable energy promotion.**

  The Renewable Energy Directive 2009/28/EC [54] establishes an overall policy for the production and promotion of energy from renewable sources in the EU. As already recalled, it requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020, to be achieved through individual national targets (ranging from 10% in Malta to 49% in Sweden). EU countries set out how they plan to meet these targets and the general course of their renewable energy policy in national renewable energy action plans. The Directive promotes cooperation amongst EU countries (and with countries outside the EU) to help them meet their renewable energy targets. This cooperation can take the form of: statistical transfers of renewable energy, joint renewable energy projects and joint renewable energy support schemes.

As far as the electricity sector is concerned, the Directive lays down that "Member States shall ensure that when dispatching electricity generating installations, transmission system operators shall give priority to generating installations using renewable energy sources in so far as the secure operation of the national electricity system permits and based on transparent and non-discriminatory criteria."

- **Internal electricity market functioning.**

  The latest round of EU energy market legislation, known as the third package, has been enacted to improve the functioning of the internal energy market and resolve structural problems. The Directive 2009/72/EC, concerning common rules for the internal market in electricity [55], covers five main areas:

  - Energy suppliers **unbundling** from network operators. Unbundling is the separation of energy supply and generation from the operation of transmission networks aimed to foster competition and fair access to infrastructure. Unbundling must take place in one of the three following ways: Ownership Unbundling - all integrated energy companies sell off their electricity networks; in this case, no supply or production company is allowed to hold a majority share or interfere in the work of a transmission system operator; Independent System Operator - energy supply companies may still formally own electricity transmission networks but must leave the entire operation, maintenance, and investment in the grid to an independent company; Independent Transmission System Operator - energy supply companies may still own and operate electricity networks but must do so through a subsidiary; all important decisions must be taken independent of the parent company.
  - **Regulators** independence strengthening. A competitive internal energy market cannot exist without independent regulators who ensure the application of the rules. Regulators must be independent from both industry interests and government. They must have their own legal entity and have authority over their own budget. National governments must also supply them with sufficient resources to carry out their operations; regulators can issue binding decisions to companies and impose penalties on those that do not comply with their legal obligations; electricity generators, gas network operators, and energy suppliers are required to provide accurate data to regulators; regulators from different EU countries must cooperate with each other to promote competition, the opening-up of the market, and an efficient and secure energy system.
  - Establishment of the **Agency for the Cooperation of Energy Regulators (ACER)**. ACER is independent from the Commission, national governments, and energy companies. Its work involves: drafting guidelines for the operation of cross-border gas pipelines and electricity networks; reviewing the implementation of EU-wide network development plans; deciding on cross-border issues if national regulators cannot agree or if they ask it to intervene; monitoring the functioning of the internal market including retail prices, network access for electricity produced from renewables, and consumer rights.
  - Cross-border cooperation between transmission system operators and establishment of the **European Network for Transmission System Operator for Electricity (ENTSO-E)**. National transmission system operators are responsible for ensuring that electricity is effectively transported through grid infrastructure. Due to the cross-border nature of Europe's energy

market, they must work together to ensure the optimal management of EU networks. This is done through ENTSO-E. This organisation: develops standards and draft network codes to help harmonise the electricity flow management across different transmission systems; coordinates the planning of new network investments and monitor the implementation of new transmission projects. This includes publishing every two years a Europe-wide 10 year network development plan.

- Increased **transparency in retail markets** to benefit consumers. The third package includes rules designed to benefit European energy consumers and protect their rights. They include the right to choose or change suppliers without extra charges, receive information on energy consumption, and quickly and cheaply resolve disputes.

- **Electricity cross-border exchanges, capacity allocation and congestion management.**

Regulation 714/2009 stipulates the conditions for network access of cross-border electricity exchanges [56]. Electricity TSOs are required to grant energy companies non-discriminatory access to their infrastructure (thus offering the same service to different users). In certain circumstances however, major new infrastructure may be exempt from third party access rules[8].

Regulation 2015/1222 establishes a guideline on capacity allocation and congestion management [57]. This Regulation sets out minimum harmonised rules for the ultimately single day-ahead and intraday coupling, in order to provide a clear legal framework for an efficient and modern capacity allocation and congestion management system. To implement single day-ahead and intraday coupling, the available cross-border capacity needs to be calculated in a coordinated manner by the TSOs. For this purpose, they should establish a common grid model including estimates on generation, load and network status for each hour. The available capacity should normally be calculated according to the flow-based allocation method[9]. Single day-ahead and intraday coupling ensures that power usually flows from low- price to high- price areas. Two new actors (which may actually coincide) are introduced: the Market Coupling Operators (MCOs), responsible for matching bids and offers through a specific algorithm and the Nominated Electricity Market Operators (NEMOs), responsible for performing tasks related to single day-ahead or single intraday coupling (including: receiving orders from market participants, having overall responsibility for matching and allocating orders, publishing prices and settling/clearing the contracts).

- **Electricity system and market network codes.**

With the growing interconnection and interdependency among countries in the internal energy market, EU-wide rules have become increasingly necessary to effectively manage electricity flows (in the past, these rules were drawn up nationally, or even sub-nationally). These rules are known as network codes and they govern all cross-border electricity market transactions and system operation.

---

[8] *The following criteria apply for electricity infrastructure exemptions: the investment must enhance competition in the electricity supply; the investment could not be undertaken without the exemption due to its risk level; the infrastructure must be owned by a legally separate firm from the TSO in whose system it will operate; users of the infrastructure must pay for access; investment for the project cannot be made from capital gained through income from transmission systems to which it will be linked; the exemption does not harm the functioning of the EU's internal market or the transmission system to which the infrastructure is linked.*

[9] *The flow-based allocation method determines physical margins on each "critical grid element" (transmission lines which are likely to become congested) and their influencing factors (how each critical grid element is affected or affects another critical grid element). This normally allows an increase in cross-border transmission capacity where it is most needed because it more accurately reflects the actual situation on the grid [63].*

As laid down in Regulation 714/2009 [56], the European Commission establishes an 'annual priority list' of areas to be included in the development of network codes for electricity [58]. Afterward, ACER develops 'framework guidelines' used by ENTSO-E to prepare a draft network code. Once ACER first and then the Commission accept the draft network code, it is adopted via the so-called comitology procedure with the approval of the Council of the European Union and the European Parliament.

Network codes under finalisation and/or recently finalised include the following ones: Network Code Operational Security [59], Network Code Operational Planning & Scheduling [60], Network Code Load Frequency Control & Reserves [61], Network Code Emergency and Restoration [62], Network Code Capacity Allocation & Congestion Management [63], Network Code on Forward Capacity Allocation [64], Network Code Electricity Balancing [65].

- **Infrastructure development and priority corridors.**

Regulation 347/2013 concerns guidelines for trans-European energy infrastructure [66]. To help build and finance important energy infrastructure, the EU identified a number of priority corridors under its Trans-European Networks (TEN-E) strategy. These corridors require urgent infrastructure development in order to connect EU power systems currently isolated from European energy markets, strengthen existing cross-border interconnections, and help integrate renewable energy.

The EU priority corridors for electricity are basically those already illustrated in Chapter 1: an offshore grid in the Northern Seas and transmission lines to Northern and Central Europe to transport power produced by offshore wind to energy consumption and storage centres; transmission lines in South Western Europe such as between Spain and France to transport power between EU countries; transmission lines in Central Eastern and South Eastern Europe to strengthen the regional network; Integration of the Baltic electricity market - Lithuania, Latvia, and Estonia - with the rest of the EU. EU thematic areas that relate to the entire EU are: smart grids to help integrate renewable energy and allow consumers to better control their energy demand; electricity highways - grids wheeling electricity over long distances across Europe (e.g.: from wind farms in the North and Baltic Seas to storage facilities in Scandinavia and the Alps).

Based on the priority corridors, the EU draws up a list of Projects of Common Interest (PCIs)[10]. They are key energy infrastructure projects contributing to one or more of the EU energy policy priorities: security of supply, affordability and sustainability. Candidate electricity and gas projects, in order to be eligible for inclusion in the second and subsequent Union lists, should be part of the 10-year network development plan. The EU updates the PCI list every two years. The projects selected can take advantage of a number of benefits including faster permitting procedures and applying for funding from the Connecting Europe Facility - the EU's €50 billion plan for boosting energy, transport, and digital infrastructure till 2020 [36][67].

[10] *The (second) Union list provides for 195 PCIs, including 108 electricity projects, 77 gas projects, 7 oil projects and 3 smart grids projects. The higher number of electricity PCIs is in line with the Union's energy policy objectives and with the TEN-E Regulation, which states that the Union list should focus more on electricity PCIs as part of the transformation of the energy system. Of the electricity PCIs, 27 have been additionally labelled as 'electricity highways' to highlight their relevance for future electricity highways across the Union and their role in accommodating significant volumes of renewable energy and transporting it over long distances [36].*

2.1.3. REGIONAL SCALE OF THE EU ENERGY POLICY MAKING

As explained above, the Lisbon Treaty included energy and trans-European networks among the areas of shared competence between the European Union and the Member States, thus better framing and promoting the EU's role and actions in the energy policy decision making.

While reaffirming the right of the Member States to decide upon their energy mix, the Treaty contributed to the Europeanisation of selected energy policies, subject to the application of the subsidiarity and proportionality principles [47]:

- Under the principle of **subsidiarity**, in areas which do not fall within its exclusive competence, the Union shall act only if and insofar as the objectives of the proposed action cannot be sufficiently achieved by the Member States.
- Under the principle of **proportionality**, the content and form of Union action shall not exceed what is necessary to achieve the objectives of the Treaties.

The Europeanisation of the energy policies can be regarded as a process including two components: a 'top-down approach', with changes emanating from the impact of the Union onto the national policies and a 'bottom-up approach', with (clusters of) Member States acting as forerunners and influencing the EU's political agenda. A clear example of this two-sided process comes from the conception of low-carbon energy policies, with the European Union on one hand being central in driving energy policy at the national level and selected Member States on the other hand influencing the Union process and pushing for more challenging EU-wide targets.

The interplay between the Union and national dimensions is critical in the context of the Energy Union initiatives, since the new energy governance explicitly refers to the two dimensions interaction. Along with the Europeanisation process, another important trend is the regionalisation of selected policy decision making processes: as described below, clusters of nations (in the following defined as regions) are embarking in more or less formalised cooperation partnerships, at several stages - from the anticipation and conception to the implementation and monitoring - of the energy policy decision making process. The regional dimension promises to be a strategic playing field where identifying synergies and reaching compromises between the EU and the Member States policy orientations in the context of the Energy Union's policy initiatives. When fragmented national systems exist, regional cooperation could become an essential part of effective governance for the Energy Union and a first step towards European Union-wide harmonisation where required. Regional cooperation among Member States could also be key to achieving the agreed European Union-level targets more cost-effectively (e.g. making better use of cooperation mechanisms to meet the renewables target), furthering the integration of the internal energy market and strengthening energy security [2][22].

Some crucial examples of the energy policy-related relations and interactions between the EU, the regional and national scales are reported in the following:

- **National energy and climate planning - regional coordination.** Since the 2030 energy strategy targets are not to be translated into national targets through EU legislation, Member States have room to steer their energy system transformation according to national preferences. The attainment of the overall EU targets needs be ensured by a new governance framework based on national energy plans for competitive, secure and sustainable energy. Building on guidance by the Commission and an iterative process with Member States, these plans will be prepared by the Member States under a common

approach, with the objective to ensure investor certainty and transparency, and policy implementation coherence and coordination. Particularly, as far as energy security is concerned, the plans shall include medium- to long-term objectives and standards relating to security of supply, addressing inter alia "diversification of energy sources and supply countries, infrastructure, storage, demand response, readiness to cope with constrained or interrupted supply of an energy source, and the deployment of alternative domestic sources". Additionally, it is stressed that "The objectives should include regional cooperation and the policy measures to achieve these objectives should be regionally coordinated." [22][32][33][34].

- **Market Integration Regional Initiatives.** The European energy regulators have been working together for many years to promote regional cooperation and the integration of energy markets (see Figure 17). The Regional Initiatives were launched in 2006 as voluntary processes aimed at bringing together national regulatory authorities, TSOs and other stakeholders to advance integration at the regional level as a step towards the creation of the internal energy market. These initiatives were used to test solutions for cross-border issues, carry out early implementation of the EU acquis and come up with pilot-projects to be replicated to other regions. Once the Network Codes enter into force, the original purpose of the Regional Initiatives will be reviewed by ACER [145], with a possible stronger focus on network codes implementation monitoring. Particularly, as set out in Regulation 2015/1222 [57], capacity calculation for the day-ahead and intraday market time-frames should be coordinated at least at regional level to ensure that capacity calculation is reliable and that optimal capacity is made available to the market. Common regional capacity calculation methodologies should be established to define inputs, calculation approaches and validation requirements. These methodologies development entails once more a tight interaction of EU, regional and national actors/dimensions as: merging of individual grid models from each TSO to form a common grid model takes place at the European level; coordination and calculation of capacities is performed on a regional level; Data collection from generators and loads, the building of individual grid models and validation of calculated capacities takes place at the national or TSO level [63].
- **Regional operational initiatives.** Regional Security Coordination Initiatives (RSCIs) have been developing on a voluntary basis, under the supervision of ENTSO-E, over the last few years (see Figure 18):
  - Coreso (COoRdination of Electricity System Operators, based in Brussels, Belgium), grouping Belgium, France, Germany, Italy, Portugal and the United Kingdom with the aim to provide coordination services for the secure operation of the regional high voltage electricity system [68].
  - TSC (Transmission System Operator Security Cooperation, based in Munich, Germany), launched by the TSOs of Germany, Austria, Czech Republic, Slovenia, Denmark, Croatia, Hungary, Poland and Switzerland in order to facilitate operational cooperation among TSOs and enhance system security [69].
  - SSC (Security Coordination Centre, based in Belgrade, Republic of Serbia), founded by the TSOs of Serbia, Montenegro and Bosnia and Herzegovina, in order to develop and conduct operation-related coordinated services [70].

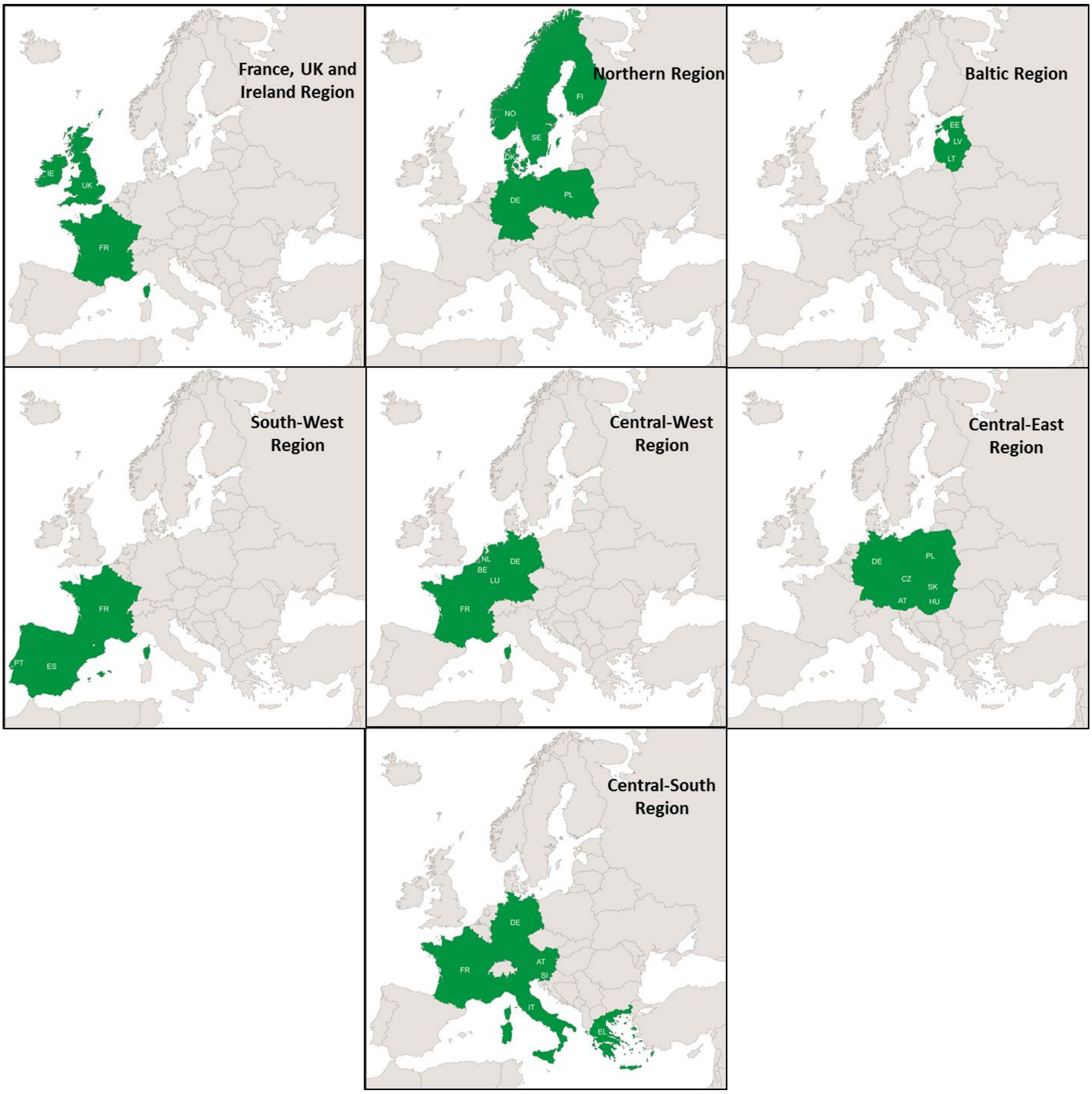


Figure 17 - Original Market Integration Regional Initiatives [146]

Starting from some of these initiatives (see Figure 18), properly upgraded and rebranded by ENTSO-E as Regional Security Coordination Service Providers (RSCSPs), the following services could be offered: common grid modelling, analysis on system security, coordination among a region of outage planning, system adequacy forecasts and coordinated calculation of transmission capacity. The Commission is considering the establishment of Regional Operational Centres (ROCs), with a higher integration level and a possible greater independence from the TSOs, towards which the existing Regional Security Cooperation Initiatives could be important but just first steps. A recent study assesses options and challenges for establishing such Regional Operational Centres throughout Europe, with centralised system operation functions before real time; the aim would be to remove national borders between countries by operating cross-border interconnectors as transmission lines within the control area of a ROC [71]-[74]. An increased coordination between

transmission system operators may, in addition to the establishment of regional operational centres, require a stronger ENTSO-E [75].

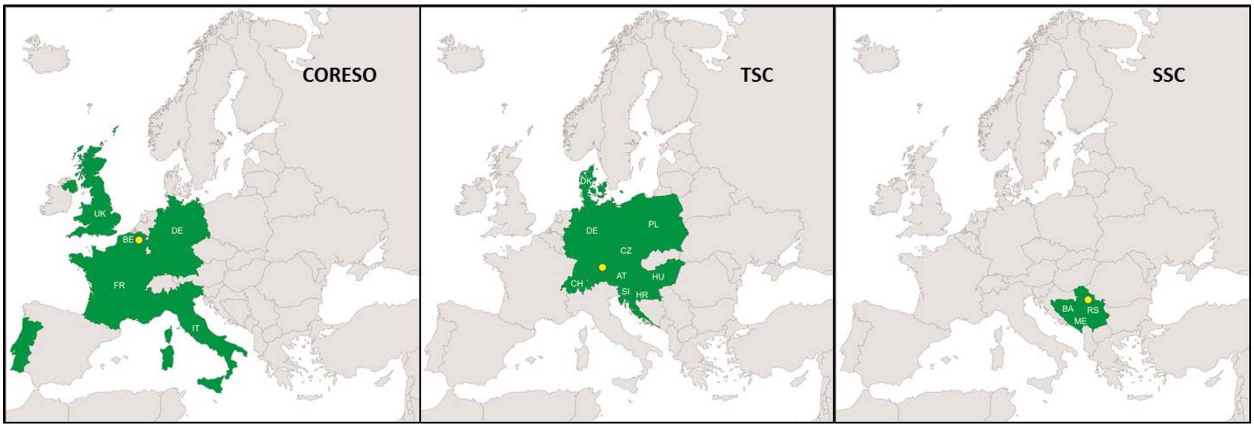


Figure 18 - Regional operational initiatives

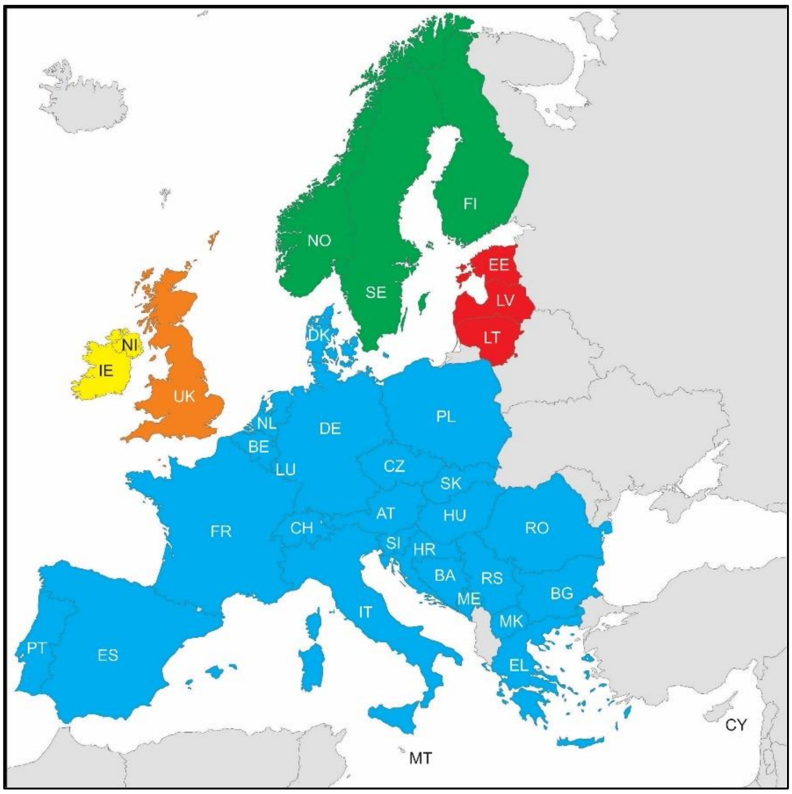


Figure 19 - ENTSO-E system operations regional groups [76]

- **ENTSO-E System Operations regional groups**. ENTSO-E System Operations Committee (see Figure 19) has 5 permanent regional groups based on the synchronous areas (Continental Europe, Nordic, Baltic, Great Britain, and Ireland-Northern Ireland), and 2 voluntary Regional Groups (Northern Europe and Isolated Systems). The groups are tasked to ensure compatibility between system operations on the one side and market solutions and system development issues on the other [76].
- **Regional Groups for the Projects of Common Interest**. The regional groups for the proposal and review of electricity Projects of Common Interest (see Figure 20) are organised according to the provisions of

Regulation 347/2013 [66]: "In order to ensure broad consensus, these regional groups should ensure close cooperation between Member States, national regulatory authorities, project promoters and relevant stakeholders". As there are evident synergies/overlaps with other regional initiatives, it is also specified that "The cooperation should rely as much as possible on existing regional cooperation structures of national regulatory authorities and TSOs and other structures established by the Member States and the Commission":

- Northern Seas offshore grid ('NSOG'): integrated offshore electricity grid development and the related interconnectors in the North Sea, the Irish Sea, the English Channel, the Baltic Sea and neighbouring waters to transport electricity from renewable offshore energy sources to centres of consumption and storage and to increase cross-border electricity exchange.
- North-South electricity interconnections in Western Europe ('NSI West Electricity'): interconnections between Member States of the region and with the Mediterranean area including the Iberian peninsula, notably to integrate electricity from renewable energy sources and reinforce internal grid infrastructures to foster market integration in the region.
- North-South electricity interconnections in Central Eastern and South Eastern Europe ('NSI East Electricity'): interconnections and internal lines in North-South and East-West directions to complete the internal market and integrate generation from renewable energy sources.
- Baltic Energy Market Interconnection Plan in electricity ('BEMIP Electricity'): interconnections between Member States in the Baltic region and reinforcing internal grid infrastructures accordingly, to end isolation of the Baltic States and to foster market integration inter alia by working towards the integration of renewable energy in the region.

- **Electricity system and market development regional initiatives.** Examples of political cooperation in energy matters, with a varying maturity level (Figure 21), include some of those illustrated in Chapter 1, like the North Seas Countries' Offshore Grid initiative (NSCOGI) [41] and the Baltic Energy Market Interconnection Plan (BEMIP) [40], as well as:
  - The Pentalateral Energy Forum (PLEF), an inter-governmental initiative of Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland to promote collaboration on cross-border exchange of electricity [77].
  - The new South-West Europe Interconnectivity Group, a regional coordination initiative to promote system development and market integration with special focus on the Iberian peninsula [42].

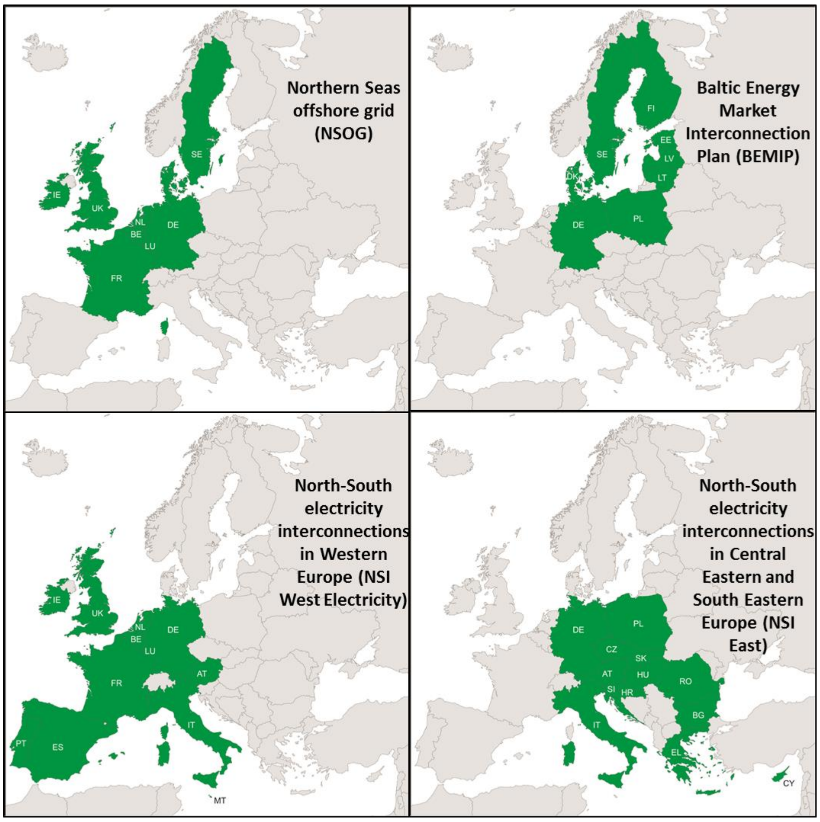


Figure 20 - Regional Groups for the Projects of Common Interest

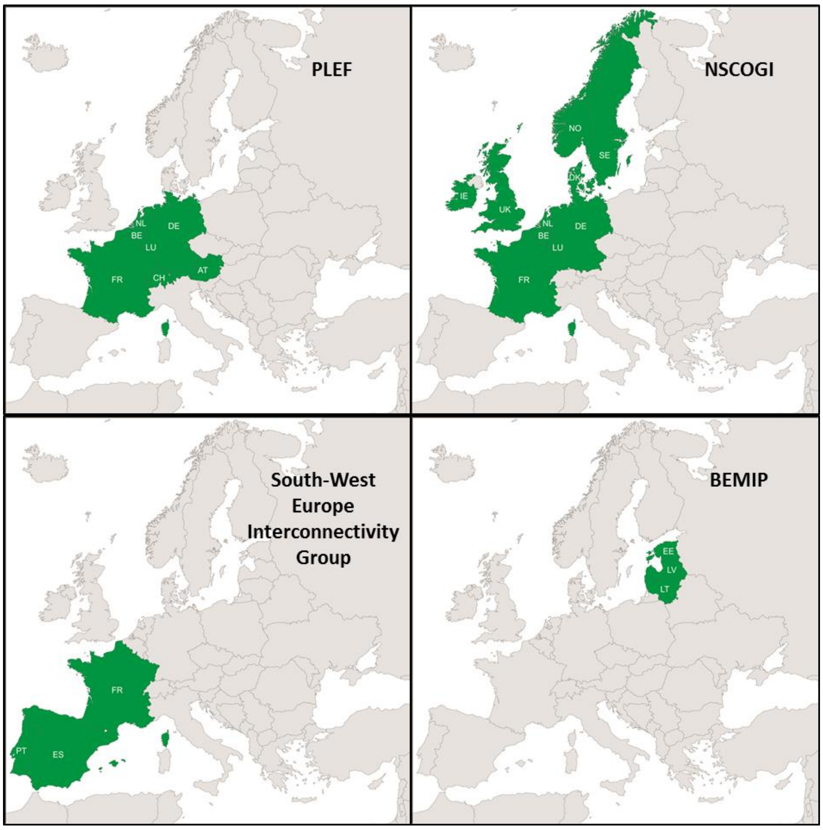


Figure 21 - Electricity system and market development regional initiatives

- **ENTSO-E regional development (investment) groups**. In compliance with Regulation 714/2009 [56], transmission system operators set up regional structures (see Figure 22) within the overall (ENTSO-E) cooperation framework, to ensure that regional developments and results are compatible with the network codes and EU-wide network development plans. The third Energy Package mandated ENTSO-E to publish a biannual, non-binding, Ten-Year Network Development Plan (TYNDP) to support decision-making processes at regional and European level. In addition to the WG TYNDP, the System Development Committee has defined six regional groups (see Figure 22): NS - North Sea, BS - Baltic Sea, CCE - Continental Central East, CSW - Continental South West, CCS - Continental Central South, CSE - Continental South East. The 2014 release includes six Regional Investment Plans and a System Outlook and Adequacy Forecast (SOAF), alongside the Europe-wide TYNDP [78]-[86].

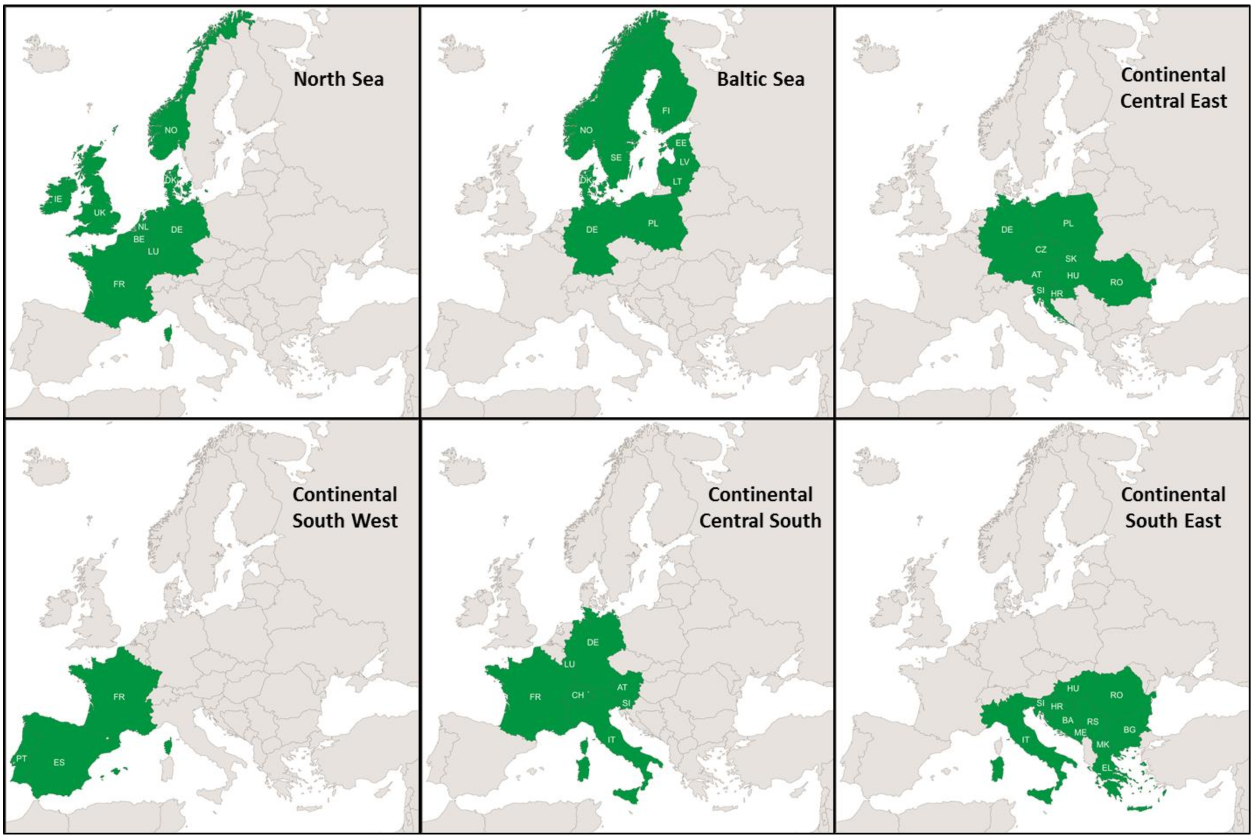


Figure 22 - ENTSO-E system development regions [39]

As we will discuss, a streamlined interaction/combination of models, approaches and actors at the EU, regional and national scale is instrumental for the proper assessment of electricity security properties and the proper definition and implementation of adequate electricity security policies in the evolving EU's electricity system and market.

2.2. EU ENERGY POLICIES AND ELECTRICITY SECURITY INTERACTIONS

The energy policy objectives and the associated policy actions are mutually interdependent: initiatives promoting more security of supply are most likely bound to have an impact - positive or negative - on the affordability and sustainability components of the EU energy policy. It may also occur that through the combined implementation of affordability/sustainability objectives, security of supply may turn out as

affected. Therefore, implementing actions pursuing the combined energy policy objectives is a delicate and challenging undertaking. It certainly requires a deep understanding of the interdependent impacts on the power system, the energy system and society at large.

However, new electricity security actions alone would not be effective without combined, mutually sustaining actions falling under the other two energy policy objectives: affordability and sustainability. In particular, as far as affordability is concerned, a number of actions targeting the wholesale and retail markets - working in tandem with security of supply actions - can be envisaged:

- At transmission/wholesale market level, market functioning and security of supply could be significantly improved by introducing market coupling, improving cross-border flows, strengthening intra-day trading as well as removing price caps to wholesale markets. All of this would improve price formation and enable peak prices that should translate into better investment signals whilst overall facilitating increased renewables penetration [75][87].
- At distribution/retail market level, demand side is expected to play a central role towards safeguarding security and quality of supply. The combination of decentralised generation and storage options with demand side flexibility can further enable consumers to become their own energy suppliers and managers. A crucial aspect to be considered, again at the cross-roads of security of supply, affordability and sustainability policies, is how much cost for the changing infrastructure should be borne by the different actors (including prosumers) [44][75].

In order to understand how a specific action pursuing a certain policy objective - i.e. connecting more large-scale and small scale renewable energy units to attain the sustainability policy target - impacts on the overall power system and market and on the other energy policy objectives, we developed the case study illustrated in Figure 23.

More in detail, assuming that the chain of events develop in a long time span, by pursuing a sustainability-driven action of integrating more renewables, a positive impact is expected on resource-related security of supply, since somehow the dependence from foreign import is going to fall (Figure 23 a)). However, if only sustainability policies are implemented without any parallel action on the power system, the infrastructure-related security is expected to drop (due to the strains put on conventional power plants for balancing variable renewables and difficulties in operating the transmission/distribution grids with more intermittent/dispersed resources). Hence, if security related actions - like improved renewables forecasting, increased system flexibility, enhanced real-time system monitoring/control etc - are flanked to the sustainability ones (Figure 23 b)), one can expect an improvement in infrastructure-related security as the network is better operated. However, issues might still arise especially at distribution system level because distributed resources are not properly enabled to contribute to system operations (e.g. via power system balancing actions) with their ancillary services. The latter could happen only if the affordability dimension (Figure 23 d)) comes into play with market-related actions creating a level playing field for large and small generators and allowing dispersed (maybe aggregated) energy resources to contributing to the power system operation and balancing actions. Clearly, what presented above is just illustrative as it assumes that security related actions at transmission level, differently from the security related actions at distribution level, do not need drastic market changes to be enabled and activated. It is also worth noticing that simply combining competitiveness/affordability actions with sustainability ones is likely not to work properly as well (Figure 23 c)): even if renewables are well supported and promoted from the market/regulation viewpoint, the infrastructure is not fit and equipped for properly managing them (e.g. transmission and distribution systems are not operated with the flexibility needed to cope with ramping up/down renewables sources). In

summary, in this particular case study, all the three policy objectives should work together to obtain an overall positive outcome.

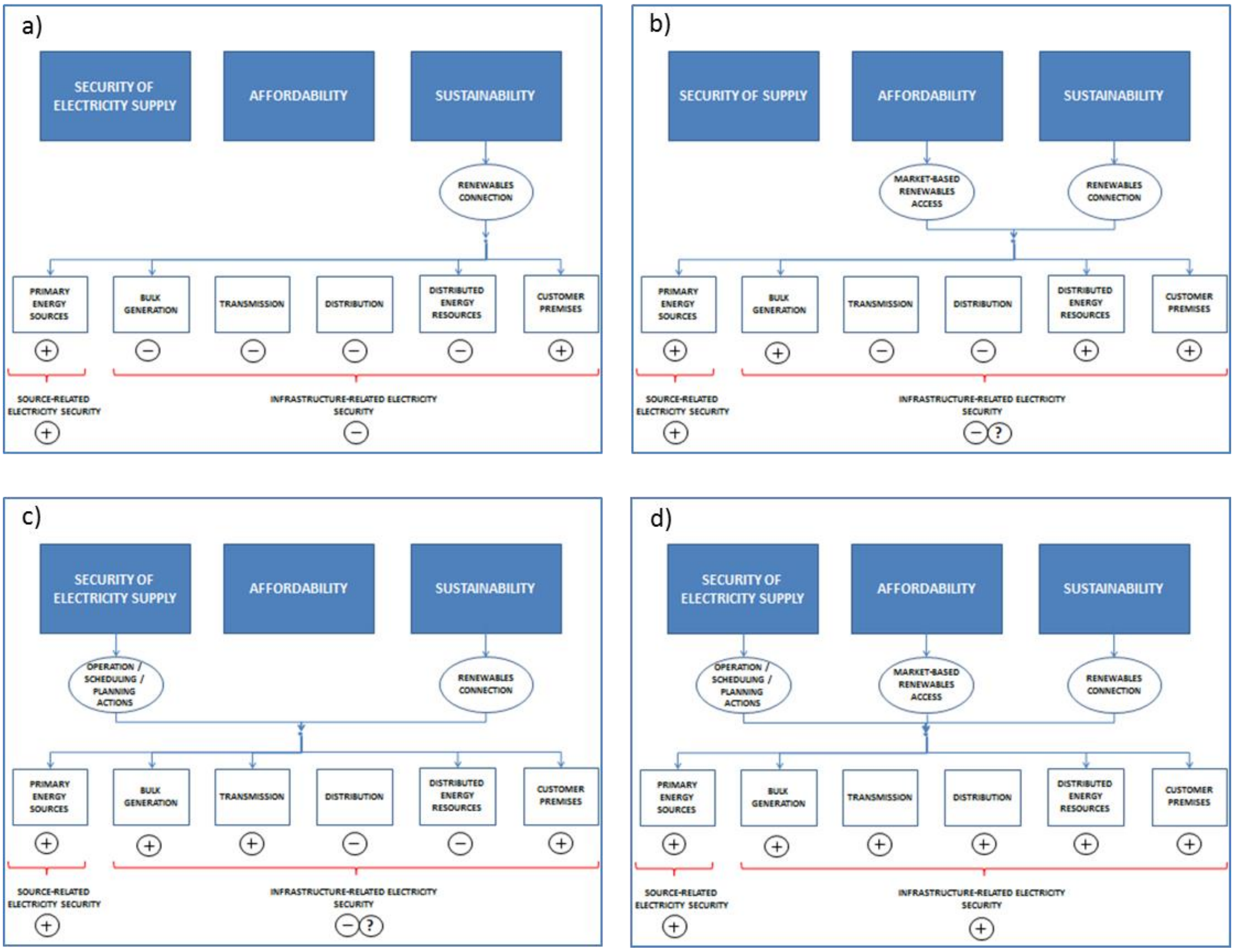


Figure 23 - Interaction of EU energy policies and implications on security of supply

Tensions that could arise between climate change and energy policies are discussed for example also in [88]. Clearly, this example cannot be generalised, however it hints at the complexity and multidimensionality facing the energy policy objectives interaction, combination and implementation to support the EU's energy transition [4][89]. A conclusion we can draw is that, when combining different actions, the impact becomes more complex to predict/quantify and only through a balanced implementation of actions within the three policy objectives, a positive result for security of supply safeguard/improvement (as well as for other policy objectives) might be achieved.

3. ATTRIBUTES OF ENERGY AND ELECTRICITY SECURITY

"People only accept change in necessity
and see necessity only in crisis."

Jean Monnet, EU founding father

In this Chapter, first the energy system and energy supply in general are characterised. Subsequently a taxonomy for energy and electricity security, at the cross-roads of science and policy, is proposed. Then the main techno-economic challenges to power system security are discussed. Finally the main threats, the related adverse events and their potential effects on electricity security are described.

3.1. A TAXONOMY FOR ENERGY AND ELECTRICITY SECURITY

3.1.1. ENERGY SUPPLY OBJECTIVES AND PROPERTIES

Energy must be provided when and where individuals and societies require it, in the amount needed and according to certain minimum criteria and standards (e.g. the power profile required by the consumers). Failing to do so would result in serious hazards to the European society and economy.

The European Union's energy policies are characterised and driven by the three security, affordability and sustainability objectives introduced in Chapter 2. In particular, the energy security objective entails ensuring a reliable energy provision whenever and wherever needed [22].

Energy can be characterised from two different viewpoints, one more linked to the priorities set out by the policy making and the other one more associated to the intrinsic techno-economic features of the energy system and the energy delivery. When discussing about energy, one can indeed refer to:

- the energy supply **overarching objectives**, which are the goals to be met in terms of long-run energy availability, energy cost-effectiveness and affordability, and desired quality and security levels.
- the energy system **specific** techno-economic **attributes**, like flexibility, stability, resilience etc, instrumental to achieving the aforementioned objectives.

The context in which energy and electricity systems evolve and interact can be described as a dynamic and complex multilayer environment composed of [90]:

- a physical layer hosting the processes/technologies for the primary energy conversion into electricity and the related electricity infrastructure (both at transmission and distribution level),
- an information and communication layer with technologies supporting current and possible new operation schemes,
- a market layer with several design and integration options at local/regional/continental level,
- and a decision making layer providing coordinated inputs to the various layers to attain the goals and the attributes of electricity delivery.

More specifically (see Figure 24) for the power system evolving towards a smart grid, the layers are identified and defined in the Smart Grid Architecture Model (SGAM) by the European Standard Organisations. While the SGAM domains represent the different sectors of the electricity value chain, the Smart Grid Architecture Model zones represent the hierarchical levels of power system management. These zones reflect the concept of data/spatial aggregation and functional separation in power system management. The layers are defined as follows [91]:

- The component layer is the physical distribution of all participating components in the smart grid context. This includes system actors, applications, power system equipment, protection and tele-control devices, network infrastructure and any kind of computers.
- The communication layer describes protocols and mechanisms for the interoperable exchange of information between components.
- The information layer describes the information that is being used and exchanged between functions, services and components.
- The function layer describes functions and services including their relationships from an architectural viewpoint. The functions are represented independently from actors and physical implementations in applications, systems and components.
- The business layer represents the business view on the information exchange related to smart grids. It can be used to map regulatory and economic (market) structures and policies, business models/portfolios/capabilities/processes.

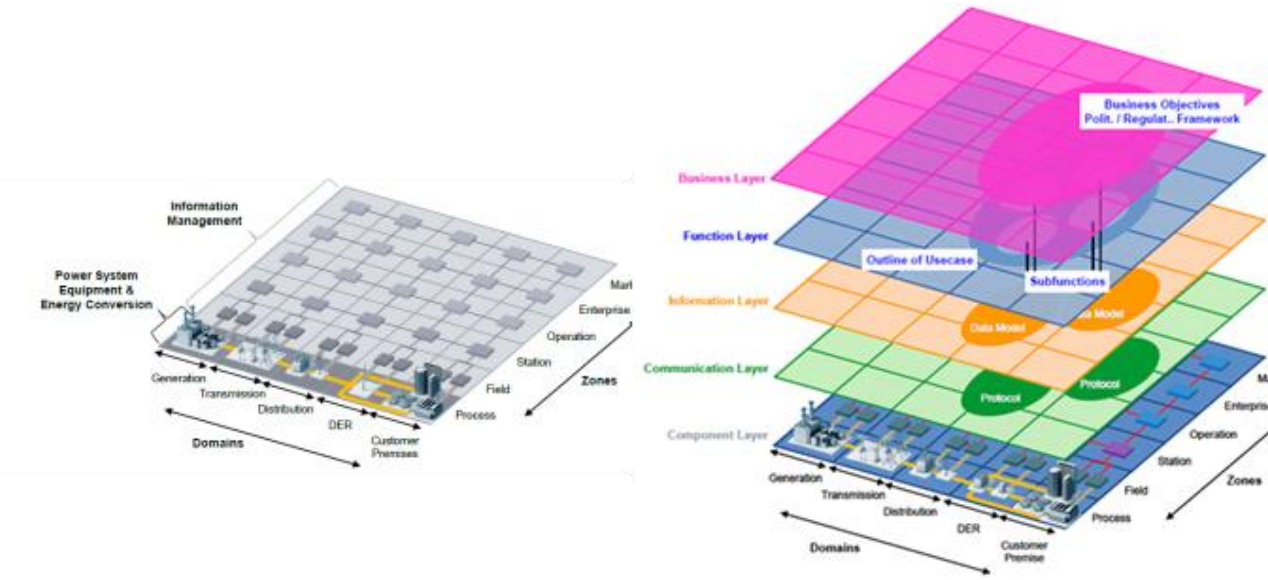


Figure 24 - Smart Grid Reference Architecture [91]

3.1.2. ENERGY SECURITY DIMENSIONS AND ATTRIBUTES

Energy needs to be converted from natural resources to forms which can be readily exploited by final users. As of consequence, identifying the components of the energy supply chain - from sources to final uses - is crucial to characterise the energy delivery process and analyse what can go wrong in the several conversion

stages. The chain can be complex and involve many steps, such as extraction, transportation, conversion, distribution and final use. The chain can also stretch over long distances and across national borders. The end user only experiences the final steps. However, researchers and policy makers may be interested in exploring different parts of the upstream supply chain to identify root causes of insecurity, bottlenecks and interactions with other policy domains [92][93].

In order to reach final users, energy sources - wherever they are located - need to be carried via transport infrastructure running through dedicated corridors (at cross-national, national, regional or local scale, depending on the size and the location of the energy sources respect to the consumption centres). Consequently, all the following aspects have a key role to play in defining the attributes of energy and electricity security:

- The energy sources location (e.g. crude oil or shale gas production), with geopolitical implications for energy security;
- The energy sources time availability (e.g. wind energy variable generation), with techno-operational implications for energy security;
- The regulatory and market arrangements governing the energy production, transformation, transportation and delivery processes;
- The corridors hosting long distance transport infrastructure (e.g. newly planned gas pipeline reaching Europe from Russia through alternative routes), with geopolitical implications for energy security;
- The infrastructure characteristics (e.g. typologies of centralised/distributed generation plants installed in the system, or number of direct current interconnectors linking two networks), with technical and operational implications for energy security/stability at transmission level and for energy security/quality at distribution level.

Reliable energy delivery can indeed be altered by several adverse events. A threat is here defined as any circumstance with the potential to adversely impact a system, whereas an adverse event is a materialised threat. The attributes of energy security can be therefore matched with properties of the threats, the events and their effects on the energy system. In particular, one can distinguish [95][101]:

- The **impact areas** of the event along the energy supply chain. The supply chain typically includes the following areas: resource extraction, transport/storage, refining/conversion, transmission/distribution and end use.
- The **time duration** of the event, i.e. the period spanning from when the risk materialises to the end of its observed (negative) effect on the energy system.
- The **internal or external provenance** - respect to the energy system under study - of the event, hence affecting the degree and type of control over/response to the threat (external threats can be rather mitigated than controlled).
- The **intrinsic nature** of the threat triggering the adverse event: **natural, accidental, malicious, systemic**. More in detail, natural threats are caused by not controllable natural forces (earthquakes, tsunamis, hurricanes...), accidental threats are caused by the failure of network devices or wrong human decisions (operational fault, system equipment failure, accident due to the poor management…); malicious threats are intentional actions to bring damages to the system (terrorist, criminal group, cyber

attackers, geopolitics…); systemic threats emerge with the evolution of the energy system (the integration of renewable energy, the interdependency between the power system and other infrastructure...)

As an example of malicious event of external provenance and impacting large areas of the national electricity supply chain, in December 2015, an unprecedented cyberattack caused a blackout on the Ukrainian power grid affecting hundreds of thousands of people; sophisticated and coordinated attacks targeted six power providers and knocked out internal systems intended to help the power companies restore power. As one more example of malicious event of external provenance, impacting large portions of the European gas supply chain, in 2009 the Russian gas supplies to Ukraine and Europe were drastically reduced and several South-East European countries recorded a drop in their gas supply ranging from 14% to 100%. As an example of natural event of external provenance affecting large areas of the European electricity supply chain, the severe heat affecting Europe in June-August 2003, brought summer temperatures 20% to 30% up beyond the seasonal average values, with a consequent massive increase of electricity demand for conditioning/refrigeration; the temperature rise caused several thermal power plants to shut down and/or work beyond their environmental/safety limits, bringing the spot market electricity price up to 1000 €/MWh. Finally, as one more example of natural event affecting local areas of the distribution system, during the floods striking north-western England in December 2015, thousands of homes were left without power for several days [97]-[100].

With the aim to understand the role played by scientific modelling and analyses in support of policy making, energy security is in the following defined in terms of inherent energy system’s operational performances and wider energy system’s capabilities to cope with adverse events.

The following definitions have been derived from a reasoned combination of relevant EU and international policy, regulatory and industrial sources (the main ones are collected in Table 3, where definitions from major international actors - primarily tackled from the electricity security angle - are displayed) and an intense research of scientific literature (see again Table 4 and particularly [89][95][101]-[104]):

- **Operational security** is the capability to withstand sudden disturbances, such as unanticipated losses of critical system components, by maintaining the energy system operation within defined boundaries. Operational security is prevalently correlated to internal threats and medium-high probability events.
- **Flexibility** is the capability to cope with the short-term uncertainty of energy system variables, by balancing any deviations between the planned or forecast supply and demand, on one side, and the realised values, on the other side. Flexibility is prevalently correlated to internal threats and medium-high probability events.
- **Adequacy** is the capability to meet demand at all times under most of the anticipated conditions. Adequacy is prevalently correlated to internal threats and medium-high probability events.
- **Resilience** is the mid-term capability to absorb the effects of a disruption and recover a certain performance level. Resilience is prevalently correlated to external threats (materialising in sudden or accumulating strains) and lower probability events.
- **Robustness** is the long-term capability to adapt the energy system evolution to economic and/or geopolitical constraints. Robustness is prevalently correlated to external threats and lower probability events.

An important distinction is between "normal" behaviour, where the focus is on how things work (either the system, or the market, etc), and "abnormal behaviour", where the focus is on how things might fail (and for this one needs to explicitly model failures, faults, hazards, errors, etc). In other terms, the first three energy security properties - operational security, flexibility and adequacy - are better placed to describe how the energy system should work, whereas the last two properties - resilience and robustness - are more suited to explain how the energy system might fail. The borders between these properties, as confirmed by relevant literature in the field, are not fully defined.

Additionally, we consider that **reliability** is the probability that a system can perform a required function under given conditions for a given time interval.

Reliability tends to be considered as a static concept, typically related to higher probability/lower impact events, describing the probability of a certain system performance over a certain period. It might combine - particularly in the power system parlance - operational security, adequacy and flexibility properties.

Resilience instead tends to be considered as a dynamic concept, typically related to lower probability/higher impact events. It helps understanding if/how quickly the system recovers after a perturbation. Resilience includes the capability to cope with mid-term changes/hazards, acting through the accumulation of effects (e.g. climate change) - either stressing the systems little by little, or reaching thresholds where normal operation, control, protection strategies are ineffective. Simple short-term shocks challenge the reliability of the system - an interaction which is better known, understood, measured and studied.

Although vulnerability draws much attention, there is no widely accepted common definition. The author [102] lists 29 different literature definitions for the vulnerability term, depending on the purposes of the studies. Most of the definitions are related to vulnerability of societies but not vulnerability of the system itself. Similarly, differences in vulnerability definitions can be found with reference to different infrastructures [106]-[109]. A common feature recurrently implied is that system vulnerability is closely connected to the system ability to keep its functionality when exposed to materialised threats. In some definitions, the ability of function restoration is also included. In addition, several factors (physical, social, economic, and environmental) that have an influence on the vulnerability of a system can be considered [105]-[109]. Some authors in the power system field [110][111] consider vulnerability simply as the antonym of robustness.

For the purposes of our research we generally assume that **vulnerability** is the lack of robustness and resilience.

3.1.3. ELECTRICITY SECURITY DIMENSIONS AND ATTRIBUTES

After having introduced the challenges and issues for energy in general, electricity is our primary focus in the remainder of this Chapter and in the following Chapters. Electricity is a very special form of energy which can be easily wheeled, converted and utilised; on the other hand, also due to its currently low level of techno-economic viable storability, electricity per se and the electricity system in general exhibit some inherent "insecurity" features which need to be assessed and accounted for.

The mission of the power system is the provision of the electricity required to meet demand at all points in time, in such a way that all customers (residential, industrial, tertiary and public service) are supplied with the needed amount of electricity at the required locations, following their required power consumption profile in different time frames.

Power system security refers to the ability of the system to continuously fulfil its function against possible adverse situations. Power system can be vulnerable to threats that, when materialised, may cause foreseeable and unforeseeable disruption. The threat against power systems can be classified into natural, accidental, malicious and systemic. More in detail [95]:

- **Natural threats** are caused by natural forces (earthquakes, tsunamis, hurricanes...) not controllable by humans in the short-run and which may happen around the world with different spatial scales (local, national, continental) and time frames (instantaneously, for minutes or for days).
- **Accidental threats** are caused by the failure of network devices or wrong human decisions (operational fault, system equipment failure, accident due to the poor management…).
- **Malicious threats** are intentional actions to bring damages to the system (terrorist, criminal group, cyber attackers, geopolitics…).
- **Systemic threats** emerge with the evolution of the power system (the integration of renewable energy, the interdependency between power system and other infrastructures...).

Table 4 summarises the definitions of electricity security and electricity properties coming from several EU and international policy related documents, sector associations and scientific/technical literature.

The present work concentrates on **electricity security**, here defined as the power system capability to withstand disturbances - i.e. events or incidents producing abnormal system conditions - and contingencies - i.e. failures or outages of system components - with minimum acceptable service disruption.

Likewise energy security, the threats potentially affecting electricity security can be characterised in terms of:

- The **impact areas** of the threat within the electricity supply chain. The main difference (compared to the energy system) regards the supply chain definition, including the following domains as defined by the European international standard organisations: bulk generation, transmission, distribution, distributed energy resources (typically in the range of 3 kW to 10,000 kW - some of them are directly controlled by the distribution system operators) and customer premises (hosting both electricity end users and producers, generally not controlled by the distribution system operators) [91].
- The **time duration** of the threat. One of the main differences (compared to the energy system) is the much more complex dynamics and much higher time granularity of the very short term events, easily occurring not only in the second time frame but also in the ms or even µs time scales. The following time frames, where rather different events and dynamics can be observed in the power system, are considered:
  - **Short-term**: from real time up to tens of minutes: in this time window demand and supply shall be instantaneously balanced by means of the "on-line control" of power plants and transmission systems and actions within the balancing market. In this frame no new grid transfer capacity can be built, generation technologies are given and assumed available (e.g. conventional generation plants are available as well as variable wind and solar power though with their inherent variability features).
  - **Mid-term**: up to weeks: particularly, a few day time frame is routinely employed for market based unit commitment/dispatch and generation scheduling in the Day Ahead Market. In this

frame no new grid transfer capacity can be built, generation technologies are given but may suffer planned/unplanned outages.

- **Long-term**: up to years: it is used for yearly bilateral negotiation or contractual trades. In this frame some new grid capacity can be built (e.g. by means of reconfiguring some substations, installing phase shifting transformers or reconductoring lines) as well as some new generation technologies even though most of the grid/generation technologies are given.
- **Very long-term**: up to decades: this is the standard horizon for energy policy planning and infrastructure reinforcement. In this time frame much larger grid capacities can be built (e.g. new electricity highways), current generation technologies can be fully replaced by new ones (for example some non-renewable sources may be depleted or, as another example, offshore wind could be replaced by wave energy).

- The **internal or external provenance** - respect to the electricity supply chain under study – of the threat. In this case the wider energy system becomes one of the external environments potentially hosting a threat; additionally, other external systems/environments (geopolitical situations, economic market conditions etc) can still originate adverse events exerting pressure on the electricity system.
- The **intrinsic nature** of the threat. As discussed already for the energy system, the threats against power systems can be classified as well into natural, accidental, malicious and systemic.

Table 4 - Electricity security definitions

	EC, ACER	NERC	IEC	ENTSO-E	IEEE, IEA, EPRI, NREL	OTHERS
RELIABILITY	**(Short-term) operational reliability** aims at maintaining sufficient system flexibility to balance the electricity system notably in response to (sudden) demand variations or unexpected outages [ACER][112].	**Reliability** consists of two concepts: - **Adequacy** (see below). - **Operating reliability** or **Reliable operation** (see below) ("operating reliability" replaced "security" in 2001 when security became synonymous of critical infrastructure protection [117][118])	**Reliability** is the probability that an electric power system can perform a required function under given conditions for a given time interval [94].	Electric system **reliability** can be addressed by considering two basic aspects: - **Adequacy** (see below). - **Security** (see below) [121].	**Reliability** is the probability of its satisfactory operation over the long run [IEEE][132].	
SECURITY	- **Security of electricity supply** is the ability of an electricity system to supply final customers with electricity [EC][50]. - **Operational network security** is the continuous operation of the transmission and, where appropriate, the distribution network under foreseeable circumstances [EC][50]. - **Operational security limits** are the acceptable operating boundaries for secure grid operation such as thermal limits, voltage limits, short-circuit current limits, frequency and dynamic stability limits [EC][57].	**Reliable operation** is operating the elements of the Bulk-Power System within equipment and electric system thermal, voltage, and stability limits so that instability, uncontrolled separation, or cascading failures of such system will not occur as a result of a sudden disturbance, including a cybersecurity incident, or unanticipated failure of system elements [117].	**Security** is the ability of an electric power system to operate in such a way that credible events do not give rise to loss of load, stresses of system components beyond their ratings, bus voltages or system frequency outside tolerances, instability, voltage collapse, or cascading [94].	**Security** is the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements [121].	- **Security** is the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service [IEEE][132]. - **Security of electricity supply** comprises: security of fuel (to generate electricity); security of system operations (avoiding blackouts); resource adequacy (avoiding load curtailment) [IEA][122].	- **Security of [electricity] supply** means that customers have access to electricity at the time they need it with the defined quality and at a transparent and cost-oriented price [CEER][139] - **Security of electricity supply** is the ability to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner, relating to the existing standards and contractual agreements at the points of delivery [EURELECTRIC][140].
STABILITY		**Stability** is the ability of an electric system to maintain a state of equilibrium during normal and abnormal conditions or disturbances [117].	**Stability** is the ability of an electric power system to regain or to retain a steady-state condition, characterized by the synchronous operation of the generators and a steady acceptable quality of the electricity supply, after a disturbance due, for example, to variation of power or impedance [94].	**Stability** is the ability of an electric system to maintain a state of equilibrium during normal and abnormal system conditions or disturbances. It includes: Small-Signal Stability and Transient Stability [121].	**Stability** is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [IEEE][132].	
ADEQUACY	- **Balance between supply and demand** means the satisfaction of foreseeable demands of consumers to use electricity without the need to enforce measures to reduce consumption [EC][50]. - **(Long-term) resource adequacy** aims at ensuring availability of sufficient capacity in the electricity systems to meet demand at all times, including at peak load periods [ACER][112].	**Adequacy** is the ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements [117].	**Adequacy** is the ability of an electric power system to supply the aggregate electric power and energy required by the customers, under steady state conditions, with system component ratings not exceeded, bus voltages and system frequency maintained within tolerances, taking into account planned and unplanned system component outages [94].	**Adequacy** is the ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements [121].	**Adequacy** is the system's capability to meet system demand within major component ratings and in the presence of scheduled and unscheduled outages of generation and transmission components or facilities [IEEE][133].	

	EC	NERC	IEC	ENTSO-E	IEEE, IEA, EPRI, NREL	OTHERS
FLEXIBILITY	**Flexible** markets can be created by: - offering consumers the possibility to actively participate - providing market signals for investments in generation and the efficient use of available resources - building missing infrastructure, better using existing infrastructure - ensuring flexible trading - eliminating regulated prices and inefficient support schemes - coordinating RES support schemes [EC][113].	System **flexibility** is defined as the ability of supply-side and demand-side resources to respond to system changes and uncertainties. Flexibility also includes the ability to store energy for delivery in the future and the operational flexibility to schedule/dispatch resources in the most efficient manner [120].		**Flexibility** is the ability of the proposed reinforcement to be adequate in different possible future development paths or scenarios, including trade of balancing services [80].	- **Flexibility** is the ability to adapt to changing conditions while providing electricity safely, reliably, affordably, and in an environmentally responsible manner [EPRI][135]. - **Flexibility** is one element to reliability and is a subset of frequency stability (other stability impacts such as voltage stability can arise when integrating wind and solar into power grids) [NREL][136].	**Flexibility** is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterize flexibility include: amount of power modulation, duration, rate of change, response time, location etc [EURELECTRIC][141],[EC SMART GRID TASK FORCE][142].
RESILIENCE	- **Resilience** is the ability of an individual, a household, a community, a country or a region to withstand, to adapt, and to quickly recover from stresses and shocks [EC][116]. - […] diversification of energy sources, suppliers and routes is crucial for ensuring secure and **resilient** energy supplies to European citizens and companies [EC][2]. - The EU has an overriding priority: to ensure that the best possible preparation and planning improve **resilience** to sudden disruptions in energy supplies [EC][9].	Infrastructure **resilience** is the ability to reduce the magnitude and/or duration of disruptive events [119].	**Resilience** of the grid is often associated with making the grid able to withstand and recover from severe weather and other physical events, but resilience should also include the ability of the cyber-physical grid to withstand and recover from malicious and inadvertent cyber events. [96].	**Technical resilience**/system safety is the ability of the system to withstand increasingly extreme system conditions (exceptional contingencies) [80].	**Resilience** of the energy sector refers to the capacity of the energy system or its components to cope with a hazardous event or trend, responding in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation [IEA][122].	**Resilience** is the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events [National Academies][138].
ROBUSTNESS		**Robustness** is the ability to keep operating or to stay standing in the face of disaster [119].		**Robustness** of a transmission project is defined as the ability to ensure that the needs of the system are met in a future scenario that differs from present projections (sensitivity scenarios concerning input data set) [80].		
VULNERABILITY	Reducing the **vulnerabilities** of critical infrastructure and increasing their resilience is one of the major objectives of the EU [EC][116]				**Vulnerability** is a measure of the system's weakness with respect to a sequence of cascading events that may include line or generator outages, malfunctions or undesirable operations of protection relays, information or communication system failures, and human errors [IEEE][137].	

We already discussed that, in order to reach final users, energy sources - wherever they are located - need to be carried via (cross-national, national, regional or local scale) infrastructure. This allows us to identify and define four main dimensions of electricity security, across which the electricity security properties of a power system can be triggered, challenged, assessed and observed (see Figure 25). The four dimensions can be regarded as a virtual extension of the electricity value chain - i.e. the infrastructure - dimension, covering increasingly wider and less physical related aspects of the reliable electricity delivery mission.

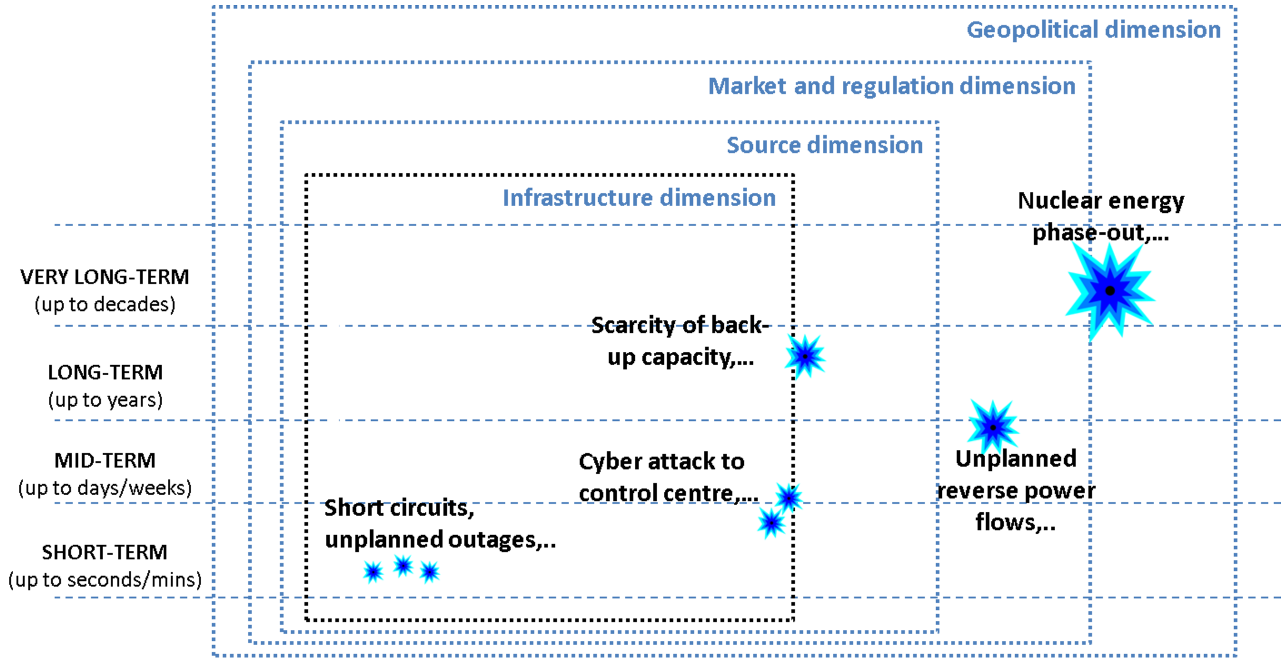


Figure 25 - Dimensions of electricity security and examples of strains affecting electricity security

More in detail:

- In the **infrastructure dimension,** electricity security is assessed in terms of the power system (i.e. the electricity value chain) capability to supply end users with minimum service standards/criteria.
- In the **source dimension,** electricity security is assessed in terms of the energy system capability to ensure the accessibility, in the various timeframes, to primary sources to be converted in the power plants to meet the required total demand of electricity.
- In the **regulation and market dimension,** electricity security is assessed in terms of the power system and market capability to adequately fulfil their electricity delivery mission with a set of laws, rules and market arrangements and price schemes.
- In the **geopolitical dimension,** electricity security is assessed in terms of the energy/power system capability to ensure the availability of primary sources and/or cross-border electricity exchanges in case of economic or geopolitical constraints/stresses (e.g. unilateral primary energy cut by international players outside the considered region).

Those dimensions have also a correlation with the spatial/time features of energy sources and electricity infrastructure: the infrastructure dimension is (also but not only) relevant to the shorter term dynamics and strains, the geopolitical dimension tends to be considered in the longer term processes (although some effects can then materialise in the short term), the source dimension and the market and regulation dimension are often (but not only) triggered in medium-term processes and events. By definition, the geopolitical, regulation and market, and source dimensions are external to the infrastructure dimension: they therefore host threats external to the electricity value chain; the latter threats might be able though,

once they materialise into adverse events, to have an indirect impact on the inner infrastructure/electricity value chain dimension. As an example, a threat (e.g. an international political dispute between a gas exporting and importing country) located in a trans-boundary energy corridor in the geopolitical dimension, may materialise in a disruption event (gas supply interruption via a critical pipeline serving a group of EU countries), on its turn impairing the power generation performances of gas-fired power plants, hence causing a disturbance to power system operation in the infrastructure dimension.

The definitions for electricity security are based on those previously introduced for energy security - thus derived from a reasoned combination of relevant EU and international policy, regulatory, industrial and scientific sources (see again Table 4 and particularly [89][95][101]-[104]) - with proper adjustments to take into account the specificities of the electricity system:

- **Operational security** is the ability of the power system to maintain or to regain an acceptable state of operational condition after disturbances. It covers dynamic issues and real-time network management issues.
- **Flexibility** is the capability of the power system to cope with the short/mid-term variability of generation (like renewable energy) and demand so that the system is kept in balance.
- **Adequacy** is the ability of the power system to supply the aggregate electrical demand at all times under normal operating conditions. It generally includes:
  - a **generation/storage adequacy** component, representing the availability of large-sized generation and storage capacity to meet demand in the various timeframes;
  - a **transmission network/import adequacy** component, representing the ability of the internal grid and cross-border interconnectors to transfer the needed power from sources to sinks;
  - whereas the **distribution network and the end user adequacy** components only recently started to be considered in conjunction with the emerging trends on smart distribution grids and **demand response** technologies;
  - a **market adequacy** component, representing the capability of the market to facilitate the exchanges between producers and consumers.

Additionally, a further crucial attribute of electricity supply is:

- **Power quality**, which is the ability of the power system to deliver electricity to the end-users with a set of energy parameters, at a certain location and time, capable of satisfying the customer needs and requirements.

As seen with energy security, electricity security can be mainly characterised via stability, flexibility and adequacy, with special reference to the internal electricity value chain challenges and constraints.

Eventually, similarly to energy security, electricity security can be mainly described in terms of robustness and resilience in the event of pressures originating outside the electricity system [80][103]:

- **Resilience** is the mid-term capability of the power system to absorb the effects of a disruption and recover a certain performance level.
- **Robustness** is the long-term capability of the power system to cope with constraints/stresses originating outside the infrastructure dimension.

Figure 26 illustrates the intersections among electricity security dimensions and properties in the different time frames. Here it is worth noticing how resilience and robustness, although mostly linked to threats and events originating outside the power system (in the energy system at large, in the geopolitical dimension,

etc.), are anyhow considered as properties and capabilities of the power system to withstand the associated strains and contribute to recover a certain performance level.

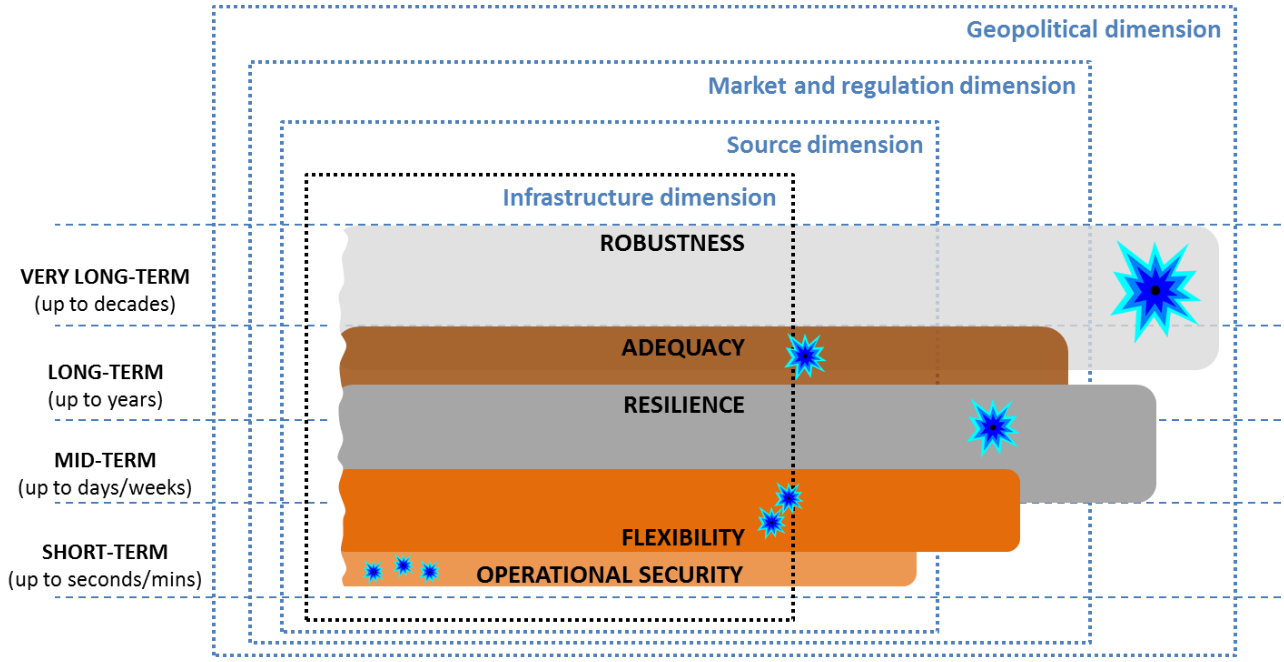


Figure 26 - Electricity security dimensions and properties

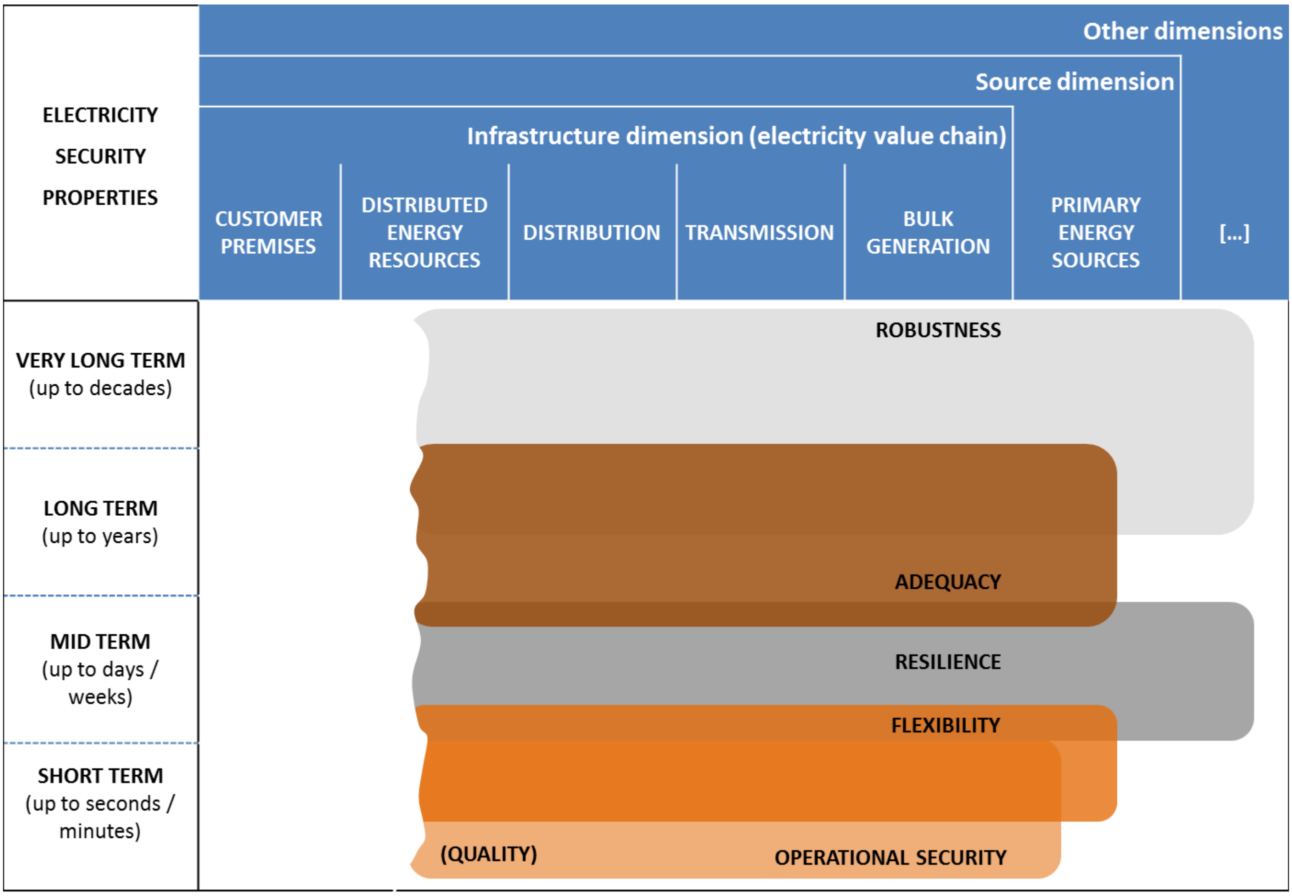


Figure 27 - Electricity security properties and the electricity value chain

In the power system terminology, the term **reliability** - which refers to the ability to supply loads with high level of probability for a certain time interval - is frequently adopted to combine operational security and adequacy properties. As explained for energy security, even if borders cannot be fully drawn, **reliability** tends to capture more the operational security, flexibility and adequacy properties of the power system, whereas **vulnerability** tends to capture more the absence of robustness and resilience. Figure 27 zooms in the infrastructure dimension - detailing the electricity value chain domains as defined by the smart grid international standardisation organisations [91] - of the electricity security problem.

Besides the above mentioned components of the system (i.e., generation and network), electricity demand can also play an increasing role in assuring "electricity security" by helping reducing/increasing load to match generation supply deficits/surpluses at different time frames. The new paradigm of electricity systems, with its shift from relatively passive to active distribution systems, poses new challenges to power system security assessment and management though.

3.2. POWER SYSTEM SECURITY CHALLENGES AND ACTIONS

In the following, we describe the main techno-economic and regulatory challenges to power system security in the four different time frames previously introduced: short-term, mid-term, long-term and very long-term. Our main focus is the transmission system and its interaction with other domains (particularly distribution) of the electricity value chain.

Most of the techno-economic challenges have to do with the fact that electricity is not easily (or better, economically) storable; consequently, frequency and voltage, due to continuous changes both in demand and supply side, are constantly subject to variations in the electric power system. Frequency and voltage should be kept as close as possible within the admissible variation ranges to ensure that all the system components operate in the most appropriate way according to their technical design specifications. To tackle this issue, power system operators have developed methods and practices for frequency and voltage regulation. These are traditionally based on the control possibilities mainly offered by synchronous generators equipped with speed governors and automatic voltage regulators [124][151].

Keeping the transmission system secure and stable is a complex task. In order to avoid disruptions and wide-area disturbances, power flows should be kept within the thermal and stability limits of the transmission infrastructure while taking care of regulating frequency and voltages. Coping with variability when balancing supply and demand is not a new task (especially on the demand side), even though wind power uptake significantly increases the imbalance correction challenges on the supply side. Indeed some renewable electricity sources - particularly wind, generally connected at transmission level and PV, generally connected at distribution level - display to a greater extent than conventional power generation two features: variability and uncertainty of the their power output [123][124][152].

3.2.1. SHORT-TERM SECURITY

Power system security in this time frame critically depends from the interaction of a few stakeholders, in particular TSOs and DSOs and conventional and renewable generation companies; also residential, industrial and commercial consumers play a role, depending on the system/region under observation [139].

The main technical challenges in this time frame can be summarised in the following ones: keeping the system stable following a perturbation, balancing generation and demand across the whole system taking

into account generation and demand statistical variability and planned/unplanned system component outages.

- **Renewable energy short-term variability and uncertainty**. Variable renewable energy - even supposing that its output is perfectly predictable - necessarily fluctuates in the short-term depending on weather conditions. This means that the system operator has to quickly react by increasing/decreasing other generation outputs to compensate for (especially) wind power ramps-up and downs. On top of that, forecasts are not 100% accurate: variable renewable power plants need to adjust inside the hour the forecasts provided inside the day. Nevertheless, their output will still (generally slightly) differ from the forecast. Consequently, the system operator must procure resources to manage the imbalance at very short notice [124].
- **Generation-demand balancing (primary and secondary frequency regulation)**. The objective of frequency regulation is the restoration of the active power balance between supply and demand after any event or perturbation. The frequency is simply a signal of supply-demand unbalances occurring in the system. Over the last years, in correspondence with the growing penetration of variable renewables, an increasing number of frequency deviations caused by short-term mismatches between power consumption and power generation has been recorded in the European synchronous regions [4][151].

  As specified in the Network Code for Load Frequency Control and Reserves [61] for Frequency Regulation, different reserves are deployed after the occurrence of an event (see also Figure 28):

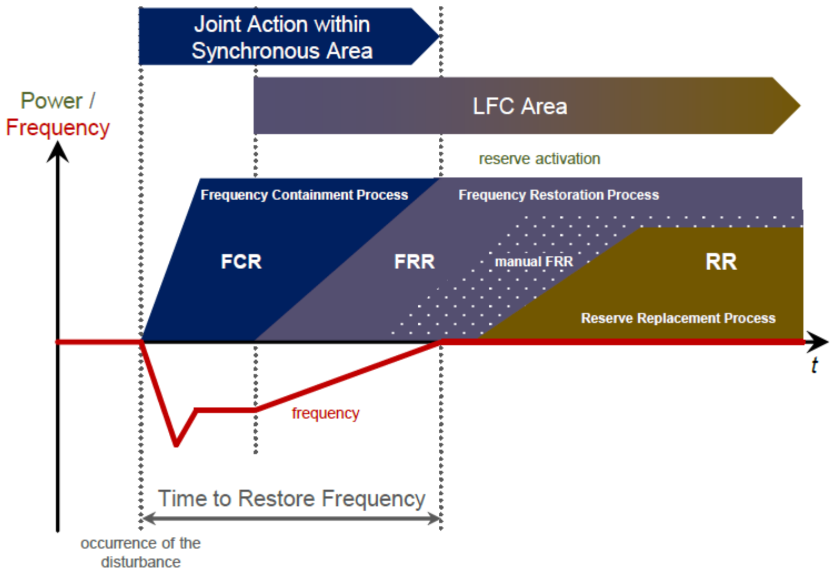


Figure 28 - Dynamic hierarchy of Load-Frequency Control (LFC) processes [61]

- Primary Reserves (Frequency Containment Reserves - FCR) are activated immediately after an event. They should be fully activated within the first 10-30 s. They remain activated until Secondary or Frequency Restoration Reserves (see below) fully replace them. This primary frequency regulation is completely automated and delegated to the large scale power plants. It is in fact performed by each generation unit connected to the power system via their respective speed governor. In presence of large disturbances, the speed governor aims to restore the equilibrium between the mechanical energy (input) and the electric energy (output) at the respective prime mover (turbine)- generator

group. For small disturbances (such as those ones caused by load increases) the speed governor of each generator carries out the primary regulation. The governor of each generator shares then the changes required to respond to the disturbance in a proportional way with the governors of the other generators contributing to the primary regulation.

- Secondary Reserves (Frequency Restoration Reserves - FRR) are activated from 30 to 60 s after the event. They should be fully activated within 10-20 min. They remain activated until Tertiary or Restoration Reserves (see Mid-term security challenges below) fully replace them. After a load change and the consequent primary regulation, the system frequency is not generally coincident with the nominal one. For this reason a secondary frequency regulation - i.e. the Frequency Restoration Reserves - is needed in order to get the system frequency back to the nominal reference value. The secondary regulation is a control action taken at central power system level. It is then executed at generation level by means of signals transmitted to a subset of generators devoted to this type of regulation.

- **Voltage regulation (primary and secondary)**. At transmission system level, the voltage amplitude is strictly related to the reactive power. For this reason the reactive power (either capacitive or inductive) needs to be supplied by generators, helping to maintain the voltage at the required level. As an immediate consequence of load variation and voltage change, the primary voltage regulation is performed at local, decentralised level by devices able to modify the voltage by changing the reactive power in the system. These elements may be the voltage regulators of the generation units, tap-changers, capacitors, reactors and static and rotating reactive power compensators. This control is carried out in an automated way as well as the secondary voltage regulation. The secondary regulation is centralised at control area level and has the scope of effectively coordinating the voltage variations on generation units. In particular, attention is paid on keeping the voltage values of critical system nodes (pilot nodes) in the due range. This control aims also at optimising the reactive power sources and minimising losses [151].

- **Stability issues with large penetration of renewables**. Stability limits are also used to establish maximum real power flows on transmission lines. Stability limits are often defined in terms of maximum power flow (i.e. the limit to the amount of power that can flow down a transmission line and this is different from the thermal limit) and voltage variation (when increasing the power transmitted, If voltage falls too low then it can collapse uncontrollably). In general, thermal limits tend to be the binding constraint on power flows over shorter distances, while stability limits tend to be the binding limits for longer distance power flows [123]. The wind turbine manufacturers have to implement fault-ride-through capabilities: wind turbines ought to stay connected and support the recovery of the power grid in case of a power disturbance, in order to allow integration of wind energy without affecting power system stability. After the fault occurred, wind power plants should supply active and reactive power to assist the recovery of frequency and voltage [152]. Beside their variability and uncertainty, variable renewable energy display very different control and electrical features compared to conventional synchronous generators. Synchronous generators, typically featuring in most of the conventional power plants, provide valuable services to the power system: they contribute to system inertia, thus helping stabilising the system and controlling frequency variations; they provide reactive power to regulate voltages and high fault currents, needed to trigger protection devices when there is a fault in the system. Wind however does not generally connect to the grid synchronously but via

inverters (power electronics), thus they are defined non-synchronous generation. Wind power also has limited spinning mass, hence limited physical inertia[11] [125][153][154].

- **Transmission-distribution system interfacing issues.** Due to the variable output from some distributed generation sources, the TSO must be able to cope with reverse power flows coming from the downstream lower voltage networks and the DSO must be able to manage fast reacting local power generation and in some cases procure the needed power reserve from the upstream transmission. By a growing penetration of intermittent renewables and CHP technologies, the costs of imbalances may consistently increase, and the application of priority dispatch mechanisms may become increasingly difficult [4]. In general, TSOs and DSOs still have to implement strategies to address in a systematic way the interfacing issues originating from smart distribution grid developments and distributed energy resources penetration. Many of the renewable-based generating units connected to distribution systems are only able to operate within limited frequency ranges and can find themselves disconnected just when they are needed to support system stability. According to ENTSO-E, "if [they are] simultaneously applied to a large number of units, such unique frequency thresholds can jeopardize the security of the entire interconnected system." [76]
- **Short-term unscheduled flows.** The current market solutions are only to a limited degree able to represent the physical realities and dynamics of the power system operation, hence scheduled flows can deviate even substantially from the actual physical flows in the electricity grid. Loop and transit flows are unscheduled flows, the former occurring *within* one bidding zone, the latter between two or more bidding zones (thus physically involving areas not being part of the commercial transaction). The main factor contributing to the scale of loop and transit flows is the market arrangement (i.e. price signals) not properly reflecting the dynamics of the physical power flows and not fully accounting for internal congestion within bidding zones (the transmission capacities made available to the market are reduced ex ante to accommodate unscheduled flows). Loop and transit flows inflict external costs on the host area when the grid is not able to accommodate the flow and when the scope of scheduled flows within the host area must be reduced. There are two types of external costs: costs related to security of supply and system services in the host country; costs stemming from reduced capacity for market trade within the host country or between the host country and other areas. The external effects incentivise implementation of measures that reduce loop and transit flows in the host area, whereas the area where the flows originate does not have adequate incentives to alleviate the problems. Hence, measures are unlikely to be efficient from a wider system efficiency perspective [17][18].

3.2.2. MID-TERM SECURITY

Power system security in this time frame depends from the interaction of an expanding number of stakeholders including: wholesale and retail market actors; ENTSO-E; TSOs and DSOs; conventional and renewable generation companies; asset owners; aggregators (bringing together demand); residential, industrial and commercial consumers [139].

In this time scale, while the system stability is not the first concern, the need for balancing generation and demand is still a primary challenge for the power system. Additionally, several risks of market failures emerge.

---

[11] However, variable renewable energy generators may be designed to emulate the characteristics of synchronous generators; for example, the inertia stored in the rotating blades of wind turbines may be used to provide "synthetic" inertia.

- **Renewable energy mid-term variability and uncertainty.** Renewable energy (and especially) wind power fluctuates also in the day. The IEA considers that a 3-day period is likely to encompass the maximum extent of variability in output that a system will see. Furthermore, the almost complete absence of renewable energy for several consecutive days in a row can cause operation challenges. And again, on top of the variability, forecast uncertainty plays a role: variable renewable power plants need to adjust inside the day the forecasts provided the day-ahead and system operator must procure resources to manage the anticipated mid-term imbalances as well [124][154].
- **Generation-demand balancing (tertiary frequency regulation).** Additional frequency regulation actions, following those illustrated above (see again Figure 28), occur in this time frame: the Tertiary Reserves (Restoration Reserves - RR) are activated in the time frame from 10-20min to 4hours. The tertiary frequency regulation represents a longer term sharing of the effects of a load change among the concerned generators with the aim of cost minimisation. All power systems (except the ones with derogation from the codes such as the one in Cyprus), have to schedule for every dispatch period adequate volume of primary FCR, secondary FRR and tertiary RR reserves.
- **Voltage regulation (tertiary).** Voltage regulation actions, following those illustrated above, occur in this time frame; more precisely, the tertiary voltage regulation is carried out at central system level for the preventive control and forecast of the voltage values on the pilot nodes and for the coordination scopes with secondary regulation.
- **Day-ahead and market flexibility.** Today markets are not sufficiently flexible, both on the supply and on the demand-side, and not fit to accommodate the growing shares of centralised and decentralised renewable energy. Indeed, markets using hourly scheduling or relying on bilateral contracts with fixed hour energy delivery can be problematic with higher penetrations of renewable energy [155]. To cope with the increasing share of RES-based generation, TSOs will have to draw on additional (flexible) resources to be able to balance systems instantly in a cost-efficient way. The most economically efficient way to pursue the deployment of sufficiently flexible resources in the system is to create a well-functioning energy market attracting existing resources through efficient pricing. The value of flexibility reflected in market prices will send appropriate market signals to stimulate the right amount of investment in both new generation (if needed) and networks. Day-ahead market coupling and "flow-based" capacity allocation are first steps towards a fully integrated market allowing short and long term trading of energy, renewable energy sources, balancing services and security of supply across borders, however there is still a lack of short-term market integration. Well-functioning intraday markets are critical to integration and to realising the benefits of RES and cross border connection for security of supply [17].
- **Generation and system flexibility.** While also in the past the (moderate) demand variability has always required a certain amount of flexibility, the higher variability of renewable energy output is introducing a step change in the way flexibility shall be procured in electricity system operation. Whereas within the traditional supply-follows-demand scheme, flexibility was offered in bulk generation, in the future flexibility might need to be offered from both (centralised and decentralised) generation and consumption sides [141]. Without sufficient flexibility, system operators may need to frequently curtail wind and solar generation. Although low levels of curtailment may be a cost-effective source of flexibility, significant amounts of curtailment can jeopardise business models of renewable energy investors/stakeholders and challenge the achievement of sustainability/environmental targets. Curtailment of variable renewable energy reduces the capacity factor and potentially the revenue stream of a plant. Likewise sustained negative wholesale prices, such as can occur in systems with

generators that cannot cycle down to low outputs, also reduce the attractiveness of investments in new generation - conventional or renewable [136].

- **Coordinated operation of intelligent technologies.** Advanced, smarter technologies are being deployed more and more at the transmission level. High-Voltage DC (HVDC) lines, already mature for long-distance and undersea applications, have now been included in several on- and offshore transmission grid projects, particularly the voltage source converter (VSC)–based HVDC system, which offers greater flexibility of operation and easier expandability to multiterminal configurations. Phase- shifting transformers (PSTs) and flexible ac transmission systems (FACTS) devices, thanks to their targeted active and/or reactive power control, are being deployed to reduce unplanned flows. And a host of information and communication technology (ICT) solutions are being adopted to increase system monitoring capabilities and controllability (e.g., wide-area monitoring and control systems that let operators optimise the power flows across very large systems thanks to satellite-based measurements and dynamic thermal power-rating techniques that take advantage of low temperatures to temporarily overload conductors without the risks of mechanical and thermal stress). It should be noted that in a highly meshed network like the European one, if intelligent control devices are extensively deployed they will deliver real benefits only when subjected to coordinated operation; since these technologies mutually influence each other, if sophisticated coordination and investment-sharing mechanisms are not put in place, grid operators face the risk that these devices will not deliver their full potential. They could even contribute to unwanted system behaviours [4][45].
- **Mid-term unscheduled flows.** Also in the mid-term scheduled flows can deviate even considerably from the actual physical flows in the electricity grid. The main factors contributing to unscheduled flows in this time frame are the increased energy imbalances linked to structural features of the power infrastructure (e.g. introduction of more variable generation sources in a system originally designed to accommodate more balanced generation and load patterns) [17][18].

3.2.3. LONG-TERM SECURITY

Power system security in this time frame depends from the interaction of an even larger number (compared to the short- and mid-term) of stakeholders including: EU institutions and agencies, including the European Commission and the Agency for cooperation of Energy Regulators (ACER); national governments and institutions; National Regulatory Authorities (NRAs); wholesale and retail market actors; ENTSO-E; TSOs and DSOs; conventional and renewable generation companies; asset owners; aggregators; residential, industrial and commercial consumers [139][142].

In this time scale, network planning and market design actions are expected to counteract the main security challenges. However, current electricity security performance and regulatory arrangements are largely a legacy of investments dating back to several decades ago. Ageing capacity needs to be replaced within a competitive market framework while also decarbonising the electricity sector [87].

- **Renewable energy resources connection to the grid.** Renewable resources, wind in particular, tend to be further away (compared to conventional power plants) from consumption centres, thus the build of new dedicated infrastructure is generally needed.
- **Market adequacy, generation capacity mechanisms and assets stranding.** According to [155], while the electricity wholesale market provide rather good short-term price signals (seconds to days), which are effective at allocating available capacity, does not generally work well in providing long term price signals for the right amount of long-term installed capacity (renewable or conventional) to meet reliability. In the long-term, generation investments will only take place at a sufficient level if prices

reflect the long run average cost of producing electricity, including capital costs. Wholesale prices, if unregulated, vary according to supply (driven by the costs of generating electricity) and demand. Revenues for most generators will often be above their short run production costs, allowing the recovery of their investment. In particular, generators which operate for only short periods need to be able to recover capital costs during those periods and short run prices will tend to rise well above short run marginal costs. ENTSO-E reports that most of the rescheduled grid investments are correlated with the postponement of the generation development project triggering them [39]. Currently, overcapacity, generation stranded assets and stalling new-built capacities are problems shared by many Member States and markets. This is a result of the financial and economic crisis and the resultant drop in demand, but may in part be related to obsolete capacities kept online. Low demand, in combination with increased deployment of wind and solar generation, has also been pushing wholesale electricity prices down in some Member States. Moreover, the recent evolution of coal and gas prices in combination with a low price of carbon has also resulted in modern gas plants being displaced in the merit order by coal plants, including those less environmentally friendly. These decisions have been motivated by different market and policy factors affecting electricity, coal, gas and carbon prices [19].

The recent need to mothball and decommission combined cycle gas-fired power plants in Europe has had significant and rapid consequences for company value, utility strategy and public policy. A number of Member States, anticipating inadequate generation capacity in future years, are introducing capacity mechanisms which involve making payments for available capacity rather than for electricity delivered. A capacity mechanism is a form of public intervention aimed at keeping sufficient dispatchable generation capacity online and stimulating investment in new generation capacity. So far, Europe has predominantly relied on the energy-only markets for delivering sufficient generation capacity (profits from selling energy form the main source of income for generators). Analysts and decisions makers now argue that energy-only markets are not always able to deliver the right amount and the right mix of generation capacity and consequently represent a threat to security of supply. Capacity mechanisms, on top of energy-only markets, begin to be implemented in order to stimulate sufficient investments. EU countries are not choosing an integrated approach; instead they propose different types of mechanisms, aimed at increasing security of supply on a national level [128][131].

Member States' generation adequacy assessments need to take account of existing and forecast interconnector capacity as well as the generation adequacy situation in neighbouring Member States. Surplus generation in neighbouring Member States may alleviate adequacy concerns; shortages may exacerbate them. With particular reference to the long-term actions, the high penetration of renewables in the grid will require detailed system planning coupled with accurate resource and load forecasting across Europe. The challenges that RES pose to security of supply, mainly in terms of "secure capacity", can be balanced by technological means such as the development of cross-border electricity transmission capacity, electricity storage and demand response [93][158].

- **Public acceptance and permitting.** The bulk power system expansion is curbed by environmental and social issues. Social acceptance of electricity infrastructures is always a concern, as the resistance of local authorities and/or public opinion to new lines is persistently high. The time required to get permits for grid facilities is generally much longer than the time needed to build new power plants. One in three planned investments by ENTSO-E faces delays in implementation due to long permitting processes, and some sections of new overhead lines have had to be replaced with underground cables [4][39].
- **Demand forecast uncertainties.** Long-term forecasts tend to be conservative and overestimate demand. Electricity demand growth plays an important role in adequacy forecasting, given the lead-time needed to build new power plants. Faced with uncertainty over electricity demand growth,

conservative policy makers and system operators are likely to prefer to size the electricity system based on optimistic estimates. This is also linked to the fact that excess reliability is not that expensive. Additionally, with the increasing penetration of distributed generation, it will be more challenging to forecast demand [122][151]. ENTSO-E warns that "the more active role of the networks themselves, as well as the expected more active participation of loads and generation embedded in the distribution systems, will impact on the forecast of the load as well as, in the long run, the design of the market models." [76] Regulatory frameworks for reliability broadly involve setting ex ante standards for the bulk power system and reporting on the performance of the electricity sector ex post. In the long run, it is possible to envisage a situation in which different consumers can express different preferences for the quality of their electricity supply. Some consumers might be willing to pay a high price for electricity in order never to reduce their consumption. Other consumers might accept reducing their consumption from time to time in order to pay a lower price. We might consider this second group as consumers with a low preference for reliability, because they accept voluntarily curtailment of some of their electricity usage. In practice, many electricity systems enjoy higher capacity than is needed to meet the strict application of their reliability standards [122].

3.2.4. VERY LONG-TERM SECURITY

Power system security in this time frame depends from the interaction of a multitude of stakeholders including: EU institutions and agencies, particularly ACER; national governments and institutions; National Regulatory Authorities (NRAs); wholesale and retail market operators; ENTSO-E; TSOs and DSOs; conventional and renewable generation companies; asset owners; aggregators; manufacturers; residential, industrial and commercial consumers; possible new actors not yet existing and/or conceived (offering new services and/or proposing new business models) [139][142].

Beyond the investment cycle, there are several challenges and strains affecting power system security, particularly in correlation with renewable energy deployment (primarily in terms of technologies, performances, and geographical siting); extension of the European electricity network towards neighbouring power grids; and the diffusion of distributed energy sources and self-consumption steering the development of a smarter power system.

A non-exhaustive list of issues facing the power system in the next decades follows:

- **Super grid schemes development.** There is a tendency in Europe (and indeed worldwide) to plan transmission system extensions beyond continental borders. Several initiatives focus on interconnecting the power systems along the Mediterranean shores; preliminary feasibility studies have been conducted to interconnect the European power system with the IPS/UPS one; and even China has shown interest in interlinking the Chinese power grid with Europe through other international power systems. The first list of Projects of Common Interest already includes links to non-EU countries. Some of the main regulatory and market obstacles in advancing this process are found in the lack of sound financing frameworks and business models, the need to develop support schemes for RES generation in some countries; a lack of shared and harmonised rules for network access, capacity allocation, congestion management, and inter-TSO compensation; and a need for allocation and remuneration mechanisms for the backup reserve and storage capacity necessary to cope with RES variability and uncertainty.
- **Super transmission grids and smart distribution grids interplay.** To make the transmission and distribution grids work together efficiently and safely, increased coordination in their development and operation must be pursued. Both transmission and distribution need to be further developed, not

necessarily just in terms of carrying capacity but also via advanced ICT infrastructure and communication and control platforms. Networks and markets must adapt to the coexistence of centralised and decentralised power generation. Several stakeholders are calling for closer coordination between transmission and distribution systems, especially for issues concerning demand and generation observability but also for interoperability and controllability, so as to ensure a suitable contribution of local resources to global system security. Linking wholesale and retail markets is crucial to deliver a new deal for consumers. Microgrids with enhanced control capabilities can integrate and coordinate local distributed resources enhancing the resilience of the EU super grid and providing local restoration capabilities [43]. In order to increase robustness, some analysts identify the following strategies: intentional islanding to stop the initial failure and prevent it from propagating; targeted network reinforcement; combining super grids/highways with smart/micro grids [159]; and pervasively implementing smart grids [111].

Once more, the list of issues above described is not comprehensive as several other factors and strains - not necessarily of technical nature and not necessarily originating from inside the electricity value chain - can drive the change into the power system.

Figure 29 frames the electricity security actions which can be put in place to maintain/increase [4][59]-[65][91][95] the previously introduced electricity security properties and with respect to the different domains of the electricity supply chain.

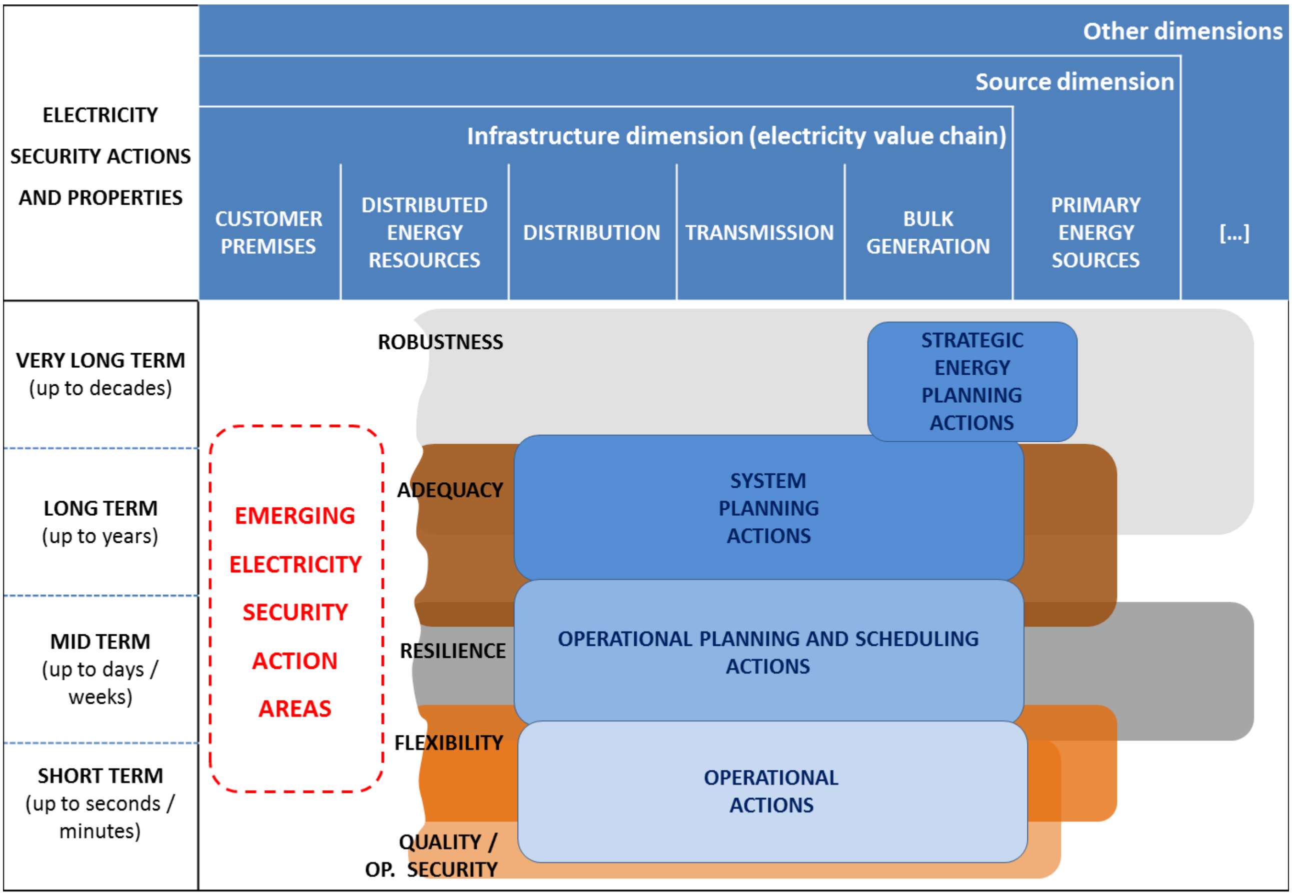


Figure 29 - Mapping of electricity security attributes and actions

More in detail:

- **Short-term system operation actions**, including: transient/dynamic stability management, pre-fault and post-fault remedial actions (based on contingency analyses) and system balancing actions[12].
- **Mid-term operational planning and scheduling actions**, including forecasting, power scheduling, ancillary service procurement, outage coordination and asset management actions.
- **Long-term system planning actions**, including: system (network) optimisation, enhancement and expansion actions.
- **Very long-term system planning actions**, including: strategic energy planning/provision actions and a wide range of policy and regulatory initiatives which may impact not only the electricity system but the wider energy system (starting from the primary energy sources made available for electricity production).

As far as the short-term actions are concerned, it is interesting to note how the operational limits/values - to which the preventive, remedial and corrective actions are linked - are generally fixed ex-ante by means of off-line (thus not real-time) assessments. The decision makers (mostly the operators) hence execute actions, especially rapid ones after an adverse event, based on incomplete datasets [157].

Both in the short- and the mid-term, more accurate forecasting techniques are needed to avoid large imbalances on the system due to forecast errors.

Both in the short- and mid-term, the increasing RES share in the European electricity systems requires both system and market adaptations - such as a market gate closure as close as possible to real time in order to allow for changes in the feed-in of variable RES-E - and system responsibility from RES power plants, such as balancing responsibility. Providing clear price signals for new investments and facilitating the further development of renewables can happen by: establishing cross-border short-term markets, fostering long-term markets, completing infrastructure for a functioning market [75].

The network code requirements play a vital role in cases where wind power represents a fair share of installed power. The network codes define the operational boundary of a wind farm connected to the power grid in terms of frequency range, voltage tolerance, power factor, and behaviour following a fault in the power system.

In areas with competitive markets, there must be sufficient investment signals regarding the potential need for flexibility. In the absence of either sufficient planning or investment clarity, the resulting power system may not have sufficient flexibility to operate efficiently [136].

3.3. THREATS, ADVERSE EVENTS AND EFFECTS ON POWER SYSTEM SECURITY

3.3.1. MALICIOUS, ACCIDENTAL AND NATURAL THREATS TO ELECTRICITY SECURITY

In the coming decades, European electricity networks will be facing several challenges. These include economic risks (e.g. under-investment and rising electricity demand) and external events (e.g. natural calamities, severe weather conditions, nuclear accidents, terrorist attacks and cyber-attacks). As an example, the 6 blackouts that occurred in 2003 within 6 weeks impacting 112 million people in the US, UK, Denmark,

---

[12] *Each TSO shall in real-time operation deploy different actions based upon five System States: a) Normal State; b) Alert State; c) Emergency State; d) Blackout State; e) Restoration. The five states are defined mainly against operational security limits and frequency control management provisions [59][62].*

Sweden and Italy suggest that the electricity security implications of market liberalisation were not properly accounted for [93].

Large power system disturbances and even blackouts are triggered by one or more threats leading to cascading events/outages and eventually to the overall/partial system collapse. Figure 30 classifies malicious, accidental and natural threats and interlink them with events and impacts on the power system [95]. The occurrence of threats initialises a chain of events (cascading failures) that may result in outages that leave extensive regions without power for shorter (seconds, minutes) or longer time (hours, days or more).

As far as the impact of natural threats is concerned, the power system (generator, transformer, substation, overhead line, cable, control centre) can be affected to various degrees. In general, earthquakes could damage all types of power system equipment, and are the most likely to cause power interruptions lasting more than a few days. Tropical cyclones primarily affect transmission and local distribution systems, but the resulting flooding could damage generating equipment. Although heat wave and drought generally cannot straightforwardly destroy power system facilities, unless the weather reaches extremely high temperature, they can lead to significantly increase the cooling/air conditioning consumption while reducing the generation capacity of hydro (for water scarcity) and thermal power (for cooling water scarcity) plants. Table 5 shows the different impacts of natural threats on power system. A single adverse event in power grids can propagate from one component to others (cascading failures) causing blackout or power supply shortage and eventually bring about great loss to the society.

Table 5 - Natural threats to power system: affected components and impacts [95]

THREATS / IMPACTS — EVENTS	THREATS TO POWER SYSTEM						POSSIBLE IMPACTS		
	GENERATOR	TRANSFOR MER	SUBSTATIO N	OVERHEAD LINE	CABLE	CONTROL CENTRE	EQUIPMENT DAMAGE	SHORT CIRCUITS	OVERLOADS
Earthquake	H	H	H	H	H	H	√	√	
Volcanic	H	H	H	H	N	H	√	√	
Landslide	H	H	H	H	N	H	√	√	
Avalanche	H	H	H	H	N	H	√	√	
Tsunami	H	H	H	H	N	H	√	√	
Flood	H	H	N	M	N	N	√	√	
Tropical	H	H	H	H	N	H	√	√	
Heat wave	H	N	N	N	N	N			√
Winter storm	M	M	N	H	N	N	√	√	√
Drought	M	N	N	N	N	N			√
H: High M: Moderate N: Negligible									

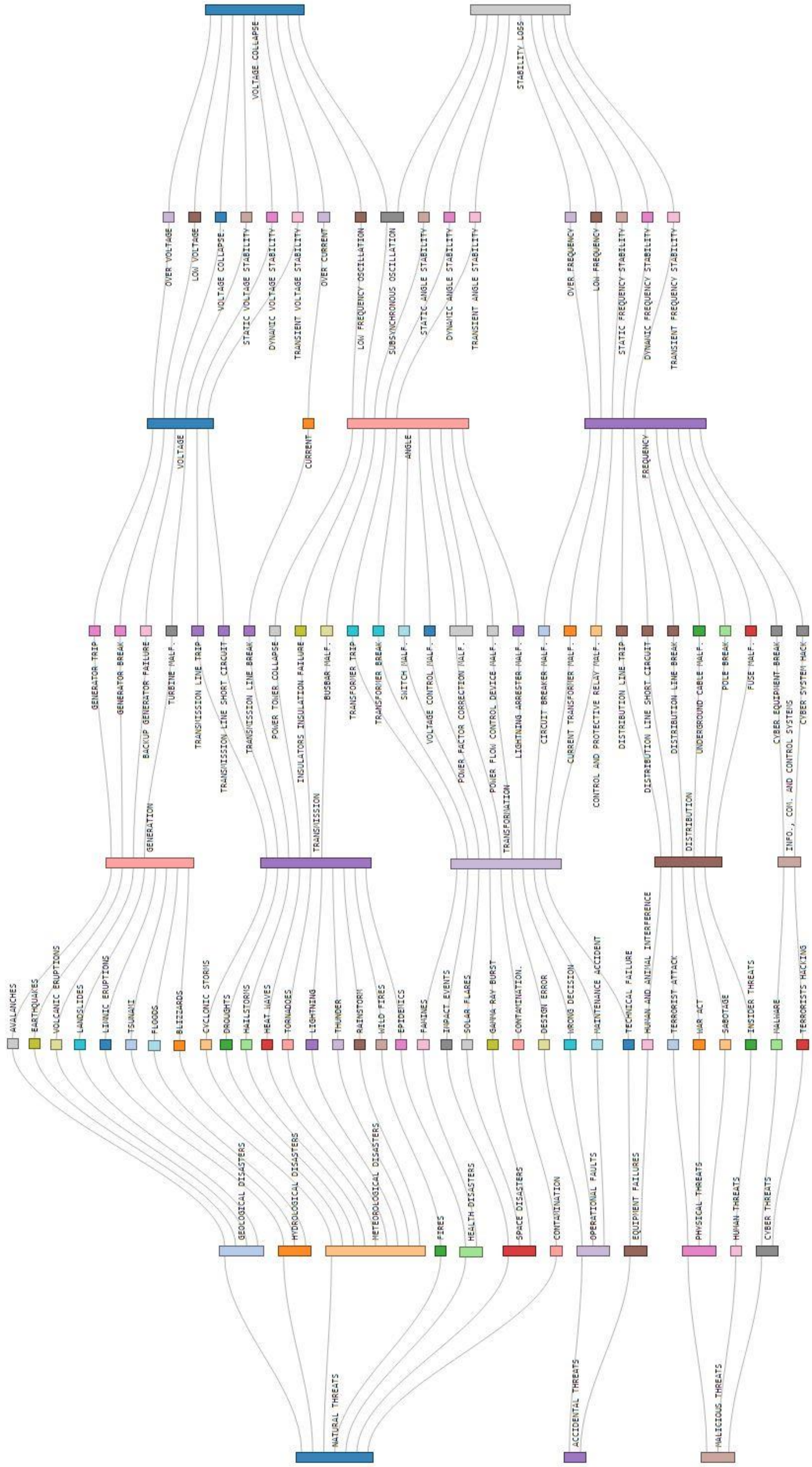


Figure 30 - Threats, adverse events and potential impact on power systems [95]

3.3.2. EMERGING THREATS TO ELECTRICITY SECURITY

As highlighted in Chapters 1 and 2, the electrical energy system is undergoing profound changes towards a more decentralised system, where the participants change their roles dynamically and interact cooperatively. Clearly, the decentralised connotation is especially correlated to renewables and does not only mean more small dispersed generation connected at distribution level, but also more large-sized - increasingly offshore - generation plants hooked up at the transmission grid.

The renewable generation integration is a powerful driver for the evolution of both the distribution system towards a smart grid and the transmission grid towards a super grid. Unavoidably, those sorts of parallel but also potentially conflicting evolutions cause tensions in the system.

Figure 31 lists some of the main challenges related to the energy transition and the large scale renewables-based centralised paradigm vs. the renewables-based decentralised paradigm faced by the European energy policies.

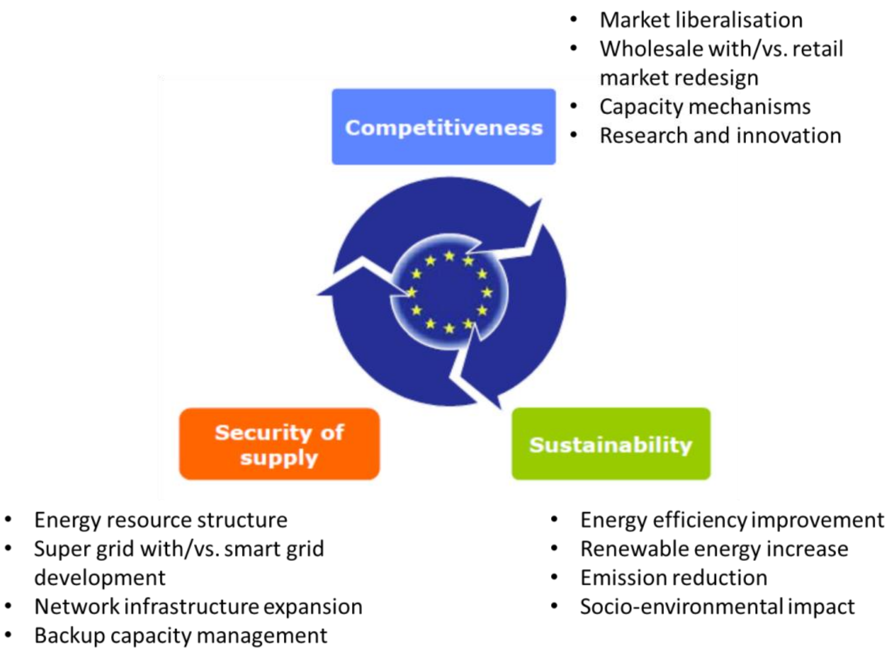


Figure 31 - Emerging power systems and EU energy policies

As explained before, the political attention on smart grids, as a means to achieve EU energy policy objectives, is rising. However, in order to unlock the market investment potential, there is a need for actions contemplating also courageous changes in the regulatory framework and in the market (especially retail) arrangements.

The security of supply stresses observed in the European transitioning system should be addressed with novel assessment methods and coordinated approaches/actions. The evolution towards super grids and smart grids generate tensions and developments which require a paradigm change in the way security of electricity supply shall be assessed and safeguarded. In particular, in terms of infrastructure related-security (see again Figure 29), the electricity supply chain domains of distribution, distributed energy resources and end use are bound to be the most targeted for new actions; however, the remaining electricity supply chain domains as well shall see a change in security of supply approaches and actions which, even though well

established and much more developed, may not be any longer suitable to protect the power system in an integrated and effective way.

Against this background, in

Table 6 we reported a qualitative assessment of the effects of some policy and/or related technological deployment actions on the energy policy objectives. Clearly this attempt shall be considered as purely illustrative for at least the following reasons:

- Each of the deployed actions/technologies cannot be considered as independent;
- The direction/intensity of their effect may change in time (short-term vs medium-term).

Table 6 - Short-term effects of power system technologies/components deployment on energy policy objectives

DOMAIN OF THE ELECTRICITY VALUE CHAIN	DEPLOYED TECHNOLOGY/ACTION	ELECTRICITY SECURITY		AFFORDABILITY	SUSTAINABILITY
		SOURCE DIMENSION	INFRASTRUCTURE DIMENSION		
BULK GENERATION	LARGE SCALE RENEWABLES (WIND)	+	-	+/-	+
TRANSMISSION	INTERCONNECTION AND TRANSFER CAPACITY INCREASE	n.a.	+	+	+/-
	NEW TRANSMISSION (HVDC, FACTS) TECHNOLOGIES	n.a.	+	+	+
DISTRIBUTION	NEW DISTRIBUTION (LINES / EQUIPMENT) TECHNOLOGIES	n.a.	+	+/-	+
	MICRO-GRIDS	n.a.	+	+/-	+
	SMART METERING ROLL-OUT	n.a.	+	+	+
DISTRIBUTED ENERGY RESOURCES	DISTRIBUTED ENERGY RESOURCES (INCL. STORAGE)	+	-	+/-	+/-
	ELECTRIC VEHICLES	n.a.	-	+	+
CUSTOMER PREMISES	PROSUMERS AND SMART HOMES	n.a.	-	+	+
	DEMAND SIDE RESPONSE	n.a.	+	+	+

As an example, the integration of large scale wind parks is expected to have a positive effect on sustainability and source-related security of supply but - without combined actions/efforts also in other energy policy-relevant fields - is likely to have negative impact on the infrastructure-related security (e.g. baseload generation forced to work in modulation regimes or localised congestion occurrences for the lack of transmission capacity between the new generation centres and the traditional consumption ones, etc).

4. MODELS AND APPROACHES FOR ELECTRICITY SECURITY ANALYSES

"The purpose of computing is insight, not numbers."

Richard Hamming, mathematician

In this Chapter, building upon the electricity security dimensions and properties introduced in Chapter 3, first a classification of the models for electricity security analysis is proposed. Afterward the main electricity security methodologies and approaches are described and then strengths, weaknesses and synergies of the different models and methodologies in support of electricity security decision making are discussed.

4.1. GENERAL NOTIONS

4.1.1. MODEL FEATURES AND CLASSES

A model is an abstract representation, usually in forms of words, graphs, symbols, mathematic formulae, or physical miniatures, of an object, a concept, a phenomenon, a relationship, a structure, or a system that allows for the recognition, understanding and study of its properties and, in some cases, prediction of its future behaviours.

A model usually contains only primary and most relevant features of the questions/phenomena to be studied, due to the complicatedness/complexity most of questions/phenomena embed [159].

There are several categories of models (Figure 32): physical, schematic, symbolic, verbal, etc. The models most deployed in the power system field, especially for aiding decision making, are symbolic models, which are the most-abstract ones, such as those featuring mathematical equations or formulae. Depending on the nature of the system under study, a model can be symbolically-mathematically formulated in a closed form or an open form:

- **Closed-form model**: it describes the overall system performances via a set of expressions/equations. This model is used to represent (even) complicated (but not complex) systems with a high degree of precision (for example, the complicated though not complex European electricity system, having numerous parts and displaying dynamic behaviours, can be precisely described via a closed-form model). A closed form model can be on its turn:
  - **Deterministic** model: it describes the system in such a way that, once input data are fed in the model, the output is known with certainty. Thus, if the description of the system state at a particular point in time is given, the next state can be perfectly predicted.
  - **Probabilistic (or stochastic)** model: it describes the system in such a way that, once input data are fed in the model, the output can only be known in probabilistic terms. Thus, a certain degree of error is always attached to the prediction of the system behaviour.
- **Open-form (or non-closed-form) model**: it reproduces the overall system performances not relying on a full set of equations - but using complex science techniques - since no set of closed expressions/equations can mimic the global system behaviour (even if the system components may well

be described through equations). Open form models are used to represent complex systems, i.e. systems featuring parts densely interacting (an example of a complex problem is the impact assessment of a new regulation on the electricity market).

Another feature of a model is its generality due to its abstraction: a model can indeed be deployed and applied for different instances. However, to solve a real world problem - that is to perform a simulation - specific data are needed to instantiate the model. For example, power flow equations as a static model of the power system can be applied to any electricity systems without specific requirements. Yet, to know the Baltic power system status, we need to apply the Baltic system dataset to the power flow model to run the simulations.

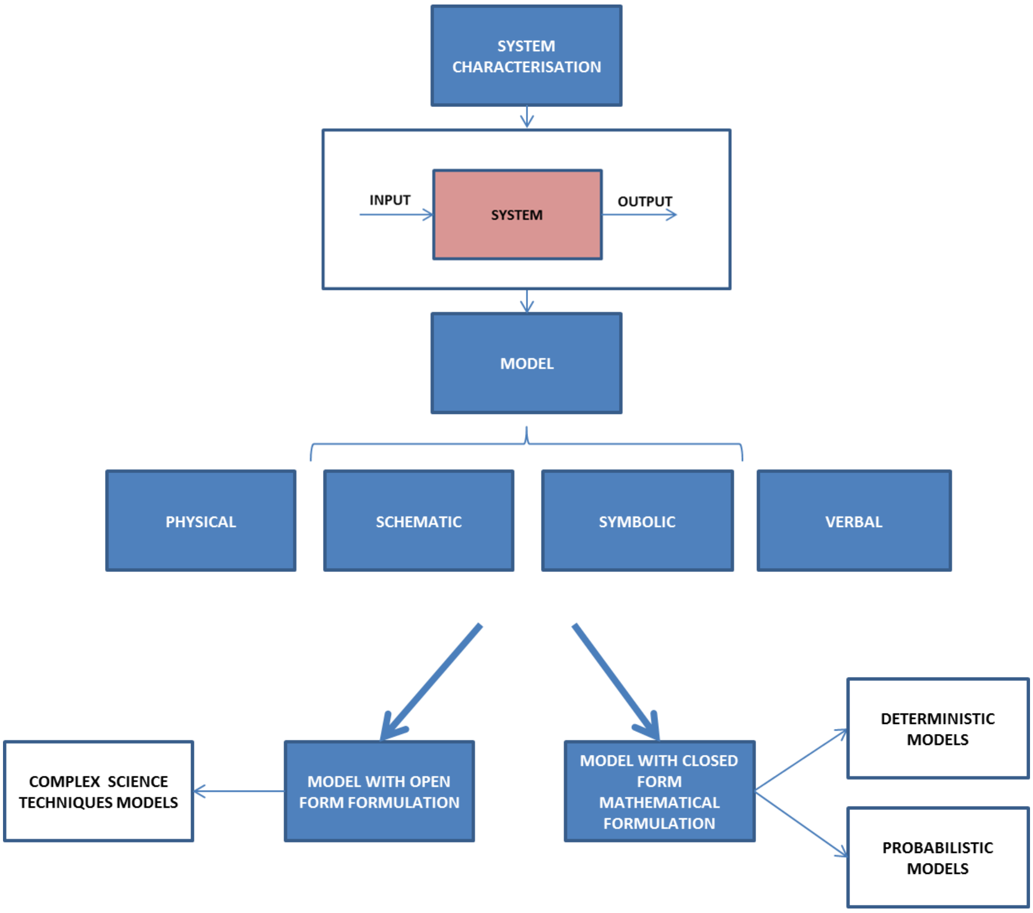


Figure 32 - Model general classification

Figure 33 recaps the differences between system/problem characterisation, mathematical model construction, problem/algorithm solution and tool[13] development. The mathematical formulation of the model generally contains the following elements: decision/control variables allowing controlling the system, state variables describing the system status and relations among variables. A solving method[14] is the instrument to solve the algorithm, i.e. the way to find values for the decision variables.

[13] *A tool is the software implementation/coding of the model. The tool can embed a solver or the solver can be an independent software module.*

[14] *As examples, CPLEX is a widely deployed linear solver and CONOPT is a non-linear solver.*

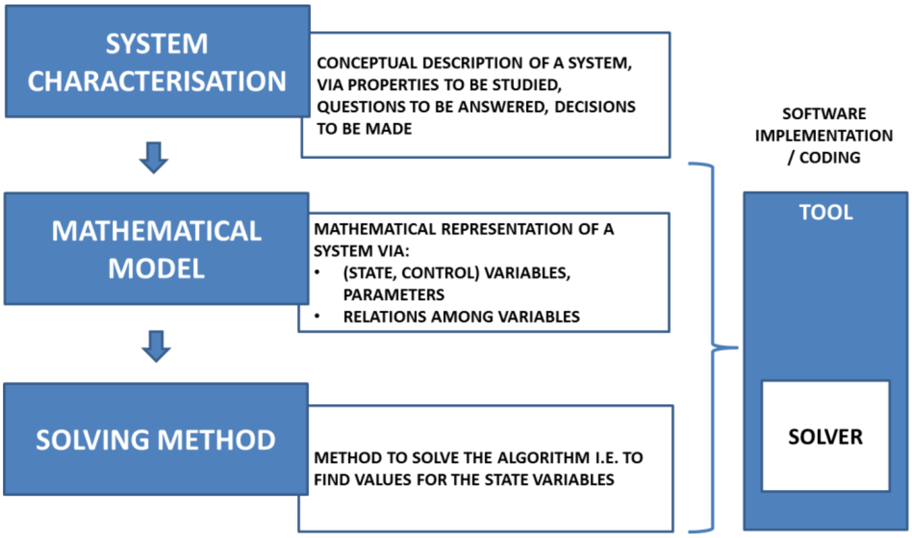


Figure 33 - Modelling aspects: problem/system characterisation, mathematical model, solving method and tool

Figure 34 provides a concrete example of the application of these logical steps for the solution of an optimal power flow, an often recurring mathematical model/problem in the power system analysis. In this specific case, running the model with a given objective function and a set of variables/constraints consists of solving a mathematical optimisation problem in order to find values for the decision variables.

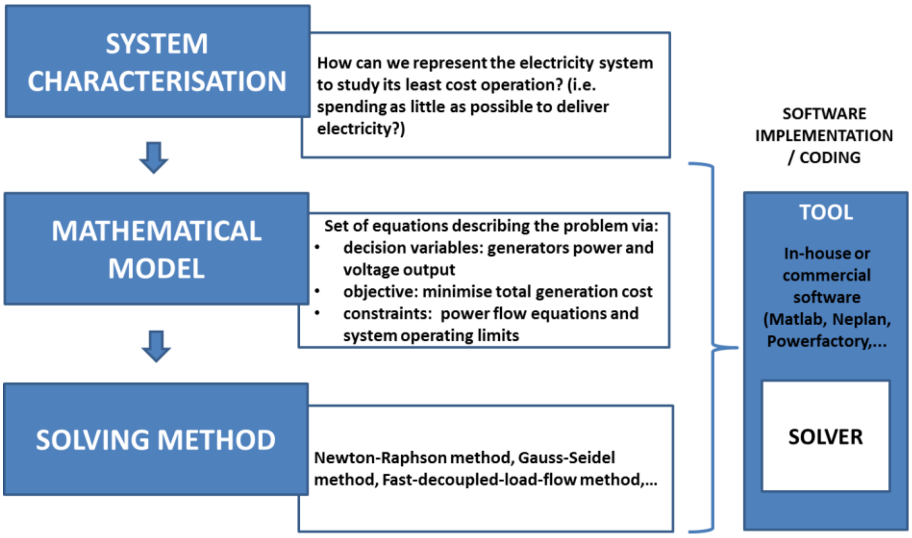


Figure 34 - Modelling aspects in a practical case: optimal power flow

In the remainder of this work, we generally:

- discuss features of power system models relevant to electricity security analysis, hence not scrutinising aspects specifically linked to e.g. market and/or sustainability analyses;
- focus on the bulk power system security aspects, thus analysing transmission (more than distribution) system issues;
- describe and assess models and tools but not solving methods; when using the term methodology, we actually refer to the approach, the sequence of logical steps, to assess electricity security system issues and properties.

4.1.2. DETERMINISTIC AND PROBABILISTIC MODELS

As seen, the closed-form models can be distinguished in two classes: deterministic and probabilistic (or stochastic). Let us discuss some of their features.

Deterministic models directly provide results for decision making without the need to define a strategy. In other terms, every set of state variables are uniquely determined by parameters in the model (and by sets of previous states of these variables); therefore, a deterministic model always performs the same way for a given set of initial conditions [161][162]. The most renowned deterministic criterion applied in power system analysis is the N-1 rule: if one component fails in a system with N components, the system is still expected to operate within acceptable security boundaries.

Although models based on deterministic approaches are simple to conceive and use, they do not capture a wide host of uncertainties. Thus, decisions based on deterministic assessment may target very low risk scenarios or lead to unintended high risk choices [163].

Indeed, power systems are traditionally characterised by uncertainties, which can be split in two categories:

- Mathematical uncertainties caused by the difference between measured, estimated and true values.
- Other uncertainties including operational conditions, transmission and generation capacity availability, demand profiles, unplanned outages, market rules and prices, weather conditions, etc.

Recently, with market liberalisation and the increased levels of variable renewable wind power, the uncertainties of power systems are increasing and getting more attention since they compound the decision making process [164].

Differently from the deterministic ones, the stochastic models take into account the fact that the future cannot be perfectly known, as some factors are uncontrollable or not fully predictable by nature. In real life, decisions are not made with a perfect view of the future, and system operators in particular and decision makers in general have to act according to a pre-defined strategy or policy. The advantage of stochastic approaches is that these allow quantifying the "value of information", by comparing results obtained with more or less uncertainty (for example, different qualities of wind prediction) [161].

Hence, different probabilistic approaches and game theory modelling techniques for power systems/markets under uncertainty have been developed [164][165]. Stochastic models propose decision making strategies, and this implies representing probabilistic processes. In other terms, state variables are described by probability distributions and not by unique values. Therefore, a stochastic modelling approach might include two steps: firstly, an optimisation to provide strategies at all the future possible states of the system; secondly, the strategy application to a given scenario (decisions/actions at every time step) [161][162].

The probabilistic models are generally numerical models[15], i.e. mathematical models using some sort of numerical time-stepping procedure to sample system states. The underlying concept is that a system state is a combination of all component states and each component state can be determined by sampling the probability of the component appearing in that state. In order to sample the system states to evaluate, two main categories of probabilistic models can be deployed [165][167][168]:

[15] *Analytical models to perform probabilistic analysis are developed as well. The basic idea is to do arithmetic with probability distribution functions of stochastic inputs variables. They are models built by assuming some probability distribution functions for the different system components and then combining the probabilities and frequencies of system states. Analytical methods often require several assumptions, approximations and simplifications when analysing large systems [165][168].*

- The **contingency enumeration** approach evaluates, using a system model, all possible combinations of failures up to a specified order (e.g. all N-1 or N-2 events) or down to a specified failure frequency limit.
- A **Monte Carlo simulation** is conducted by sampling the system states based on the component failure probability distributions or the probability distributions of state-transitions. The system performances are then assessed by observing the experiments and the sampled states are evaluated (e.g. through a different model) to determine the consequences. They are the most common and accurate stochastic methods since they are system size-independent and can be used with highly nonlinear and complicated systems with many uncertain variables. Monte Carlo methods can be classified in:
  - **Non-sequential Monte Carlo** methods (sometimes called time collapsed models or state sampling approaches): they consider each time point independent of another, thus neglecting the transitioning relations between system states. It is widely used in power system risk evaluation.
  - **Sequential Monte Carlo** methods: they consider instead the time-related interdependencies of the system states when computing the posterior distribution. The sequential techniques permit chronological issues to be considered and distributions of the reliability indices to be calculated (these methods hence allows preserving the characteristics of the time series e.g. of variable energy resources - wind and hydro inflows - and variable load). These methods usually require greater computational capabilities compared to the non-sequential techniques.

4.1.3. COMPLEX SYSTEM MODELS

Electrical engineering models are sensitive to power system operational conditions, hence the results they provide differ based on operational conditions. As a consequence, it is difficult to predict a power system collapse, caused by unexpected or unforeseen operational conditions, by using these models. Besides, most of these models just focus on understanding one phenomenon rather than the overall phenomena; however, serious disturbances on power systems, like large blackouts, usually occur owing to complicated interactions between system operators and power grids via information and communication technologies/systems, which can be hardly analytically described [169][170].

Complex system theory could come in handy to describe and analyse the power systems from a different angle. Complex systems could be described as possessing the following properties: the system consists of a multitude of components; each component has its own behaviour, attitude and goal; complicated interactions among these components result in organization and emergent behaviours of the system which cannot be expressed by a set of equations or functions. Power systems could be regarded as complex multi-layer systems (see again the Smart Grid Reference Architecture in Figure 24 of Chapter 2) exhibiting intense interactions within the layers, among different layers and among different power systems as well [169][170].

First, the interaction patterns among components needs to be studied, in order to understand the emergent behaviours of the power system as a whole and better grasp its evolution mechanisms and dynamics. The complex network methodology, which can be conceptualised at the intersection of graph theory and statistical mechanics, is widely accepted to analyse complex networked systems from the topological standpoint [169][170].

In complex system studies it is assumed that systems are dynamic, adaptive and system parts interact through feedback mechanisms. Methods from this field have been used to analyse interdependencies between infrastructures and to identify components that are critical for the functionality of the energy system. Generally, these methods require a detailed description of system properties and, consequently, have primarily been used to analyse energy systems similar to existing ones and not facing profound changes

over longer timeframes. Properties of the energy system are seen as affecting the severity and consequences a disturbance would have while threats and hazards are exogenous [169][170].

The methodology studies the structure and dynamics of power systems as a whole instead of analysing details. Although the structure of networked complex systems can be effectively studied by complex network method, electrical engineering specificity should be considered in complex network methodology when it is used to analyse real topological features of power systems and to identify critical components in power grids. On the other hand, dynamical robustness model in complex network method cannot reflect dynamics of cascading failures in power systems. Another complex system theory (i.e., self-organised criticality) could to some degree explain the mechanism of blackouts in power systems. Nevertheless, the introduction of dynamic stability and interaction of complex systems still remain challenging in existing models [171].

It is important to differentiate the meaning of "dynamical behaviour" (or simply dynamics) when dealing with complex networks, in contrast with its meaning in the power generation, operation and control field. While complex networks' dynamics is related to the flow of information, energy or matter through the networked system and the different temporal values that characterise the resulting feature vector, power systems' dynamics is related to frequency, synchronization, swings and transient stability performance [170].

The debate is open about the ability of complex networks (even when including simplified power flow models from electrical engineering) to provide insights into all aspects of real power grids. On the other hand, the complex network approach focuses on the emergence of unforeseen collective behaviour, and is not intended to predict all the individual behaviours of its constituent parts. Both communities - the electrical engineering and the complex system ones - seem to have different yet not opposing interests. There are indeed reasons to support both viewpoints [111][170].

4.2. MODELS FOR ELECTRICITY SECURITY ANALYSES

A great variety of methods and models can be employed to assess energy and electricity security, depending on several factors including: the policy maker's requests, the researcher's background, the characteristics of the system/phenomenon under observation [89][93].

In order to distinguish the very diverse models used to perform energy security analysis and study the interactions of the different domains of the energy/electricity value chain, several authors proposed ad-hoc classifications. Energy security models can represent a specific sector (like: supply of primary energy, upstream markets and imports and domestic markets and infrastructure), or they can integrate several domains of the energy supply chain. On a different perspective, energy security models can analyse one energy security property (e.g. stability or operational security) or more than one (e.g. adequacy and robustness). Furthermore, energy security models can integrate different sectors and assess different properties. Finally, some researchers evaluate and compare several of the above aspects and integrate different perspectives, using complex indicators and/or multi-criteria analysis [89][93][95][172].

For the purposes of our research on electricity supply security, we first cluster the models (in Table 7) according to the time horizon, the time granularity and the domains of the electricity value chain they primarily consider:

- Dynamic power system/grid models;
- Static power system/grid models;
- Power market/system models;

- Energy system/power market models.

Their main features are described in the following.

Table 7 - Clustering of electricity security models

MODEL CLUSTER \ FEATURES	TIME HORIZON				SYSTEM REPRESENTATION DETAIL		
	SHORT TERM	MID TERM	LONG TERM	VERY LONG TERM	ENERGY SYSTEM	POWER MARKET	POWER SYSTEM / GRID
DYNAMIC POWER SYSTEM / GRID MODELS	X	-	-	-	-	-	H
STATIC POWER SYSTEM / GRID MODELS	X	X	X	-	-	M	H
POWER MARKET / SYSTEM MODELS	X	X	X	-	-	H	M/L
ENERGY SYSTEM / POWER MARKET MODELS	-	X	X	X	H	H/M	-

4.2.1. Dynamic power system/grid models

The dynamic power system/grid models provide a detailed short-term description of the power system, grid and protection components. They mainly target the infrastructure dimension of electricity security, i.e. they model as endogenous factors and variables included in the electricity value chain. The typical time horizon is up to seconds (minutes) and the time steps are in the order of milliseconds or even microseconds. The dynamic power system/grid models necessarily embed a static model of the power system/grid (described in the next section).

The dynamic power system/grid models help to evaluate the power system's ability to ride through disturbances and to reach a normal operating condition. Under normal operating conditions, all the (synchronous) machines connected to the power system run at their synchronous speed. If a disturbance occurs, the machines swing with respect to each other. Power system stability is a condition in which the various synchronous machines remain "in synchronism" or "in step". Conversely, instability implies falling "out of step".

Large power systems are subjected to a wide range of operating conditions, depending on load level and equipment availability. They may experience many disturbances involving faults, loss of generation, loss of transmission facilities and loss of load. Electromechanical transients initiated by such disturbances cannot be easily predicted. They differ from one power system to another and from one situation to another. They also depend on type, location and severity of disturbance.

An interconnected system is also threatened by tendencies toward dynamic instability: power oscillations - initiated by some disturbance - increase in magnitude to the point of causing system separation. Long-distance transmission lines typically display such behaviour.

Power system stability models can be differentiated in the following groups, based upon the kind of events they want to portray and analyse [132]:

- **Rotor angle stability models** describe the ability of synchronous machines of a power system to remain in synchronism after a disturbance. They include two subcategories: *small-disturbance (or small-signal) rotor angle stability*: the disturbances are considered to be sufficiently small that system equations can be linearised; l*arge-disturbance rotor angle stability (or transient stability)*: the resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship.
- **Voltage stability models** describe the ability of a power system to maintain steady voltages at all buses after a disturbance. They include two subcategories: *large-disturbance voltage stability,* for example in case of system faults, loss of generation, or circuit contingencies*; small-disturbance voltage stability,* for example in case of incremental changes in system load.
- **Frequency stability models** describe the ability of a power system to maintain (contain and restore) steady frequency following a severe system upset resulting in a significant imbalance between generation and load.

The general formulation of a stability problem is a set of differential-algebraic equations [157]:

$$\dot{x} = \mathrm{f}(x, y, u) \tag{1}$$

$$0 = \mathrm{g}(x, y, u) \tag{2}$$

in which x is a vector of state variables, u is the vector of system inputs, and y is the vector of algebraic variables, with many entries similar to the power flow variables such as the bus voltage magnitudes and angles (see next section). The starting point for a transient stability study is usually a power flow, and the initial values for x are determined by solving $\mathrm{f}(x, y, u) = 0$.

Many of the differential equations contained in f are associated with modelling the behaviour of the synchronous machines during this time frame. The most important of the synchronous generator differential equations is what is known as the generator swing equation, which can be expressed for generator k as two first-order differential equations,

$$\begin{gathered} \frac{\mathrm{d}\delta_k}{\mathrm{dx}} = \Delta\omega_k \\ \frac{\mathrm{d}\Delta\omega_k}{\mathrm{dx}} = \frac{1}{M_k}\left[T_{mech,k}(x, y, u) - T_{elec,k}(x, y, u) - D_k\Delta\omega_k\right] \end{gathered} \tag{3}$$

where δ_k and $\Delta\omega_k$ are state variables (elements of x) that represent the generator's rotor torque angle and the generator's deviation from synchronous speed; $T_{mech,k}$ is the mechanical torque input to the generator; $T_{elec,k}$ is the electrical torque output from the generator; D_k is a damping coefficient; and M_k is a value that depends on the inertia of the electric generator. The generator swing equation is commonly written in terms of mechanical and electric power rather than torque, with the rationale that the machine's speed is usually quite close to synchronous speed [157].

Commonly generators are represented with additional differential equations for the electric machines, for their exciters (to control the terminal voltage), for their governors (to control the mechanical power input), and for their stabilisers (to reduce system oscillations). Load dynamics, such as those of induction motors, can also be included. For a large system a single transient stability solution might involve the integration of more than 100,000 differential equations with tens of thousands of algebraic constraints [157].

ENTSO-E recently developed a "Dynamic Study Model for the Interconnected Power System of Continental Europe", which can run with different simulation tools (including PowerFactory, PSS Netomac, Eurostag and PSSE) [173][174]. It includes standard dynamic models for generation units and the relevant control system; through a parameter variation process the model has been tuned to match frequency transients and a typical oscillation mode recorded within Continental Europe.

A dynamic model of the European power grid has been also developed within the PEGASE research project [175]. The model features 15,226 buses and 21,765 branches and around 146,000 differential-algebraic states and it is used to test methods to speed up time simulations for large-scale power systems [176].

Finally, practically all the models built/running with the OPAL [177] and RTDS [178] real-time simulation tools fall in this category.

4.2.2. STATIC POWER SYSTEM/GRID MODELS

The static power system/grid models offer detailed representations of the power grid (component by component). The static power system/grid models mainly target as endogenous the infrastructure-related electricity security dimension (some elements of the primary energy sources dimension might be included). The typical time horizon is one or several years. The time steps largely vary depending on the very different models within this cluster (power flow, topological, graph-based, etc): they might not even be specified (when studying system snapshots or topological features) or they could typically be hours or fractions of hours.

The following typologies of models (the list is not exhaustive) can be identified as primarily belonging to this cluster [179]:

- **Power flow models**, i.e. analytical input-output models allowing determining, under given loading conditions, the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line. The power flow model is a snapshot of the power injections, withdrawals and flows in the network and it is the basis for several other power system analyses. Nearly all the closed-form power system models and tools - including those listed in our review [180]-[197] - feature/include a power flow model.
- **Optimal power flow models**, i.e. analytical optimisation models combining a power flow problem with a system/generation minimisation cost problem. The goal is to minimise a cost function, such as the operating cost, taking into account equality constraints (bus real and reactive power balance, generator voltage set points, area power interchange, etc) and inequality constraints (system components flow limits, generators' output limits, bus voltage limits etc) [161]. The same models/tools mentioned above can perform optimal power flow analyses as well.
- **Complex network models,** i.e. graph-based models abstracting the power system in a network with a set of edges (or lines) connecting a set of vertices (or nodes). Then, structural and evolution properties of the abstracted network can be studied by a set of informative indices based only on time-independent geometric features of the system. However, the real networks are inherently difficult to understand due to their structural complexity: the connection can be represented in various ways since vertices and edges have different functions in different complex systems; furthermore, the network is evolving with time when some of old vertices and edges are replaced with new ones; the various factors impacting the structural complexity could have interactions which lead to more complicated effects on the network structure [169][198]. Three complex network models have been mainly researched in combination with real power systems/grids: random networks [201], small-world networks [202] and

scale-free networks [203], though these models cannot interpret all phenomena observed in real networks.

Generally two types of strains can be applied on these graph-based models, structural and functional. Structural strains affect the structural properties of the system in terms of removal of nodes and/or edges. Functional strains affect physical properties of the system, e.g. increased loading. The modelling approach can also describe the cascading of failures, i.e. capturing functional properties of the system that affect structural properties [104]. Advanced models, as used in system engineering approaches, are superior in capturing the physical behaviour of the system, but they usually require unfeasible computational times for the type of analyses carried out here. On the contrary, abstracted models, e.g. purely connectivity-based/topological models as used within the field of Network Theory, are computationally very fast but may not capture the relevant behaviour of the system [104][204].

TSOs use power system/grid models on hourly/daily basis to check flows in all lines, and also to plan investments (need for future reinforcement). Static power system/grid models may also embed selected dispatching features, but their main focus remains to check the flows in the grid, based on a detailed representation of the system.

For the sake of illustration, we here below describe the equations formulating the power flow (or load flow) model [157][179].

An alternating current (AC) transmission grid comprises of generators, loads, transformers, buses and lines. Buses which are connected with a generator are defined as generation buses and generally characterised by the real power (P) and reactive power (Q) produced. Buses feeding loads are instead defined as load buses and again characterised by the real power (P) and reactive power (Q) withdrawn. The apparent power S consists of real power P and reactive power Q. As the objective of the AC power flow analysis is to compute the steady-state values of the bus voltages, the loads are generally represented as constant power loads.

The power transmitted over a line is denoted by P and is defined is the product of voltage V and current I: $P = V * I$

The individual component models are then combined into a system model. The main laws describing how these components work together are:

- The first law, known as Kirchhoff`s current law (KCL), states that the sum of the (ingoing/outgoing) currents in a bus is zero: $\sum_{i=1}^{m} I_i = 0$, where m is the number of currents injected and/or withdrawn from the bus. The law holds for all the power grid buses.
- The second law, known as the Kirchhof's voltage law (KVL), states that the sum of the potential differences in a loop is equal to zero: $\sum_{i \epsilon C} V_i = 0$, where C is the set of busses included in loop and V_i describes the i^{th} voltage drop.
- The Ohm's law describes the proportionality between current and voltage: $R = \frac{V}{I}$ where the resistance R is actually replaced by the impedance Z in AC power networks.

Since the total real power generation must exactly match the total real-power-load plus losses, the outputs of all the generators cannot be independently specified. Rather, at least one generator is designated as the slack (or swing) bus, in which the voltage magnitude and angle are specified, and the power flow algorithm determines the generator’s real and reactive power output.

In an n-bus transmission network, the currents and voltages in the n buses are linked by the following relation

$$\bar{I}_{BUS} = \bar{Y}_{BUS}\bar{V}_{BUS} \tag{4}$$

where $\bar{I}_{BUS} = [\bar{I}_1, \bar{I}_2, \cdots, \bar{I}_n]^T \rightarrow (n * 1)$ is the vector of bus injection currents, $\bar{V}_{BUS} = [\bar{V}_1, \bar{V}_2, \cdots, \bar{V}_n]^T \rightarrow (n * 1)$ is the vector of bus voltages, and $\bar{Y}_{BUS} \rightarrow (n * n)$ is the bus admittance matrix.

$\bar{Y}_{BUS}$ matrix depends on the power grid topology and the admittance of all transmission lines. Transmission lines consist of series resistance, inductance and capacitance. These components can be modelled as a complex impedance Z, the inverse of Z is the admittance Y.

$$\begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \\ \vdots \\ \bar{I}_n \end{bmatrix} = \begin{bmatrix} \bar{Y}_{11} & \bar{Y}_{12} & \cdots & \bar{Y}_{1n} \\ \bar{Y}_{21} & \bar{Y}_{22} & \cdots & \bar{Y}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \bar{Y}_{n1} & \bar{Y}_{n2} & \cdots & \bar{Y}_{nn} \end{bmatrix} \begin{bmatrix} \bar{V}_1 \\ \bar{V}_2 \\ \vdots \\ \bar{V}_n \end{bmatrix} \tag{5}$$

$$\bar{I}_i = \sum_{j=1}^{n} \bar{Y}_{ij}\bar{V}_j \tag{6}$$

The apparent complex power injected at bus i is given b:

$$\bar{S}_i = P_i + jQ_i = \bar{V}_i\bar{I}_i^* \tag{7}$$

where $\bar{V}_i = V_i e^{j\theta_i}$; $\bar{V}_j = V_j e^{j\theta_j}$; $\bar{Y}_{ij} = Y_{ij} e^{j\alpha_{ij}}$;

$$\bar{S}_i = P_i + jQ_i = V_i e^{j\theta_i} \left[\sum_{j=1}^{n} Y_{ij} V_j e^{j(\theta_j + \alpha_{ij})} \right]^* \tag{8}$$

which leads to the most known formulation of load flow equations:

$$\begin{aligned} P_i &= \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\theta_i - \theta_j - \alpha_{ij}) \\ Q_i &= \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\theta_i - \theta_j - \alpha_{ij}) \end{aligned} \tag{9}$$

It can be seen that for any i^{th} bus, there are two equations and four variables (P_i, V_i, θ_i and Q_i). Thus for the n-bus system, there are a total of 4n variables and only 2n equations. Out of these 4n variables, 2n quantities need to be specified and the remaining 2n quantities are calculated from the 2n load flow equations. To this aim, the buses in a system are classified into three categories and in each category two different quantities (in brackets) are fixed as described below:

- Load buses (PQ): Generally the values of loads (real and reactive) connected at these buses are known and hence, at these buses P_i and Q_i are specified (or known). Consequently, V_i and θ_i need to be calculated for these buses.
- Generation buses (PV): Generally, the real power supplied by the generator is known and also, the voltage output of the generator is kept constant by the exciter (provided that the reactive power supplied or absorbed by the generator is within the limits). Thus, at a PV bus, P_i and V_i are specified and Q_i and θ_i need to be calculated.

- Slack Bus (V,θ): A reference angle needs to be specified so that all the other bus voltage angles are calculated with respect to this reference angle. Moreover, the total power supplied by all the generation must equal the total system load and power losses. However, as the system losses cannot be computed before the load flow problem is solved, there should be at least one generator in the system which would cover the loss (on top of supplying its share of loads); thus, for this generator, the real power output cannot be pre-specified. However, because of the exciter action, V_i for this generator can still be specified. Hence for this generator, V_i and θ_i (= 0) are specified and the quantities P_i and Q_i need to be calculated.

Since the load flow equations (9) are a set of non-linear algebraic equations, they need to be solved by numerical techniques (like: Gauss-Seidel, Newton Raphson, etc).

The static power system/grid models of ENTSO-E contain the full detail of the physical pan-European transmission grid and they are used to calculate the actual load flows in the network under given generation/load conditions and to compute the grid transfer capacities for the market studies (see next section). They take into account several constraints such as flexibility and availability of thermal units, hydro conditions, wind and solar profiles, load profile and uncertainties. ENTSO-E coordinates the regional network studies, which analyse the grid power flows at regional level and deliver the technical part of the cost-benefit assessment [80][144].

ENTSO-E uses different models and tools in the different regions[16] for the static power system/grid analysis: Convergence, PSSE, UPLAN (in the CSW region), Convergence, Spira, ISPEN, PSSE/ODMS, Integral, NEPLAN (in the CCS region), PSSE and NEPLAN (in the CSE region), Integral, PSSE, Neplan, PSLF (in the CCE region), PSSE, SAMLAST, PowerFactory (in the BS region), PSSE, PowerFactory, Convergence, PSA Integral (in the NS Region). Some of these models (e.g. UPLAN, SAMLAST) combine market and load flow analysis [180]-[191].

4.2.3. POWER MARKET/SYSTEM MODELS

The power market/system models generally represent the demand-supply equilibrium, and might use simplified assumptions for describing the grid ("single node" or more detailed representations). They mainly consider as endogenous factors within the infrastructure and the primary energy source dimensions of electricity security, as well as some aspects of the market and regulation dimension. The typical time horizon is up to one year (or several years) and the typical time steps are hours/weeks (or weeks/months).

Recently, with market liberalisation and the increased levels of variable renewable wind power, elements of game theory and stochastic techniques have become more wide spread in power market/system modelling. Game theory techniques study the behaviours of decision makers who are aware that the actions of their competitors affect their utility. The "rules of a game" include: the players - the individuals/entities who make decisions; the action set - the choices available to each player; the payoff - the utility that each player receives at the end of the game; the strategy - a rule that tells a player which action to take at each instant of the game; the information set - the knowledge available to each player when they decide the action; nature - a non-player who takes random actions at specified points in the game with certain probabilities. The modeller’s objective is to describe a given scenario in terms of the rules of a game so as to model the context and figure out what will happen in that scenario [166].

[16] ENTSO-E System Development Committee, as explained in Chapter 2, has six regional groups: CSW - Continental South West, CCS - Continental Central South, CSE - Continental South East, CCE - Continental Central East, BS - Baltic Sea, NS - North Sea.

Even this cluster includes a wide host of models. The main difference with the energy system/power market models cluster are: market/power system models are more sectorial (thus more power system oriented than energy system oriented) and they describe in much more detail the electricity infrastructure (the energy features are only sketched and their related factors/variables are usually exogenous). Power market/system models can include a form of stochastic modelling (e.g. for water values calculation for a power system hosting storage hydro power plants). This implies using scenarios (e.g. based on historical production profiles), and then elaborating a strategy to face the uncertainties of each scenario [161]. The boundary between market and network models is not clear: ideally, a "power system model" should be both a market and a network model, and some studies give insights on both the generation and networks needs with a single model, as for example [245].

The following typologies of models (the list is not exhaustive) can be identified as primarily belonging to this cluster:

- **Unit commitment and economic dispatch models**: These models help understanding when/how much the generation units shall be started and stopped and how much shall they produce so that the total demand is met with the minimum production cost, in the short-to-mid-term time horizon. The unit commitment problem involves two variables: the generation output and the number of production units turned on; since the decision concerning the units to be turned/kept on/off is binary, the mathematical problem is not continuous; furthermore, a number of generation technical constraints shall be met, including: minimum/maximum production output, maximum ramp-up /-down rates, minimum up-/down-time of the unit. Originally these models did not provide detailed representations of the network. Currently, these models can cover from a few regions with some interconnection capacity to detailed node by node grid characterisation. For example, the Plexos models/tools fall in this category [161][193]. A reduced form dispatch model (REFflex) that compares variable generation supply with demand and calculates the fraction of load potentially met by variable generation is discussed in [207]. As an example, the authors in [208] present a unit commitment and economic dispatch model for Ireland. As another example, WILMAR is the model - featuring stochastic unit commitment decisions - developed by VTT [194].
- **Hydrothermal coordination models**: These models are generally used to determine the optimal, coordinated maintenance/scheduling of hydro and thermal plants - over a mid-term (or shorter) time horizon - which allows supplying demand at a minimum cost and complying with a set of constraints. Examples of research and industrial models are [209][210][211].
- **Production cost models**: These models were originally developed several decades ago to manage fuel inventories and budget by capturing all the costs of operating a fleet of generators. These models help to forecast in the mid-to-long-term the expected amount of electricity produced by different power generation units and the expected production costs. Currently, they tend to be used by power industry to study shorter term scenarios (see also generation capacity planning models). An example of application of a production cost model with the PLEXOS tool is provided in [212].
- **Generation capacity planning models**: These models calculate the capacity, location, and timing of installing new generation sources. The long term generation expansion planning receives less attention in the existing liberalised markets as long term capacity investment is seen as less profitable. These models have become far more complicated since the introduction of market liberalisation where the price of electricity is determined in a wholesale market. In addition, market schemes and arrangements vary from country to country and this adds another level of complexity [164]. As an example. WASP is the Power Generating System Expansion Planning developed by the International Atomic Energy Agency (IAEA); it finds the economically optimal generation expansion policy for an electric utility system within

user-specified exogenous constraints (environmental emissions, fuel availability and electricity generation by some plants) [213]. As another example, ReEDS (Regional Energy Deployment System) is the long-term capacity-expansion model developed by NREL to study the deployment of electric power generation technologies and transmission infrastructure in the United States [214][215][216].

Just for illustration, we report in the following the formulation of the Unit Commitment and Economic Dispatch problem (without considering reserves, transmission constraints and storage devices). This is an economic optimisation problem through time, solved by mixed-integer programming. Let the studied time period (usually 24 hours) be divided into *T* dispatch periods, of duration t_d minutes, and let the total number of generating units in the System be *G*. *i=1, . . . ,G* is the generating unit index and *t=1, . . . , T* is the time index.

The minimisation problem to solve is the following:

$$\min_{S_{i,t},P_{,it}} \sum_{t=1}^{T} \sum_{i=1}^{G} [TR_{on,i,t} \cdot C_{start-up,i} + TR_{off,i,t} \cdot C_{shut-down,i} + C_{i,t} \cdot S_{i,t}]$$

$$TR_{on,i,t} = \begin{cases} 1 \; when \; S_{i,t-1} = 0 \; AND \; S_{i,t} = 1 \\ 0 \; for \; all \; the \; other \; cases \end{cases} \tag{10}$$

$$TR_{off,i,t} = \begin{cases} 1 \; when \; S_{i,t-1} = 1 \; AND \; S_{i,t} = 0 \\ 0 \; for \; all \; the \; other \; cases \end{cases}$$

subject to the following constraints:

- Power balance constraint (neglecting losses):

$$\sum_{i=1}^{G} S_{i,t} \cdot P_{i,t} = D_t \, , t = 1, \ldots., T \tag{11}$$

- Power output of generating units:

$$P_{min,i} \leq P_{i,t} \leq P_{max,i}, i = 1, \ldots, G, t = 1, \ldots, T \tag{12}$$

- Ramp rates of generating units:

$$R_{down,i} \cdot t_d \leq P_{i,t} - P_{i,t-1} \leq R_{up,i} \cdot t_d, i = 1, \ldots, G, t = 1, \ldots, T \tag{13}$$

- Minimum up and down time:

$$SU_{i,t} = \begin{cases} SU_{i,t-1} + 1, if \; S_{i,t-1} = 1 \\ 0, if \; S_{i,t-1} = 0 \end{cases}$$

$$SU_{i,t} = \begin{cases} SU_{i,t-1} + 1, if \; S_{i,t-1} = 1 \\ 0, if \; S_{i,t-1} = 0 \end{cases} \tag{14}$$

$$S_{i,t} = \begin{cases} 1, if \; S_{i,t-1} = 1 \; AND \; SU_{i,t} \cdot t_d < T_{up,i} \\ 0, if \; S_{i,t-1} = 0 \; AND \; SD_{i,t} < T_{down,i} \\ 0 \; or \; 1 \; in \; all \; the \; other \; cases \end{cases} , i = 1, \ldots, G, t = 1, \ldots, T$$

Where:

Continuous independent variables: $P_{i,t}$: Power output of generating unit *i* at time *t* (in MW)

Binary independent variables: $S_{i,t}$: indicating whether unit *i* is up ($S_{i,t}$ =1) or down ($S_{i,t}$ =0) at time *t*

Continuous dependent variables: $C_{i,t}=f(P_{i,t})$: Variable cost of generating unit *i* at time *t*

Binary dependent variables:

$TR_{on,i,t}=f(S_{i,t},S_{i,t-1})$: "Transition-on" variable of generating unit *i* at time *t*. It is 1 only when at the beginning of time *t* the generating unit *i* is turned on.

$TR_{off,i,t}=f(S_{i,t},S_{i,t-1})$: "Transition-off" variable of generating unit *i* at time *t*. It is 1 only when at the beginning of time *t* the generating unit *i* is turned off.

Integer dependent variables:

$SU_{i,t}$ and $SD_{i,t}$ are the variables indicating the time length where unit *i* is respectively on and off at the beginning of time *t*

Generating units technical constraints:

$P_{min,I}$ and $P_{max,I}$ are the minimum and maximum power output of generating unit *i* (in MW)

$T_{up,I}$ and $T_{down,I}$ are the minimum up and down time of generating unit *i* (in min)

$R_{up,I}$ and $R_{down,I}$ are the ramp-up and ramp-down rate of generating unit *i* (in +/- MW/min)

Constants: $C_{start\text{-}up,I}$ and $C_{shut\text{-}down,i}$: are start-up and shut-down cost of generating unit *i*

Inputs: D_t is the (forecasted) demand at time *t* (in MW)

As a general observation, most of the above described model typologies were originally developed and applied by vertically integrated utilities in non-liberalised market regimes with a view to optimise the overall system cost. In the current liberalised systems, the decisions on the unit commitment and the generation output levels are mostly taken by private parties competing in a market context; this entails a move from a system-wide cost-based to a profit-based production optimisation. Different modelling techniques, such as those based on game theory, are therefore frequently applied in combination with the traditional ones to represent and observe the electricity system and market dynamics. As an example, the authors [217] illustrate an electricity market simulator based on game theory allowing simulating the long run evolution of a generation set.

Power market/system models are used by ENTSO-E to calculate the dispatch of generation units and load all along the year on an hourly basis, using a simplified physical grid representation: each bidding area, represented as a single node, is linked to the adjoining bidding area(s) via a branch displaying an equivalent grid transfer capacity. Power market/system models (compared to static power system/grid models) are better suited to spot structural, rather than incidental, bottlenecks [80]. ENTSO-E deploys the following suite of power market/system models to assess projects: pan-European market studies for each scenario (Vision) to define parameters and datasets and to provide the boundary conditions for the regional market studies; regional market studies (i.e. market studies undertaken by every regional group), which deliver bulk power flows, pinpoint specific cases for network studies and deliver the economic part of the CBA assessment. ENTSO-E utilises nine different power market/system models in the regional investment analyses and plans: ANTARES (in CCS, CSW and NS regions), BID (in BS and NS regions), MAPS (BS), POWRSYM4 (CCE, CCS and NS), PROMED (CCS), PROMOD (NS), PROSIM (CSE), SAMLAST (BS) and UPLAN (in CSW)[191]-[199]; the latter three models feature also a detailed network representation, which however may require the use of DC load flow calculation approach [81]-[86][144].

4.2.4. ENERGY SYSTEM/POWER MARKET MODELS

The energy system/power market models represent the whole energy system and selected portions of the power system/market. They target the source and the market and regulation dimensions of electricity security (the latter, as well as the geopolitical dimension, may be exogenous to the model). The typical time horizon is up to years or decades and the typical time steps (named also time slices) are weeks/months (i.e. a few tens per year).

For example, TIMES [218] and MARKAL [219] models fall in this category: they are optimisation partial equilibrium bottom-up model that generates scenarios of technologies that minimises total system cost. Hence they have been frequently used to observe how energy systems could develop [93]. Energy system models can represent a country's or region's whole energy system over time periods extending beyond the investment cycle. System studies significantly vary in the spatial coverage, sector boundaries representation, in their objectives and structure. Energy system/power market models usually aim at finding a least cost solution for the supply of energy services under a number of constraints which could be policies (e.g. RES-E targets, climate goals etc) or infrastructure limitations. These models typically do not aim at modelling an individual actor's behaviour. A number of factors are generally exogenous to a system model such as demand, commodity prices; possibly those exogenous variables are themselves the output of other models. The power generation portfolio might be either exogenously given or result from an optimisation model. The key limiting factor of energy system/power market models is linked to the aggregated time/spatial representation of the electrical power system: generally a few tens time slices/steps per year are used to describe the electricity system and the power grid is not modelled (and/or represented via interconnection transfer capacity values only) [161].

Energy system/power market models can be used to assess electricity security aspects in many respects: electricity security features can be incorporated as a constraint (e.g. a certain level of installed back up capacity) in the model, single/composite indicators can be calculated after the model has produced some scenarios. These models however cannot generally capture threats and events occurring in the short-term (e.g. generation variability, interregional trade/price volatility) and are less suitable to study radical system changes and longer timeframes if this alters the structure and feedbacks within the system [93].

The following typologies of models (the list is not exhaustive) can be identified as mainly belonging to this model cluster [93][101][104]:

- **Energy market models.** These models are used to evaluate whether the infrastructure and market design ensure an adequate level of energy security. Under the energy market models fall also the multi-energy carrier models, like gas & power, heat & power etc, which are not yet frequently developed. Electricity infrastructure is modelled for example in [220], where a static power system/grid model for electricity and gas is deployed [257]: the model helps the decision makers in assessing where electricity generation capacity should be located and how much gas and electricity infrastructure should be built. Other models include electricity infrastructure within the wider energy system models and concentrate on assessing reliability features [132]. Technical performance of current systems and future changes in system characteristics under different regulations and market designs are the main focus areas of the energy market models. Agent-based modelling techniques begin to be adopted to model complex socio-technical systems and assess the interdependencies of policies and different business models [93].
- **Energy corridor models.** These models try to evaluate the aggregated risks from entire supply routes: electricity plays a secondary/indirect role respect to oil and gas. Clearly, oil and gas pipelines - due to their geopolitical relevance and their structural/operational features - are more frequently targeted than electricity transmission lines in these models. For example, the authors [221] calculate the risk of

each supply corridor and discuss how to manage the aggregated risk: they study how the import and transit risk develops in different scenarios until 2040 through TIMES model, and they assess the trade-off between system cost and import risk. In contrast to the previous examples, in which the import volume is considered to be predefined, this enables the analysis of how changing levels of imports could impact the import risk. Some limitations of the above described models are: the lack of risk associated with domestic supply and the fact that static values are used to analyse threats that are dynamic over time (depending on geopolitical dynamics) [93].

- **Energy sources (upstream markets and imports) models.** These models typically frame nations as referent objects that import energy from suppliers or a global market and energy trade is sometimes characterised as of strategic importance since there are interactions with foreign policy objectives. For example, there is a risk of exporting or transit countries interrupting power supply. Thus, independence of imports in general and less reliance on individual exporters in particular are usually regarded as something to strive for. Energy markets and imports are commonly analysed for two broad groups of interrelated risks: a diversifiable risk that is unique to every exporter or supply route; a systematic risk (not diversifiable) that affects all agents on the market [93].

The different electricity security model typologies in which the previously defined model clusters can be broken down are summarised in Table 8:

Table 8 - Model clusters vs. model types

MODEL CLUSTERS / MODEL TYPES	DYNAMIC POWER SYSTEM/GRID MODELS	STATIC POWER SYSTEM/GRID MODELS	POWER MARKET / SYSTEM MODELS	ENERGY SYSTEM / POWER MARKET MODELS
ROTOR ANGLE STABILITY	X	-	-	-
VOLTAGE STABILITY	X	-	-	-
FREQUENCY STABILITY	X	-	-	-
POWER FLOW	-	X	-	-
OPTIMAL POWER FLOW	-	X	X	-
COMPLEX NETWORK	-	X	X	-
UNIT COMMITMENT AND ECONOMIC DISPATCH	-	X	X	-
HYDROTHERMAL COORDINATION	-	X	X	-
PRODUCTION COST	-	X	X	-
GENERATION CAPACITY PLANNING	-	X	X	-
ENERGY MARKETS	-	-	X	X
ENERGY CORRIDORS	-	-	X	X
ENERGY SOURCES	-	-	X	X

4.3. APPROACHES FOR ELECTRICITY SECURITY ANALYSES

In the following, we illustrate the security assessment approaches mainly targeting one of the five electricity security properties previously discussed: operational security, flexibility, adequacy, resilience, robustness. We also describe which model clusters (dynamic power system/grid models, static power system/grid models, power market/system models, energy system/power market models) - or combination of them - are mainly used.

Finally we discuss some aspects and challenges of approaches - generally resorting to suites of models - targeting multiple security properties.

4.3.1. OPERATIONAL SECURITY APPROACHES

4.3.1.1. METHODOLOGICAL CHALLENGES

In Chapter 3 we defined operational security as the ability of the power system to maintain or to regain an acceptable state of operational condition after disturbances. It covers (close to) real-time and stability system performances. The most deployed models to perform operational security analyses are the dynamic power system/grid models and the static power system/grid models (see also Table 9 below and Figure 35 below).

Clearly, a prerequisite for all the analyses is to make modelling assumptions and formulate a mathematical model appropriate for the time-scales and phenomena under study. We previously explained how especially (dynamic) power system/grid models and static power system/grid models can be completely different despite the very narrow time frame of the events under observation [132].

The most deployed methodology to check real-time and close to real-time system security performances is the contingency analysis. This entails checking the system behaviour following the alternative or combined loss of one or more components, according to a scenario of events generally pre-defined in a contingency list. The contingency analysis is the tool par excellence to understand how the system behaves and to have a preview on how the system can evolve. Deterministic and probabilistic approaches can be used to verify security properties, the latter implying a very high number of combinations to be simulated.

An overview of the power system reliability methods using contingency and cascading failure analysis is in [222]. Among others, the following ones are highlighted: in the CASCADE model [223], many identical components are randomly loaded; an initial disturbance adds load to each component and causes some components to fail; this causes a fixed load increase for other components. As components fail, the system becomes more loaded and cascading failure of further components becomes likely. The probability distribution of the number of failed components is studied accordingly. TRELSS (Transmission Reliability Evolution of Large Slack Systems) tool, simulating enumerated contingencies with up to four generating units and/or two circuits taken out [224]; the Oak Ridge-PSERC-Alaska (OPA) tool [225]-[228], originally based on DC load flow model, tests disturbance propagation by means of random line tripping and subsequent re-dispatching actions (until no line is overloaded); several variants have been produced since then, including: improved OPA model [229], AC OPA model [230][231], OPA with slow process [232]. The Manchester model, based on AC power flow and simple load shedding rules, represents a range of interactions, including cascading and sympathetic tripping of transmission lines, heuristic representation of generator instability, under-frequency load shedding, post-contingency re-dispatch of active and reactive resources, and emergency load shedding to prevent a complete system blackout caused by the voltage collapse [233][234][235]. Most of the cascading/stability analysis tools focus on the electrical phenomena and do not

model protection behaviours: the authors [236] instead model a large set of current automatic remedial actions and optimal operational human decisions.

In order to understand how a system can be driven to a certain desired operational point, stability analyses are fundamental since they can prove the feasibility of a certain system state and illustrate the path from one operational point to another. The stability conditions could be even the most demanding ones to design the power system (especially in small power systems or power system with large penetration of RES). In order to perform a study to check power system stability aspects, one first needs to define the power system stability event under analysis, secondly the model is instantiated with the proper dataset, typically using a scenario of events; finally results are reviewed in light of assumptions, are compared with the engineering experience ("reality"), and simulations are repeated if necessary [132].

As an example, the authors [235] review power system stability methods and approaches with high wind penetration and carry out transient and small-signal stability analyses by using aggregate wind farm models. As another example, the capabilities of emerging transmission technologies - namely Voltage Source Converter High Voltage Direct Current (VSC-HVDC) lines - to improve power system stability are analysed in [238] by comparing VSC-HVDC and AC transmission lines performances. In [239] the authors, combining the PSSE tool, a single-bus frequency model developed with MATLAB [182] and Simulink [183], assess the frequency stability risks (in terms of in-feed losses and wind turbine active power dips induced by network faults) of high wind penetrations on an island system.

The general industry practice for stability assessment has been to use a deterministic approach. The power system is designed and operated to withstand a set of contingencies referred to as "normal contingencies" recognised as having significant likelihood of occurrence. In practice, they are usually defined as the loss of any single element in a power system either spontaneously or preceded by a single-, double-, or three-phase fault. This is usually referred to as the criterion because it examines the system behaviour following the loss of any one of its major components. In addition, loss of load or cascading outages may not be allowed for multiple-related outages such as loss of a double-circuit line. Consideration may be given to extreme contingencies that exceed in severity the normal design contingencies [132].

The deterministic approach widely applied by the power industry in the past is considered to have preserved adequate security levels while saving on computational resources. Its main limitation, however, is that it treats all security-limiting scenarios as having the same risk. It also does not give adequate consideration as to how likely or unlikely various contingencies are. In today's utility environment, with a diversity of participants with different business interests, the deterministic approach may not be acceptable. There is a need to account for the probabilistic nature of system conditions and events, and to quantify and manage risk. The trend will be to expand the use of risk-based security assessment. In this approach, the probability of the system becoming unstable and its consequences are examined, and the degree of exposure to system failure is estimated. This approach is computationally intensive but seems doable with today's high performing computing resources [132][133].

4.3.1.2. Actors

As we have seen, even though there are numerous decision makers responsible for electricity security, the TSOs and DSOs bear most of the burden in the short term.

The TSOs, and to a certain extent ENTSO-E, have a key role to play in performing operational security analyses and deploying the correlated actions. Indeed, as set out in the Operational Security Network Code:

- To identify Contingencies which would endanger the Operational Security and lead to unplanned outages, the Transmission System Operators should rely on Contingency Analysis. The Contingency

Analysis should be performed during the operational planning and in real-time operation. The results of the Contingency Analysis will allow identifying and deploying necessary pre-fault or post-fault Remedial Actions [59].

- In order to determine the System State, each TSO shall at least every 15 minutes perform Contingency Analysis in real-time, monitoring the parameters against a common set of criteria, while taking into account the effect of potential Remedial Actions and measures of the System Defence Plan [59].

As far as stability analyses are concerned, ENTSO-E [59] adopts the definitions and classifications of stability phenomena in [132], adding that the objective of their stability studies is the rotor angle stability, frequency stability and voltage stability in case of ordinary contingencies, i.e. incidents which are specifically foreseen in the planning and operation of the system. The following operational security rules are also introduced:

- Transient stability. Any 3-phase short circuits successfully cleared shall not result in the loss of the rotor angle and the disconnection of the generation unit (unless the protection scheme requires the disconnection of a generation unit from the grid).
- Small Disturbance Angle Stability. Possible phase swinging and power oscillations (e.g. triggered by switching operation) in the transmission grid shall not result in poorly damped or even un-damped power oscillations.
- Voltage security. Ordinary contingencies (including loss of reactive power in-feed) must not lead to violation of the admissible voltage range (generally 0.95 - 1.05 per unit)

R&D actors often flank institutional actors like governments, regulators and operators in refining assessment methodologies and proposing innovative approaches for operational security assessment, even though the power sector is rather rigid to changes due to the high security implications of any change.

As earlier discussed, at regional scale, new cooperation entities among clusters of TSOs/Member States are emerging and/or being proposed: the option of establishing Regional Operational Centres (ROCs) throughout Europe is under debate (ENTSO-E promotes the roll out of regional security coordination service providers - RSCSPs). These new actors could play a role (also) in coordinated operational security analyses [72][73][74].

4.3.2. FLEXIBILITY APPROACHES

4.3.2.1. METHODOLOGICAL CHALLENGES

In Chapter 3 we defined flexibility as the capability of the power system to cope with the short/mid-term variability of generation (like renewable energy) and demand so that the system is kept in balance. The most deployed models to perform flexibility analysis are the static power system/grid models and the power market/system models (see also Table 9 below and Figure 35 below).

In order to analyse flexibility it is necessary to improve the understanding of at least the following aspects [136][153]:

- Physical system aspects, such as transmission constraints, balancing area size, characteristics of the renewable and traditional energy generation units, characteristics of demand.
- Organisational and market aspects such as: system operation practices, such as forecasting accuracy, scheduling, thermal cycling; economic and market contexts, to assess incentives and costs to provide flexibility.

- Energy system integration aspects, particularly the interdependencies and synergies with the transportation and combined heat and power (CHP) networks.

There are multiple methods employed to assess flexibility. Some methodologies use heuristics, others perform detailed simulation of one year. Several analyses use unit commitment and economic dispatch models, with differences in how variability and uncertainty are represented, how shortfalls are assessed, and how the requirements are considered. While there are many emerging flexibility metrics and assessment methods, there is no standard metric for measuring flexibility to date, and metrics continue to evolve [93][136][240].

As an example, the authors [241] propose a new metric (derived from traditional generation adequacy), the insufficient ramping resource expectation (IRRE), to measure power system flexibility for use in long-term planning. New indices based on contingency analysis and named Bulk System Flexibility Indices, are also proposed by [242] to support flexibility evaluation at the operational planning stage. An "offline" index is proposed by [243] to estimate the flexibility properties of a generation fleet and a "rolling" market arrangement is analysed. The authors in [208] presents an Irish system unit commitment and economic dispatch model for one year period at 5, 15, 30 and 60 min time steps confirming the feasibility of capturing shorter-term flexibility issues (even though on a limited geographical scale). As another example, the Western Interconnection Flexibility assessment, considers three specific measures to facilitate renewable integration: increased regional coordination, investments in energy storage technologies; and investments in flexible gas generation and highlights the organisational and stakeholder-interaction issues which may arise to coordinate and implement optimal techno-economic solutions [244].

Some methodologies focus on stochastic analyses, attempting to examine system operations over a wide range of conditions; in this context, the sequential Monte Carlo - compared to the non-sequential - techniques are the only suited to capture flexibility issues since they consider the operating cycle of all the system components and allow to analyse typically chronological issues like ramp-up or ramp-down constraints, outage times, etc; conversely, non-sequential Monte Carlo techniques investigate the probability distribution of the margin of available generation over demand at multiple independent randomly chosen points in time without considering chronologically dependent issues.

TIMES-like models are able to establish a correct and useful cost hierarchy, but that does not provide information about issues such as technical viability, user acceptance, or profitability of future options. Moreover, in TIMES-like models, increasing the number of time slices alone addresses only the variability itself but does not generally address the operational constraints and thus, those models are in many cases not suitable to address flexibility. Also that option increases significantly the complexity and running time of the model. Therefore, coupling large-size energy system model to sector-specific models, rather than relying on one, extremely complex model, seems to be the most adequate approach currently available for analysing flexibility in real-sized energy systems. However, model coupling is a complex and demanding undertaking that raises several technical and conceptual issues (such as which parameters or indicators are exchanged between the coupled models) [93][153].

4.3.2.2. Actors

ENTSO-E is mandated by the EU legislation to adopt annual summer and winter generation adequacy outlooks and a long-term European generation adequacy outlook every two years. ENTSO-E's Scenario Outlook & Adequacy Forecasts (SOAF) report not only includes adequacy analyses (see relevant section below) but, as a recent improvement, features also calculations of the national residual load, useful to obtain a first understanding of the flexibility/ramping needs in the EU power systems. ENTSO-E defines the residual load as the actual load minus wind, solar and must-run generation within the hourly time interval.

Additional indices measuring the hourly RES penetration are calculated, particularly RES Load Penetration Index (RLPI) = Maximum hourly coverage of Load by RES, RES Energy Penetration Index (REPI) = Share of annual energy demand covered by RES production and RES Curtailment Risk (RCR) = (number of hours in a year with negative residual load)/(total number of hours in the year) [79].

The R&D community is rather active in the intriguing and challenging flexibility topic. There are several studies assessing the impact of a technology (e.g. storage) on the evolving energy systems. These studies often focus on a specific country and use a rather limited number of scenarios to represent the uncertainty of load and renewable generation. The interest of studying these models, in addition to those used by the TSOs, is that some of them have features that are not used so far in TSO's models such as e.g. the endogenous capability to make investment decisions. Also, academic studies often focus on more extreme scenarios than TSOs, as for example systems with 100% RES supply. Studies providing endogenous investment modules are particularly interesting, as they can predict the evolution of systems under given circumstances (e.g. commodity prices, CO_2 caps, RES targets) as opposed to normative scenarios (such as a 100% RES system) [161]. This task is complex, as optimal states can be defined for production, transmission, storage, etc. The number of variables can therefore be very high, and the computational time also. The authors [245] propose a model, taking into account all the domains of the electricity value chain, from production to distribution, endogenously making investments in transmission, distribution, interconnections, generation and storage. During the last years, many power system and renewable integration studies were also commissioned by dena, the German Energy Agency [205][206].

As earlier discussed, at regional scale, new cooperation entities among clusters of TSOs/Member States are emerging and/or being proposed: the option of establishing Regional Operational Centres (ROCs) throughout Europe is under debate (ENTSO-E promotes the roll out of regional security coordination service providers - RSCSPs). These new actors could play a role (also) in coordinated flexibility analyses [72][73][74].

Table 9 - Electricity security model clusters relevance mapping to electricity security properties

ELECTRICITY SECURITY PROPERTIES / MODEL CLUSTER	OPERATIONAL SECURITY	FLEXIBILITY	RESILIENCE	ADEQUACY	ROBUSTNESS	USE OF DETERMINISTIC APPROACHES IN SUPPORT OF DECISION MAKING	USE OF PROBABILISTIC APPROACHES IN SUPPORT OF DECISION MAKING
DYNAMIC POWER SYSTEM/GRID MODELS	H	L/M	L/M	-	L/M	H	-
STATIC POWER SYSTEM/GRID MODELS	H	H	M	H	M	H	L
POWER MARKET / SYSTEM MODELS	-	H	H/M	H	H/M	H	L/M
ENERGY SYSTEM / POWER MARKET MODELS	-	-	H	M	H	H	L/M

4.3.3. Adequacy approaches

4.3.3.1. Methodological challenges

In Chapter 3 we defined adequacy as the ability of the power system to supply the aggregate electrical demand at all times under normal operating conditions. Models frequently adopted to perform adequacy analyses fall in the static power system/grid model and the power market/system model clusters, but also energy system/power market models are sometime utilised (see also Table 9 above and Figure 35 below).

The basic elements of a traditional generation adequacy evaluation are [78][167]:

1. Construct a generation capacity model based upon the operating characteristics of the generating units.
2. Build an appropriate load model.
3. Combine the generation capacity model with the load model in order to quantify some system performance.

The traditional adequacy methodologies did not consider grid constraints or grid reliability parameters. Targeted adequacy analyses then started to be conducted on other domains of the electricity value chain - particularly transmission and distribution - and on overarching market and regulation aspects [147][246][247]. A generation adequacy assessment requires a judgement about likely energy market developments as well as wider economic developments, and thus a degree of uncertainty in the assessment is unavoidable [128].

As explained in Chapter 3, adequacy assessment has evolved to include:

- a generation/storage adequacy component, representing the availability of large-sized generation and storage capacity to meet demand in the various timeframes;
- a transmission network/import adequacy component, representing the ability of the internal grid and cross-border interconnectors to transfer the needed power from sources to sinks;
- whereas the distribution network and the end user adequacy components only recently started to be considered in conjunction with the emerging trends on smart distribution grids and demand response technologies;
- a market adequacy component, representing the capability of the market to facilitate the exchanges between producers and consumers.

There are two main methods to assess adequacy:

- Deterministic methods. The aim is to calculate the surplus of available generation relative to demand at some points in time (usually winter and summer peak demand). In this context, traditionally wind and solar generation used to be considered contributing with zero capacity. As an example, the Reserve Margin (RM) is the most common deterministic index, defined as the ratio between the expected available generation power during the peak demand and the value of peak demand.
- Probabilistic methods. The objective is to estimate the probability of the system being unable to supply demand considering the uncertainties associated with generation resources and demand. A risk model is built by combining generation and load models in order to estimate one or several indices quantifying the system reliability performances. Examples of frequently used reliability indices are: Loss of load probability (LOLP), defined as the fraction of time (days or hours per year) with insufficient available generating capacity (in the US the adequacy is assessed with a LOLP target of one day in ten years)[17];

[17] *Although it is the most commonly deployed indicator, it has several drawbacks: it leads to confusion as it represents the expected duration for all the outages rather than the probability of an outage occurring; its value depends on the type of data used for the demand. If LOLP is calculated with daily data it produces higher values than when calculated with hourly data.*

Loss of Load Expectation (LOLE), representing the number of hours (days) per year in which there will be not enough available generation capacity to supply demand; Expected Energy Not Supplied (EENS), measuring the expected amount of energy not supplied due to shortages or deficiencies in available generation capacity.

Deterministic approaches are simpler, requires little data and seem somehow easier to communicate to policy decision makers; however they cannot account for some inherent stochastic aspects like: mismatch between measured and real data/value, errors in load forecasts, errors in (especially) variable and (to a lesser extent) conventional generation forecast, failure rates of generating units and other system components, etc [246][247].

As a matter of fact, considering the increasingly interconnected and integrated European electricity system and market, the growing penetration of renewable energy into the electricity system, the emergence of smarter technologies/functionalities (like storage, demand side response/management, etc.), there is a need for an improved, more coordinated and integrated adequacy assessment methodology capable to provide a body of understanding to all the affected actors and decision makers. In other terms, the challenges nowadays is to understand how especially cross-border interconnectors, storage devices and demand side response can supplement or even replace the traditional power plants in guaranteeing the system adequacy [147][246][247][248]. Furthermore, several studies have analysed the potential complementarities of wind and solar energy sources over time/space. Intuitively, and due to the time/space correlation of variable renewable energy resources, a larger interconnected area provides a higher RES capacity credit, which means that secured capacity needs from other energy sources (such as gas-fired power plants) will be lower [158][248].

The boundaries between the adequacy assessment approaches and the flexibility analysis - and possibly even the operational security analysis - are becoming more and more blurred due to the need to scrutinise the short-term performances of the different balancing resources. The debate on whether flexibility - whose importance is growing along with the penetration of non-dispatchable renewable energy generation and the need to compensate for its rapid and uncontrollable fluctuations - is a sub-problem of adequacy is open. A similar debate is anticipated to include operational security in the coming future.

4.3.3.2. Actors

Responsibility for ensuring generation adequacy in almost all the EU countries is attributed to the national governments. The TSOs (and the DSOs) are always the responsible parties for close to and real time balancing operations. Monitoring responsibilities are shared among Institutional bodies (i.e. TSOs, National Regulatory Authorities and governments). In the medium and long terms, the share of responsibility remains similar to that in the short term, with a stronger role of regulators/governments though [147].

As written, ENTSO-E is mandated by the EU legislation to adopt annual summer and winter generation adequacy outlooks and a long-term European generation adequacy outlook every two years. ENTSO-E's Scenario Outlook & Adequacy Forecasts (SOAF) report is the main Union-wide assessment of generation adequacy; however, since this report draws upon national assessments, it embeds differing methodologies employed at Member State level and it cannot comprehensively capture the mutual interdependences of Member States when it comes to generation adequacy and security of supply. For example, national TSOs continue to apply different methods to calculate the required margin against peak load; in some countries adequacy is assessed in "normal conditions" whereas in others the assessment is done in "stress conditions"; variable RES is not treated in a harmonised way, despite the importance of understanding the cross border impact of changes in wind and solar production [9][127][128].

In October 2014, ENTSO-E published a target methodology for the Adequacy Assessment [78]. The aim is to move from the deterministic power balance assessment to a fully probabilistic methodology by 2018. The first steps towards this new methodology were made in the SO&AF 2015 [79], which features some novelties including: shorter time horizon (10 years instead of 15 years) to better deal with uncertainties; monthly power balances (rather than two yearly snapshots); proper valuation of wind and solar contribution to firm capacity[18]; regional assessments including the role of interconnection capacity.

An important measure used by ENTSO-E for the generation adequacy analysis in a specified country or region is the Reliable Available Capacity (RAC), which equals the Net Generating Capacity (NGC) minus the Unavailable Capacity. The latter includes Non Usable Capacity[19], maintenance, overhauls, outages and system reserves. ENTSO-E assessed the adequacy based on a deterministic power balance at two particular points in time (third Wednesday in January at 7 pm and third Wednesday in July at 11am) [79]. The main objectives of this analysis are:

- to check if the remaining capacity (RC), which is the difference between the Reliable Available Capacity and the load, is a non-negative value. This means that there is enough available generation capacity under normal conditions. If this value is negative, the power system is short of available generation capacity under normal conditions. It does not mean that there would be a shortage as energy can be imported.
- to compare the remaining capacity with the Adequacy Reference Margin (ARM). The Adequacy Reference Margin is the sum of the Spare Capacity (SC) and the Margin against Seasonal Peak Load (MaSPL). The Spare capacity is an estimation of the required capacity to add to the system services reserves to cope with unforeseen extreme conditions. The MaSPL is considered as the peak load does not necessarily correspond with the reference time in which the power balance is performed. The analysis is based on several scenarios under normal conditions (demand estimated considering average temperatures). If RC ≥ ARM then the security of supply of the system is likely to be guaranteed in most of the situations. Otherwise, the system will rely on imports at moments of seasonal peak demand or severe conditions.

As recommended in [128], "Generation adequacy assessments should be transparent and open. In particular modelling, data sets and assumptions feeding into the assessment should be made available to all stakeholders (including system users) so that they have an opportunity to express their views and challenge the data before the assessment is finalised". Recently, integrated adequacy approaches - covering several of the aforementioned elements - commenced to appear, not only at R&D level but also in regulatory/industrial applications.

Even though with no institutional role, R&D actors continuously propose innovative approaches for adequacy assessment, both at national level than in the framework of European projects (Horizon 2020 and alike).

As earlier discussed, at regional scale, new cooperation entities among clusters of TSOs/Member States are emerging and/or being proposed: the option of establishing Regional Operational Centres (ROCs) throughout

---

[18] As an example, for the winter reference hour (3rd Wednesday of January at 7 pm), the available capacity for PV is obviously zero whereas wind is estimated to contribute with an available capacity of 6.67% (referred to the wind installed capacity).

[19] European TSOs account for the Non Usable Capacity of wind and solar energy sources in very different ways. According to some TSOs, wind generation capacity must be considered totally (100%) or almost totally (94-96%) as Non Usable generation. Other TSOs only consider the average unavailability factor (70-75%) of wind power generation.

Europe is under debate (ENTSO-E promotes the roll out of regional security coordination service providers - RSCSPs). These new actors could play a role (also) in coordinated adequacy analyses [72][73][74].

In the study of the Pentalateral Forum, an advanced probabilistic adequacy assessment methodology is applied for the first time. Such approach is different from the current methodology applied at the Pan-European level by ENTSO-E: rather than assessing the reserve margins at only two specific time points in a year, the PLEF approach provides results on an hourly basis for the whole year. This study, carried out in parallel with two different tools (Antares and the Amprion's in-house tool), can therefore serve as a pilot for replication/scalability to other EU regions [249].

4.3.4. RESILIENCE APPROACHES

4.3.4.1. METHODOLOGICAL CHALLENGES

In Chapter 3 we defined resilience as the mid-term capability of the power system to absorb the effects of a disruption and recover a certain performance level. Since resilience is prevalently correlated to external threats (materialising in sudden or accumulating strains) and lower probability events, the approaches assessing resilience shall use models allowing such abnormal situations to develop and somehow including the sources of those abnormalities; these models can be still considered to belong to the previously introduced static power system/grid model, the power market/system model (and to a lesser degree the energy system/market model clusters) (see also Table 9 above and Figure 35 below). Resilience analyses often require combining and interlinking the above mentioned models.

According to [103], the resilience evaluation procedures can be generally separated into two major categories:

- **Qualitative assessment methods** (without numerical descriptors). They contain on their turn two sub-categories: conceptual frameworks identifying best practices; semi-quantitative indices providing expert assessments of different qualitative aspects of resilience.
- **Quantitative assessment methods** (with numerical descriptors). They include two sub-categories as well: general approaches adopting domain-agnostic measures to quantify resilience across applications; structural-based modelling approaches focusing on sectorial representations of the resilience component.

Recent works [250] attempted to define a general metric for quantifying resilience for complex systems as a relationship of performance of the systems against time. This model allows to compare the resilience among systems (or among different states of a system), by means a new metric called stress (term borrowed from material science) which is quantified and visualised in heat maps. In the area of network analysis, the concept of resilience has been applied to measure the importance of components [251]. Other works have combined instead network resilience metrics with cost estimation [252].

Fuel flexibility of individual system components, such as power generators, has been used as a proxy of response capacity to disruptions [171][253]. In studies of system resilience the focus is the entire system's ability to respond and/or rapidly recover and the costs are analysed in addition to how the disturbance directly impacts on the system, see e.g. Refs. [220][253]. Another characteristic of system resilience studies is that they emphasise structure, relationships and interactions between different parts of the system rather than the performance of individual parts or components [254]. A characteristic of resilient systems is that they possess an adaptive capacity that enables adjustment to new conditions [255]. Thus, the surrounding environment and exogenous factors of the system are framed as being in a state of constant transition and hence the system needs to be agile. As the system recovers from disturbances it should reach a stable state,

although this does not have to be the same as the original state. The disturbance is sometimes assumed to appear randomly, for which deterministic methodologies are used [220], and/or with a certain probability, for which probabilistic methods are used [256]. Deterministic methodologies make it difficult to conduct traditional CBA, as the likelihood of the disturbances studied is unknown. However, even if costs and benefits cannot be quantified, increasing system robustness or resilience can be considered a hedge against future uncertainty. As an example, the resilience of the UK physical gas and electricity infrastructure was studied sequentially using three models: MARKAL-MED - a wider energy system/power market model [219], WASP - a power market/system model [213] and CGEN - a power market/system model for both electricity and gas [257], to create four detailed scenarios. System shocks were simulated by testing the consequences of disconnecting major gas terminals for different lengths of time, i.e. the shock was caused by physically unavailable primary energy. The cause and probability of the disturbance were thus irrelevant for the analysis, as it was the system's resilience that was analysed [93][220].

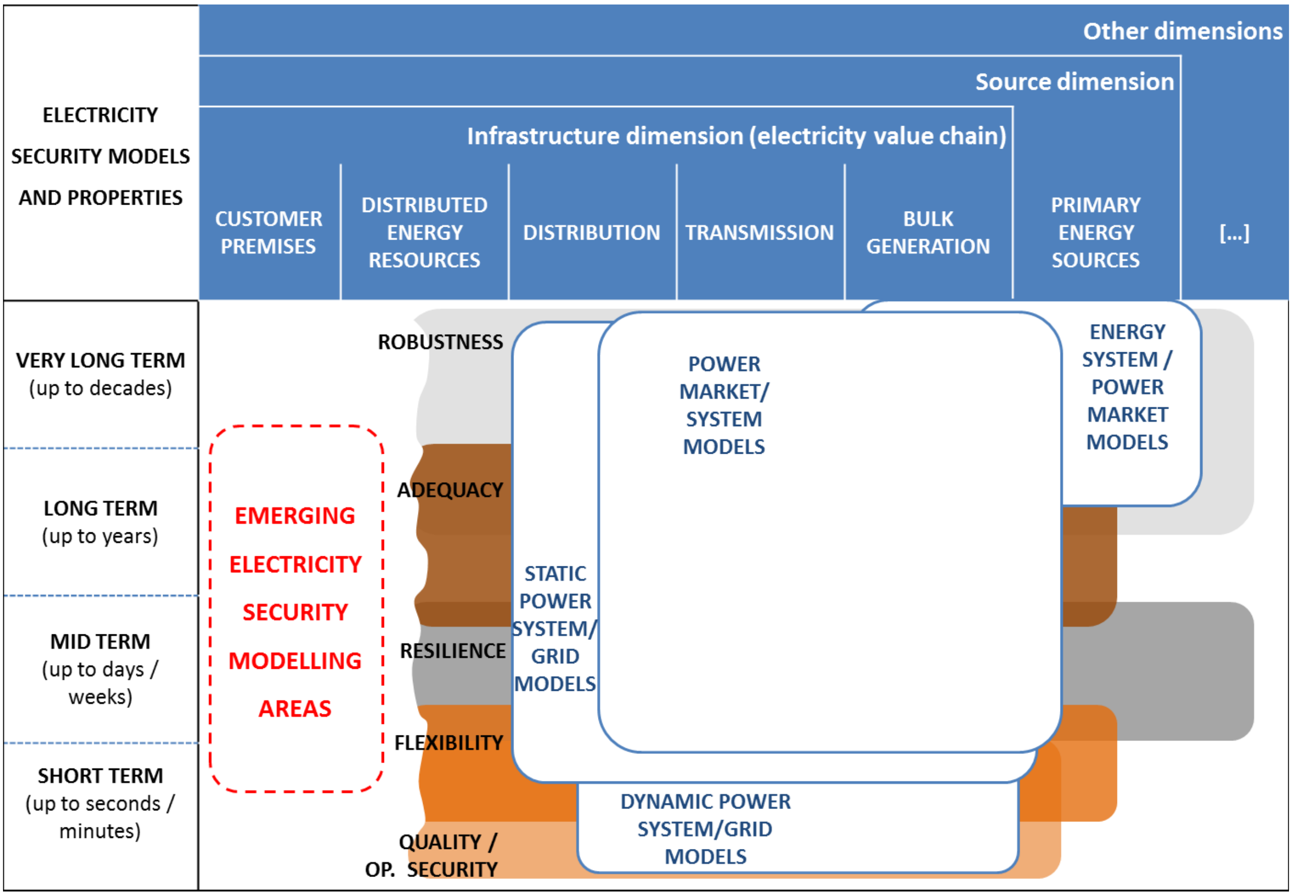


Figure 35 - Mapping of power system security models to electricity security properties

4.3.4.2. Actors

Depending on the spatial scale, the main actors responsible for assessing power system resilience are ENTSO-E at the EU level and the individual TSOs at national level. As also highlighted in some of the examples of the approaches and methodologies, the interdependencies of infrastructures is a must to assess the resilience features: therefore other networks infrastructure operators (firstly the gas operators) have a clear role to play to assess the power system resilience: for the time being, this kind of analyses is

prevalently contracted out to R&D entities collaborating with the industrial/regulatory parties. There is no recognised authority or body assessing the power system resilience at regional level.

We already introduced ENTSO-E's definition of technical resilience as the ability of the system to withstand increasingly extreme system conditions (exceptional contingencies) (see Table 4 in Chapter 3 and [80]). Additionally, according to ENTSO-E "It is only by recognising all the elements in power system resilience that market solutions truly deliver for the consumer and satisfactorily and efficiently meet policy objectives. Nowadays, energy markets do not fully reflect the value of system scarcities or missing system services that provide resilience and security to power systems." [149].

At regional scale, the emerging cooperation entities among clusters of TSOs/Member States - Regional Operational Centres (ROCs) or regional security coordination service providers (RSCSPs), with more or less delegated functions on power system security - could play a role on resilience analyses as well [72][73][74].

4.3.5. ROBUSTNESS APPROACHES

4.3.5.1. METHODOLOGICAL CHALLENGES

In Chapter 3 we defined robustness as the long-term capability of the power system to cope with constraints/stresses originating outside the infrastructure dimension. In the following we mainly discuss robustness approaches starting from vulnerability analyses (as illustrated in Chapter 3, vulnerability is a lack of robustness: while for some authors vulnerability is exactly the opposite of robustness, for others it might include system recovery/resilience aspects). The most deployed models to perform robustness analyses are the static power system/grid models, power market/system models and energy system/market models (see also Table 9 above and Figure 35 above). Robustness assessment approaches - perhaps to a lesser extent than resilience analyses - rely upon model combination/interlinking.

Two main aspects need to be considered to characterise and assess power system vulnerability: the severity of the adverse event and the system’s strength [105][169]. For example, the impact of a storm on a transmission line depends on the severity of the storm and the strength of the line, the latter varying among others with the line’s length and construction materials. Clearly, system vulnerability is more complex than the component vulnerability illustrated via the previous example: vulnerability analyses tend to evaluate the operational functionalities of the system with multiple components dynamically responding to the changes triggered by threats and adverse events. Therefore, vulnerability analyses may address the system susceptibility - i.e. tendency of the system to create unwanted events when subject to a threat -, and/or specifically designed countermeasures against certain threats [105].

In general, vulnerability analysis aims at estimating the magnitude of the negative consequences that arise when a strain is imposed on the system. It is an emerging approach used within the critical infrastructure management. A strain can be defined in different ways, either concrete, e.g. an earthquake of a given magnitude or a hurricane with wind speeds of a certain force, or in more abstract terms, e.g. a random removal of components in an infrastructure system or specific combinations of component failures (e.g. N-1, N-2, N-3, etc.). Defining a strain in a concrete way requires that the hazard, from which the strain stems, is known and that some knowledge about the characteristics of the hazard exists [104]. By their very nature, indicators are unable to assess the energy system’s response to adverse events, i.e. the vulnerability of the system in terms of the actual consequences of energy insecurity [92].

The vulnerabilities of a system can be analysed in order to understand its dynamic behaviour in response to a disturbance and to identify causes of system instability [93]. Such analysis commonly makes use of a deterministic approach, as the characteristic of the disturbance, e.g. magnitude, is predetermined and its

likelihood of occurring is ignored, as only the severity of the consequences is assessed. Strains can originate from different causes, e.g. an external attack on the system that causes component failures, a technical malfunction, accidents or natural disasters. Studies of vulnerabilities are sometimes framed as part of Critical Infrastructure Protection, as in [258]. Some CIP approaches can be used to simulate energy systems and their interdependencies with other systems, such as a physical, cyber, geographical or logical relationship between infrastructures [259]. Frequently used methods include relational databases, network theory, rating matrices, system dynamics and multi-agent systems [93]. As an example, a network topology model can be used to represent an energy system as nodes (e.g. generators) and edges (e.g. transmission lines). The system is tested by disabling nodes and edges, either randomly or in a predefined pattern (e.g. a geographical area), and simulating how the system functionality is affected. CIP simulations can reveal cascading effects and identify the components that are critical for a system's functionality. They can also be applicable for studying various aspects, for example how to prioritise where proactive measures should be implemented (e.g. redundancy, increased protection, etc.) and which components should be restored first after an outage. The system can be considered robust if it has a low vulnerability, i.e. it has the capacity to restrain disturbances [93].

One of the main purposes of a vulnerability analysis is to identify the chain of events during the evolutions of the failure leading to critical situations with huge negative consequences [105].

The authors [105][169] propose to study electricity infrastructure vulnerability from two standpoints:

- **Structural vulnerability** refers to the weakest components or their interconnection in the topologies of the physical infrastructures which could cause a large loss of system functionalities. Structural vulnerability intrinsically depends on the structure of the network and is independent from the system operational status. Power system vulnerability is based on graphical representation of a network considering the specificities of power systems; therefore it is a physical property of the system, which means even if the system is not in operation, the structural vulnerable points still exists. However, to observe this kind of vulnerabilities, operation is needed to exceed the maximal capability of these vulnerable points [105]. Many researchers have embraced the idea of structural vulnerability: for example, an analysis of the structural vulnerability of the Italian power grid, using a graph-based model of cascading failures can be found in [260]. The authors [261] use a linear approximation and standard optimisation to represent cascading transmission line overloads to identify the vulnerable branches in the system. Despite the existence of several topologies in high-voltage transmission power grids, most of them have in common that they are vulnerable to targeted attacks on the most connected nodes, and robust against random failures [111].
- **Operational vulnerability** refers to a large loss of system functionalities during the operation, usually caused by cascading failures leading to operational constraints violations (usually static problems like overload, over voltage, etc.) or power grid instabilities (usually dynamic problems, like oscillation, loss of synchronisation, etc.). Not only the static aspect is interesting to be studied for the operational vulnerability, but also dynamic phenomena should be included [105].

  Since the system operation status is constantly changing, the operational vulnerability is shifting accordingly and is not easy to detect. During the network management, system operators may face insecure states due to events much different from what were predicted in the planning and other online/offline studies. Since such events are somehow unexpected, the operators may not have enough information or resources/countermeasures to take timely preventive or emergency control actions [105].

In several blackouts occurred in the past the cascades might have been limited to a certain extent if the operational vulnerabilities were detected ex ante with more general approaches and tools. To quickly scan the operational vulnerability under emergencies usually requires a lot of calculations with multiple focuses on different aspects and events. If there is a generic pattern pointing out where the system operation would most probably go wrong, attentions can be focused primarily on the most vulnerable points in the operation. Nevertheless, it is not easy to identify the common pattern purely by simulation. The observation from history of blackouts and the corresponding chains of events can provide valuable information to identify the most vulnerable operational points. For forming the common pattern, firstly the most vulnerable elements of the network after the materialisation of a threat need to be identified, and then the most probable effects of failures of such vulnerable components need to be captured. Considering the difficulties of detecting operational vulnerability, studying of the cascading failures (chain of events) in historic blackouts could provide privileged information about from where the vulnerability arises in operation [105].

Modelling robustness of power grids against cascading failures is the main reason why many scientists and engineers have decided to apply the complex network approach. Complex network concepts application to smart grids - despite its potential usefulness in proposing/understanding new structures - is still less frequent compared to the same applications to transmission high voltage power grids [111].

The complex network approach with purely topological concepts - or even with extended ones to take into account minimal electrical characteristics - has been useful to detect critical elements and to evaluate the structural robustness. The assessment of these results has been done by correlating topological and extended metrics with load shedding in real power grids (over several time intervals), or even with statistical data corresponding to failures in real blackouts. Most of the works, mainly focused on high voltage transmission grids, aim at discovering what type of prevailing complex network structure (if any) lies beneath real power grids; no definitive answer has been reached as there are power grids with scale-free nature and others with small-world properties. In the novel field of smart grids, small-world property has been recently suggested as the best structure to fulfil the requirements for the local exchange of electric energy between prosumers [111][262].

4.3.5.2. Actors

Differently from other electricity security properties, at EU level there is no formal actor thoroughly checking the electricity system robustness, even though ENTSO-E started considering robustness elements in its techno-economic analyses [80].

Electricity system robustness is handled more by stakeholders - prevalently system operators - acting at national level and begins to be discussed and analysed at regional (cluster of nations) level as well.

Even if the structural vulnerability identification of electricity infrastructure via complex science is a promising research field, it has not been widely appreciated by electricity industry, primarily due to the fact that operational conditions are neglected [105]. These considerations suggest the need for a better and deeper collaboration between the complex network community, grid operators and electrical engineers in a joint effort towards clarifying the controversial issues [111][170].

As already previously explained, at regional scale, new cooperation entities among clusters of TSOs/Member States are emerging: Regional Operational Centres (ROCs) or regional security coordination service providers (RSCSPs). Among the power system security functions, also robustness analyses might be delegated the them [72][73][74].

4.3.6. Integrated approaches

4.3.6.1. Methodological challenges

As seen in the first part of this chapter, a great variety of methodologies exist to evaluate energy security and several models (or model clusters) can be deployed to study the electricity system security in terms of operational security, flexibility, adequacy, resilience and robustness. This variety is partly due to the researcher's background in different scientific fields, but also to enable the valuation of different aspects of energy security. Since the methods have different strengths and weaknesses, there is not one which is always the best option. The suitability depends on the policy and research questions.

As summarised in Table 9 above, the approaches employed to assess the different electricity security properties - operational security, flexibility, adequacy, resilience and robustness - make progressively use of combination of models rather than single models. Particularly, static power system/grid models (basically power flow or graph-based topological models) are the main ingredient of nearly every electricity security assessment.

Figure 35 shows model clusters mapped to electricity security properties, indicating the time horizon and the electricity value chain domains. As recalled, the emerging electricity security modelling area linked to smart grids is not discussed into detail in this work. The static power system/grid models are the ones covering more domains of the electricity value chain, though not expanding by definition beyond the infrastructure dimension.

Resuming what discussed in Chapter 3, we might consider two groups of electricity security assessment approaches: reliability approaches (addressing operational security, flexibility and adequacy) and vulnerability approaches (addressing the lack of resilience and robustness) [104][167][263]:

- The **reliability assessment approaches** target the ability of the system to perform its intended function. They are traditional risk assessment approaches used in power system operation, design and planning and they generally target the previously introduced operational security, flexibility and robustness properties. Reliability analysis provides useful information about a system likely behaviour in terms of indices describing characteristics such as how often failures can be expected per year and the average duration and magnitude of these failures. Most commonly, the results of reliability analyses are presented as average values of these indices over a long period of time (e.g. over hundreds of years). This information allows decision makers to get a sense of the system general ability to perform its intended function and which components are contributing the most to the system unreliability. In the current approaches, reliability targets - typically based on historical patterns and common practices - are generally established ex ante. Since the focus of reliability analysis is on the system's likely behaviour, events that are estimated to have low probability/frequency of occurrence have a minor impact on the results or will not even be captured. Hence, relying too heavily on reliability analysis results to support decision making could lead to a reliable but at the same time vulnerable system. Reliability analyses provide a good picture of the system likely behaviour, but miss to capture a large portion of the high consequence scenarios, which are instead targeted by vulnerability analyses.
- The **vulnerability assessment approaches** focus on the inability of the system to withstand strains and on the effects of the consequent failures. They are emerging approaches used within critical infrastructure management and they generally target the previously introduced robustness and resilience properties. In general, vulnerability analyses aim at estimating the magnitude of the negative consequences arising when a strain is imposed on the system. In the context of vulnerability analyses, the role of probabilities of failures, threats and hazardous events, which instead is crucial for reliability

analyses, is less emphasised. When analysing vulnerability, the focus is not on estimating these probabilities but rather to systematically explore the effects of failures and stresses in order to identify system weaknesses that may be exploited by some, perhaps unknown, threats or hazards. Aspects like threats interdependence, adverse events propagation or failure mechanisms cannot be easily captured by reliability analyses. Several authors therefore argue that quantitative risk and reliability assessments shall be flanked by vulnerability analyses to have a thorough overview of the power system security characteristics and performances.

Even if the borders between the above described reliability and vulnerability approaches are, the two families of approaches display differences with regard to what type of system information they can provide to the policy decision makers. There are occasions where assumption of failure independence is not appropriate, such as in case of external hazard exposures (e.g. adverse weather or malicious threats), unforeseen failure mechanisms or interactions, or other types of common cause failures. This might imply that the probabilities of multiple simultaneous failures estimated in reliability analyses can lead to distorted results [104].

The challenge is to understand whether a further level of combination and integration of electricity security approaches is viable and useful for the decision making process, particularly on policy matters. In the previous paragraphs we identified and/or hinted at features of the current integrated assessment practices, which we discuss further in the following:

- **Cost-benefit analyses.** Integrating different modelling and methodological aspects of electricity security assessment is not easy. An effective way of soft linking diverse modelling outcomes would be the economic one: indeed, one of the prime ambitions of the decision maker would be to monetise and assess every aspect through cost-benefit analyses (see ENTSO-E's approach for transmission projects [80] and the JRC's guidelines for smart grids [264] - it is noted that both approaches go well beyond electricity security analyses as they cover also the affordability and sustainability dimensions). Ideally, from a societal perspective, as many benefits and costs as possible should be monetised so that the interests of all the stakeholders are properly reflected [265]. However this approach can hardly be used when there is no thorough knowledge of the features (e.g. magnitude and probability) of the security threats, the outcome of the impacts (e.g. severity) and the options for a prevention policy [93]. If this information is not available other methods may be used, such as multi-criteria analyses and indicators [93].
- **Multi-criteria analyses.** Multi-criteria analyses can be used to analyse both qualitative and quantitative aspects. If only quantitative data is evaluated, the ranking weights can be used to construct a complex indicator. As an example, in order to assess smart grid Projects of Common Interests, the JRC developed a multi-criteria assessment framework including: a) a checklist for minimum selection criteria; b) a techno-economic assessment through Key Performance Indicators; c) a Cost Benefit Analysis of each projects [264][266]. A kind of multi-criteria method is the analytical hierarchy process, whereby experts make pairwise comparisons of various aspects, policies or scenarios and rank them individually based on their judgement and a set of predefined criteria. Real options theory has been used to optimise investments when the future is uncertain (i.e. agents can decide to either invest now or wait one or several time periods and see how the future unfolds) [93].
- **Indicators**. Also named complex or composite indicators, they are constructed by adding the results from several quantitative indicators into a single value. An index value can be interpreted as a proxy of a general level of 'insecurity'. To construct an index a scoring scheme is needed (i.e. the scale on each indicator) as well as a weighting scheme (i.e. the aggregation rule that determines how indicators should be added). Some indices rely on expert opinions to come up with weight factors, whereas others

use the same weight factor for all indicators. However, the selection of criteria (e.g. choice of different indicators) and weight factors is usually not transparent or well explained. A good review of indicators applied to power system security is provided in [267]. The authors [268] conclude that transmission grid reliability indicators must be used carefully as rare events can cover a large fraction of the consequences on the system (in terms of energy not supplied, loss of power or restoration time).

Integrated assessment approaches might be based on integrated modelling approaches. Models can be coupled in different manners and of course in a combination of these manners: sequentially (the output of one model is the input of another); iteratively (the models are combined in a loop); or heuristically. Coupling can happen along one or more scales (e.g. time resolution, geographical scale) and dimensions/sectors (power transmission and distribution, electricity and gas, energy and water, etc) [153]. As an example, the Eastern Renewable Generation Integration Study (ERGIS) simulates a rather large power system with hourly day-ahead unit commitment, a 5-minute real-time dispatch, and a nodal DC-power flow. Models integration can happen via hard linking ("direct integration") or soft-linking: the latter may decrease computational costs, but implies handling different models. Furthermore, the question of which information and how this information is exchanged needs to be addressed. To limit the computational cost, highly stylized constraints are often deployed [153][269][270]. Using a suite of soft-linked tools to address complex questions, rather than relying on a single extremely complex model, would seem a reasonable solution. As an example, coupling large-size energy system models to sector-specific models seems to be the prevailing approach for analysing flexibility in real-sized energy systems. Model coupling might be key towards improving electricity security analyses, however soft-linking might be preferred to model integration, given the features and complexity of the models to combine [153].

To derive qualitative policy advice, there is a need for a higher level of detail in the energy/electricity models at hand. However, a drastic increase of the level of detail cannot be realised due to computational limits. Thus, the key is to determine the required level of detail [153]. Properly capturing security properties requires finding the right trade-off between modelling details and scope.

In the following paragraph, some specific challenges linked to model integration/combination, in order to assess flexibility features, are described. Integration studies provide details on options to optimise operations and investments for many objectives, one of which is flexibility. Flexibility assessment would therefore be a component of these larger analyses [136]. Flexibility requirements are bringing energy/electricity system planning and operation decision-making much closer than in the past [153]. Linking energy system/power market model clusters with one or more of the other three model clusters (power market/system models, static power system/grid models, dynamic power system/grid models) is a recurring way of addressing flexibility issues in the power system. Two main options are possible to cope with this problem: use conventional modelling paradigms and carry out ex-post flexibility assessments, or develop and use new modelling tools, trade detail for scope, and increase computing power. The second option seems particularly promising [153][239]. There are several sources of flexibility (such as transmission, hydropower, thermal plants, or district heating) but current models are not able of representing them accurately without becoming extremely complex, and therefore new holistic approaches relying on suites of tools are needed. These new approaches must improve the representation of the decision making processes, consumer behaviour, and the new business models that are appearing, without neglecting market aspects, but these elements lead to even more complex models [153][240].

The relation between traditional engineering approaches and complex science/network techniques towards assessing electricity security properties, particularly vulnerability and resilience, also deserves special attention. In the last years, complex networks theory has appeared as a new framework to study complex systems. A network is a simplified representation of a system. It reduces it to a graph, an abstract entity that

captures essentially its structure. Complex network theory applied to infrastructures in general, and to power grids in particular, has produced a huge amount of literature centred on three issues: structure, dynamics and evolution. The authors [170] highlight the disconnection between the emerging complex and the more traditional engineering communities in fully understanding and comparing the pros and cons of their respective models and approaches. One of the issues is that although experimental observations are possible, these are usually not considered a part of the field of complex systems itself, which is primarily devoted to theoretical developments. A complete characterisation of a network's topology is motivated by the expectation that modelling the structure of a complex network would lead to a better understanding of its evolutionary mechanisms and to a better comprehension of its dynamical and functional behaviour. However, when it comes to modelling the dynamics, the situation is far more complicated since the components of a network may have different dynamical behaviours and flows are often a highly variable quantity, both in space and time. In order to fully comprehend a network we must deal with its evolution, as well as with its structure and topology [170].

Few authors, like [271], focused so far on electricity infrastructure evolution studies: they compare grid topological characteristics with economic and demographic indicators and then complex networks science related topological efficiency and vulnerability measures are derived. As networked systems grow by adding elements and, at the same time, by coupling their dynamics to those already present, the level of interaction between elements varies and this process modifies the information and energy flows. Infrastructure networks in general (and power grids in particular) belong to the engineering field, where objectives and constraints are clear a priori. However, most technological networks have been continuously going through changes, spanning and crossing urban and natural systems from their early stages, adapting and being adapted by human societies, landscapes, territories and other constraints. This adaptive process has the power to modify the initial objective functions [170]. Some of the engineering areas where complexity concepts applied to power systems have potential for developing sound scientific frameworks are: smart grids [272], agent-based modelling [273] and interdependent networks [274][275].

Finally, as stressed in Chapters 1 and 2, affordability and environmental issues and dimensions - due to their tight interdependence with energy security - require careful consideration in order to have a thorough picture of electricity security at socio-economic level. As an example, the authors [276] characterised Japanese electricity security in terms of global environmental sustainability and local environmental protection, besides availability, reliability and technological development. Electricity security analyses need to account for these interfaces, interactions and dimensions as well.

4.3.6.2. Actors

Currently, one of the main products of EU-wide integrated assessment efforts - not only tackling the electricity security aspect (but also the affordability and sustainability ones) - is the Ten-Year Network Development Plan (TYNDP). The national development plans (in particular, their "cross-border" part) contribute as building blocks of the EU TYNDP, together with the regional investment plans and the regional and European studies performed in the EU TYNDP framework. The regional and European studies are particularly focused on the investments which have a cross-border nature (interconnectors or internal network elements which affect cross-border transfer capacities) and can identify improved planning solutions, to be included in next/amended national development plans. After the preparation of the EU TYNDP, in the drafting phase of national development plans "succeeding" the EU TYNDP, ACER and the national regulatory authorities assess the consistency of the national development plans with the EU TYNDP and can recommend modifying the plans [39]-[86].

ENTSO-E utilises static power system/grid models and power market/system models in combination and in an iterative manner as they provide different information and they complement each other. The static power system/grid models have the advantage of representing the precise network flows that would be created by the dispatch and load patterns, possibly obtained through power market/system models. Calculations using static power system/grid models are required to adequately represent grid transfer capacity values in power market/system models [80].

In the context of the scientific support to policy making, the JRC was mandated to conceive an overall assessment framework for smart grid projects of common interest[20] [264][266]. On top of the eligibility requirements (most notably: the potential overall benefits of the project shall outweigh its costs), the candidate Projects of Common Interest have been assessed through a multi-criteria analyses including several criteria like: capacity of transmission and distribution grids to connect and bring electricity from and to users (valued in terms of allowable maximum injection of electricity without congestion risks in the energy transmission networks, and the energy not withdrawn from renewable sources due to congestion or security risks); security and quality of supply (valued in terms of the ratio of reliably available generation capacity and peak demand, the share of electricity generated from renewable sources, the stability of the electricity system, the duration and frequency of interruptions per customer and the voltage quality performance); contribution to cross-border electricity markets by load-flow control to alleviate loop-flows and increase interconnection capacities (valued in terms of the ratio between interconnection capacity of a Member State and its electricity demand, the exploitation of interconnection capacities, and the congestion rents across interconnections).

It is interesting to note how, differently from adequacy and flexibility, the number of metrics capturing other electricity security properties, particularly resilience and robustness, but also operational security/stability, is somewhat limited (despite e.g. the EU aims at establishing a resilient Energy Union). The most relevant indicator agreed so far is the interconnection capacity target, which however is not sufficient to properly describe the operational security performances of the power system.

Some analysts [157] believe that the R&D community can further support electricity security and power system analyses as the power industry is not making sufficient use of the data available to it (perhaps not fully recognising the value of such data).

Currently, a new modelling and analysis framework to analyse up to 100% renewable energy systems is being developed by VTT, including soft/hard linked integrated models - from physical electricity models up to market models - and other models for dynamic process simulation of regions/districts, for robust decision making, and for business analysis of new flexible energy systems. Soft-linkage of several models is their preferred option (especially to address flexibility), given the effort required by other approaches [240]. This analysis is carried out with a toolbox of integrated models comprising: Balmorel - generation planning [196], WILMAR - unit commitment and economic dispatch [195], PSSE - power system simulation [185] and energy/power market soft-linked models (VTT EMM: electricity market model for the Nordic market area, TIAM/TIMES: integrated energy system model [218]) [209][240].

[20] *Smart grid Projects of common interest refer to equipment and installations at high-voltage and medium-voltage level designed for a voltage of 10 kV or more. They involve transmission and distribution system operators from at least two Member States, which cover at least 50 000 users that generate or consume electricity or do both in a consumption area of at least 300 GWh/year, of which at least 20 % originate from renewable resources [36].*

5. A DECISION-ANALYTIC FRAMEWORK ON ELECTRICITY SECURITY

"Politics is more difficult than physics."

Albert Einstein, scientist

In this Chapter, after having provided a conceptual synthesis of the electricity security problem and grouped the issues faced by assessment approaches against the different spatial scales, a conceptual framework for electricity security analyses is discussed. Possible applications within the new framework, and in the context of the Energy Union's initiatives, are eventually introduced.

5.1. CONCEPTUAL SYNTHESIS OF THE ELECTRICITY SECURITY PROBLEM

In order to identify elements and recommendations for a redefined decision analytic framework, we begin summarising the main features of the electricity security problem.

As a matter of fact (see also Figure 36), electricity security is:

- a **multi-threat problem**. Electricity security is challenged by threats of natural, accidental, malicious and systemic nature.
- a **multi-time scale problem.** Various time frames (short-term, mid-term, long term and very long term) shall be considered due to the inherently different electricity security challenges, system performances and actions which can be put in place.
- a **multi-spatial scale problem.** Electricity security has both local and far-reaching features, for the sake of our research on electricity transmission security classified in the EU, regional and national scale.
- a **multi-dimension problem.** The threats materialise in adverse events surfacing in different dimensions: from the infrastructure to the primary energy sources dimension, from the market and regulation to the geopolitical dimension.
- a **multi-disciplinary problem.** Electricity security analysts are interested in observing, assessing and valuing electricity security from different perspectives, with different disciplines and in different fields (political, strategic, economic, regulatory, scientific, technical, etc.).
- a **multi-stakeholder problem.** Numerous and diversified electricity security players (policy decision makers, regulators, system operators, etc.) interact in different fields, spatial scales and time frames of the electricity security problem. Table 10 describes the main responsibilities towards electricity security of existing (EU and national) and emerging (regional) actors.
- both a **complicated and complex problem**. Depending from the angle one looks at it, electricity security can "just" be a complicated problem - the electricity grid is often defined as the most complicated man-made machinery ruled by nonlinear equations - or a complex problem, where very diverse actors interact in different layers (component, communication, information, function and business) and whose collective behaviour can be hardly described by any set of equations.

- a **multi-faceted problem.** Electricity security properties can be broken down into operational security, flexibility, adequacy, resilience and robustness.
- a **multi-model problem.** Several model clusters are deployed: dynamic power system/grid models, static power system/grid models, power market/system models, energy system/power market models.
- a **multi-action problem**. Decision makers can indeed deploy several actions to prevent, mitigate and respond to security threats. The main role is played by the TSO which, depending on the time scale, can resort to operational actions, operational planning and scheduling actions, system planning actions and (partly) strategic energy planning actions to safeguard electricity security.

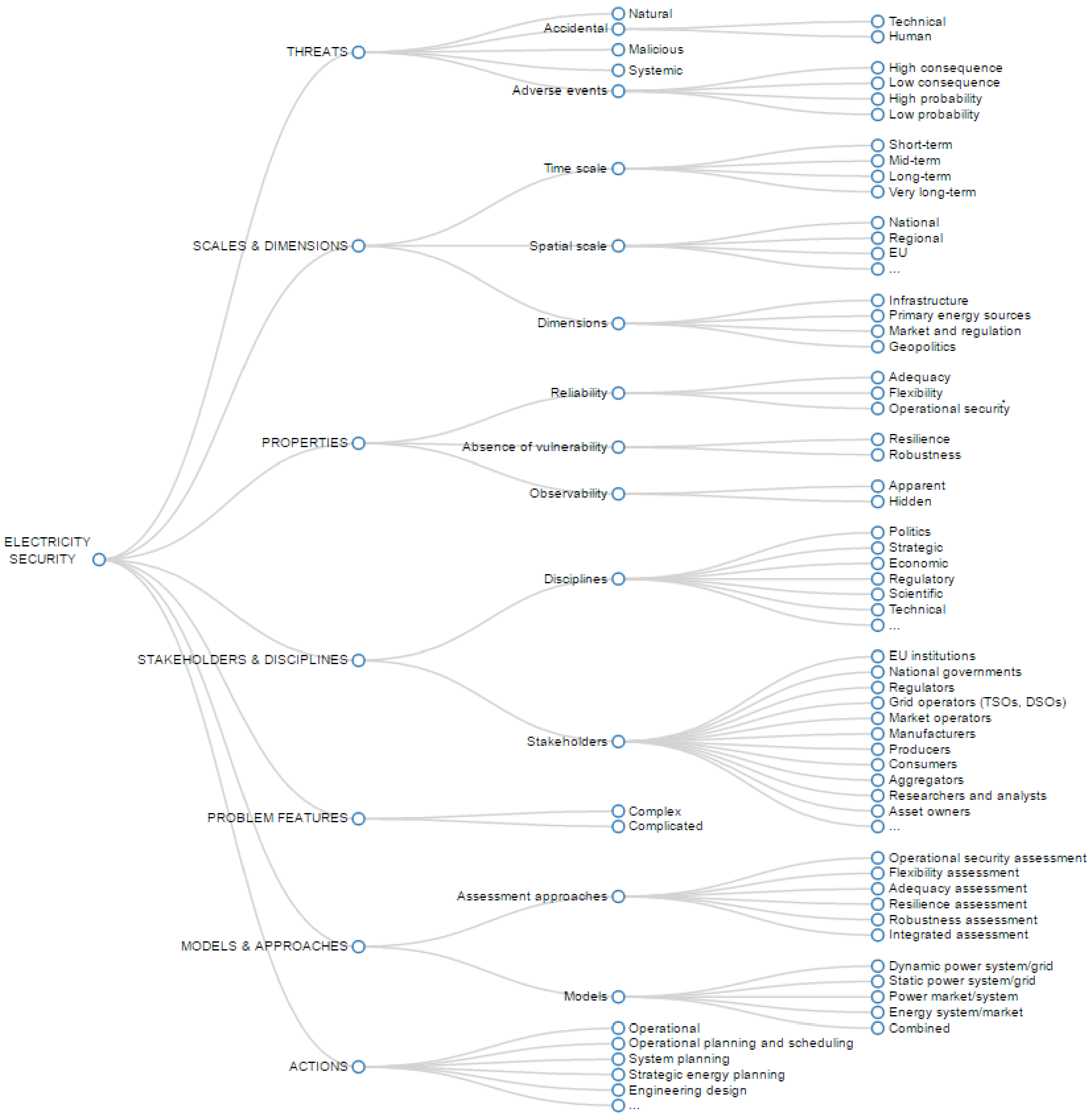


Figure 36 - Electricity security mind map

Table 10 - Actors and decision makers' relative weight (qualitative) in electricity transmission security analyses

FEATURES / MODEL	EU			REGIONAL				NATIONAL		
	EC/ACER	ENTSOE	R&D	Regional market initiatives (ACER)	PCI Regional Groups	ROC / RSCSP initiatives	R&D	Government / Regulator	TSO	R&D
OPERATIONAL SECURITY	H/M	H/M	L/M	L	L	M	L	H	H	L/M
FLEXIBILITY	H/M	H/M	L	M	H	M	L	H	H	L
RESILIENCE	M	M	L	L	L/M	M	L	H	H	L
ADEQUACY	M	M	L/M	H	H	M	L	H	H	L/M
ROBUSTNESS	M	M	L	L	L/M	L	L	H	H	L

5.2. STATUS AND ISSUES OF CURRENT APPROACHES

The current status and some the main issues relating to electricity transmission system security in the different spatial scales (see Table 10 above and Figure 37 below) are summarised in the following:

- At **national level,** the main electricity security actors are the TSOs, partly flanked by governmental/regulatory bodies. The TSOs have very detailed and complete dynamic and static models of the national transmission system under their responsibility and they are considered as the official owners of the related datasets. The further electricity modelling moves from grids towards market/energy systems, the larger the number of actors, including market operators, having a stake (in terms of data ownership) and playing a role (in terms of assessment perspectives). Electricity security models are used for supporting decision making across all the electricity security actions - operation, operational planning and scheduling, system planning, strategic energy planning. R&D actors frequently contribute to electricity security analyses and propose methodological improvements but they lack reliable data for their models. The whole range of electricity security analyses is conducted, both on reliability (operational security, flexibility, adequacy) aspects and vulnerability (resilience and robustness) aspects. Electricity models, from the time frame viewpoint, tend to be more and more combined or at least soft linked; probabilistic approaches (vs deterministic ones) are increasingly used - but their results are not necessarily embedded in the decision making process - for reliability analyses, whereas vulnerability analyses rely upon the most diversified (not always sophisticated) approaches. Areas for improvement at national scale include: following the best practices (e.g. UK) for model interlinking, including domains/subsystems/systems like: the electricity distribution grid, the gas system, the heat system etc; encouraging utilities to fully incorporate innovative approaches - as e.g. those based on advanced probabilistic/complex system techniques, generally proposed by the R&D community -, in the decision making process.
- At **regional (cross-national) level,** there are emerging actors - even though not fully formalised yet - performing electricity security analyses: particularly CORESO, the Pentalateral Energy Forum and other nascent regional operational initiatives. R&D actors are less active than at national and EU level as the regional scale represents a rather recent EU development. Electricity models are quite detailed and (compared to the national scale) better capture the cross-border aspects of the region under study. The

electricity security models are used for supporting some of the electricity security actions: the focus is more on operational planning and scheduling actions and system planning actions (since operational actions and strategic energy planning actions are beyond the current remit of these regional bodies). As for the electricity security analyses, operational security, flexibility and adequacy analyses seem to have priority on resilience and robustness analyses. Time-wise, selected electricity security models are better linked and probabilistic approaches (vs deterministic ones) begin to be used for reliability analyses. Areas for improvement at regional scale include: better defining roles and responsibilities of the actors (so that the even accurate and innovative analyses can be used to support the decision making process), expanding security analyses in the vulnerability area and in modelling the interfaces with other energy systems.

- At **EU level**, the main actors are the ENTSO-E, ACER and the European Commission. ENTSO-E is tasked to perform EU-wide analysis and coordinated national/regional studies. ENTSO-E is progressing well in combining primarily static power system/grid models with power market/system models. Like explained above for the regional scale, the electricity security models are used for supporting decision making (especially) on operational planning and scheduling actions and system planning actions, (rather than) operational actions and strategic energy planning actions). In the scientific area, several R&D (FP7/H2020) projects are producing advanced models however with partially reliable datasets (if no formal agreement with the TSOs/ENTSO-E is in place). Probabilistic approaches (vs deterministic ones) begin to be proposed in the reliability assessment area, particularly for power system adequacy and flexibility. At this level, the visibility/observability of dynamics/issues occurring at regional/local level is however limited. Areas for improvement at EU level include a deeper assessment of issues occurring at the transmission-distribution interface, whereas first trials for interlinking gas and electricity models are ongoing, streamlining the modelling interactions and the assessment processes between the EU-wide and the regional scale, advancing the dynamic representation of the whole transmission system (e.g. via real-time simulation) targeting the emerging smart/super electricity systems challenges and tensions.

Additionally, a crucial, overarching issue regards the interaction between science and policy in the electricity security sphere. As seen, specific electricity security models and analysis are pervasively embedded in the decision making process of power system industry, particularly in the operational and planning phases. The same, despite society heavily depends on electricity service provision, does not generally hold for the connections between scientific/technical electricity security analysis and the policy decision making process. There are several reasons for this disconnection: the political and scientific/engineering communities speak different languages; policy making is a mixture of politics, facts and values, whereas science primarily contributes to one of these, namely facts; technical results are often too complex to interpret and grasp, etc. However, as a paradox, even if politicians’ risk aversion can be generally considered high, not being aware or informed of the security implications of some policy decision may lead to security of supply deterioration rather than safeguard [278][279].

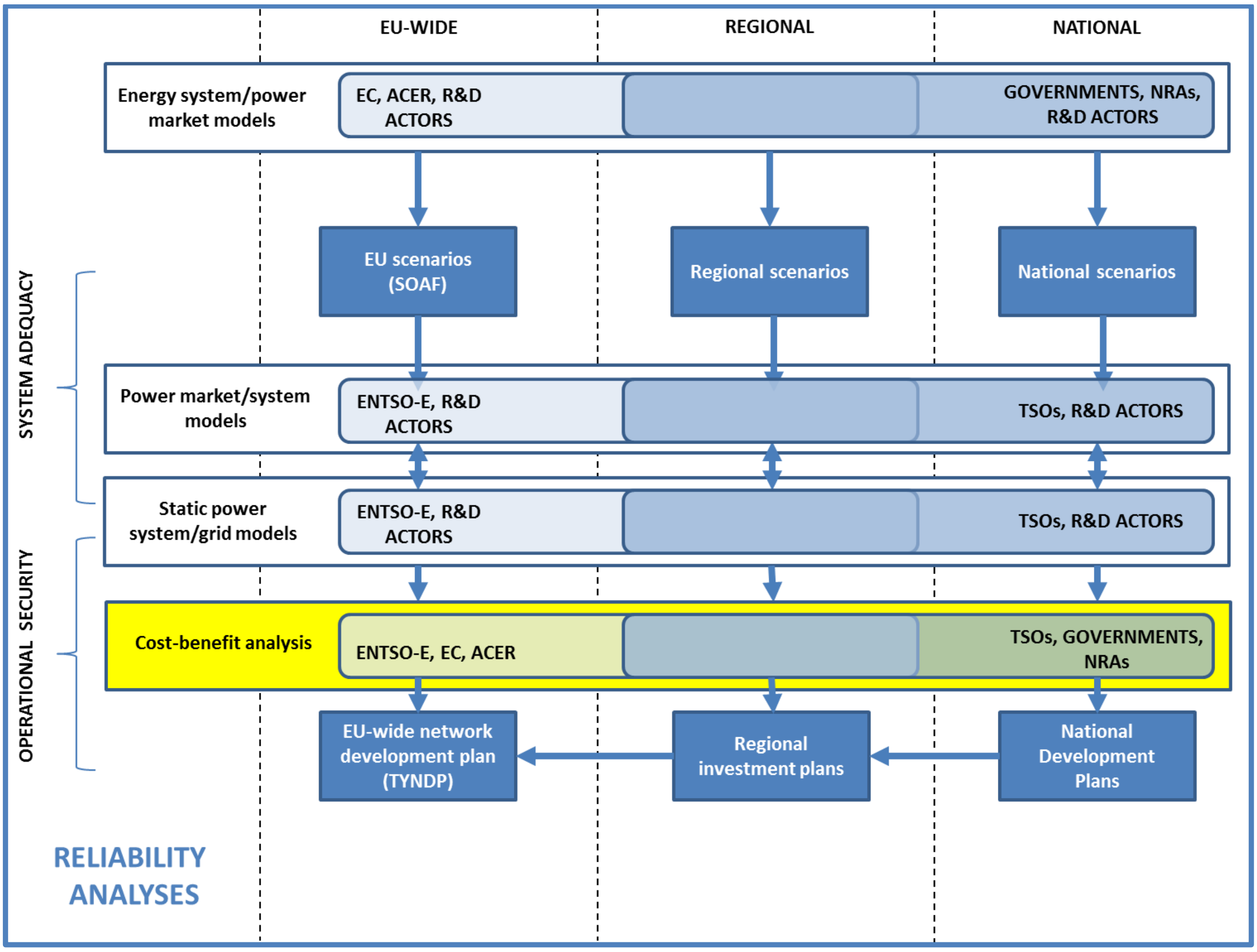


Figure 37 - Current framework for electricity security analysis and decision making at the planning level

5.3. FEATURES OF THE NOVEL FRAMEWORK

Having in mind the features and issues discussed in the previous sections, we argue that the following features shall be considered for a revisited conceptual framework for electricity security analyses and decision making:

GOVERNANCE FEATURES

- **Multi-stakeholder platforms**, with proper governance and structured interaction mechanisms, should be further developed at all spatial scales - national, regional and pan-European - to perform joint assessments and carry out harmonised actions in the electricity security field. These platforms should be instrumental to bridge the local with the regional dimensions of electricity security and allow stakeholders developing and applying common assessment methodologies to discuss cross-cutting electricity security issues and solutions. Indeed, several tensions and strains are arising not only within the electricity (transmission) system but at its manifold interfaces (transmission-distribution, electricity-gas, ICT-physical system, etc.), thus making the involvement of actors from the relevant sectors imperative.
- The **regional scale of decision making** should be fostered and streamlined. In the current geopolitical context, the regional scale appears as a strategic playing field where identifying synergies and reaching compromises between the EU and the Member States energy policy

orientations. The current regional pilots offer valuable experience and lessons learned; still, harmonising the geographical/physical boundaries of the regions, considering the wealth and the variable geometry of the initiatives currently in place, is a prerequisite.

- Truly **collaborative and integrated security analyses** - again at wider geographical scale (than the traditional national one) **-** should be used to combine different aspects of security and include as many electricity security properties as feasible. They should take into account the different perspectives/interests of the electricity system stakeholders. By using a common framework and consistent evaluation methodologies, stakeholders can better compare studies and strategies and they can make the results understandable and replicable. Additionally, given the interdependence of the main energy policy objectives - security, affordability and sustainability - these integrated security analyses, even if focused on electricity security, should be framed in a wider energy and economic context. Assessing the socio-political-technical interactions linked to electricity security - so as to increase policy relevance of electricity systems models - might require shifting from solution analysis to solution discovery (heuristics) [280].
- **Cooperative decision making mechanisms**, steering the coordinated implementation of concerted actions stemming from the integrated security analyses, should be established. This would improve the overall electricity security performances, thanks to the stronger synergies and complementarities of balancing resources ranging from interconnectors, conventional/renewable generation capacity, storage and demand response. Even if the best spatial scale would be the EU-wide or continental one, since addressing security issues does not just entail solving technical problems but also letting several actors and decision makers interact effectively, it may turn out as more feasible - and less complex - to implement regional (cross-national) electricity security analyses-actions, also considering the evolving EU policy framework. A fully-functioning internal energy market requires that Member States coordinate and cooperate with their neighbours when developing their energy policies. Likewise, it needs to be assured that all regional initiatives evolve in a coherent way and lead to a fully-integrated energy market [75].

STRATEGIC FEATURES

- **All the electricity security dimensions** should be covered by the security assessment approaches: **infrastructure, sources, market and regulation, and geopolitics.** The electricity security assessment methodologies should be able to better observe and interpret the interactions of the electricity value chain system with the wider energy system and all the other surrounding dimensions. As an example, models should be able of representing the market signals that anticipate the lack of flexibility, such as the high prices in balancing markets as flexibility options become scarce [153].
- **Smart/super grid and multi-energy carrier systems assessments should be intensified**. Given the growing interdependences within the electricity domains (e.g. transmission and distribution) and between different energy systems (gas, heat, etc), electricity security aspects related to these interdependencies shall be studied. As an example, flexibility in wholesale electricity markets (including RES balancing) also requires efficient and well-integrated gas markets, which depend on, inter alia, balancing regimes, flexibility tools bundled capacity products at border points, and well-functioning secondary capacity markets and platforms [73]. The modelling efforts in emerging areas - like distributed energy resources, end user's demand response - shall be boosted with the aim to integrate these aspects in wider national/regional models. On the same note, the modelling efforts and the electricity security analysis on super grids shall be interlinked with the modelling efforts on

smart grids since major tensions are expected to develop at the interface between these emerging transmission and distribution systems. Additionally, the dynamics of demand-response, which are crucial in modern power system balancing, should be captured through other tailored models to obtain a finer time granularity and a better representation of the final consumers classes and communities [93][153].

- **Electricity security analyses should move from assessing flow security to assessing service security**. Smart grids promise to radically change the way power system is operated, designed and planned. Studying security of supply of smart grids is not only about interlinking transmission and distribution, but changing the prospective from electricity supply to electricity services. This shift could help identifying different means and pathways to achieve/safeguard security and identify different opportunities throughout the supply chain (e.g. linked to demand response) [93][264].
- Emerging **vulnerability assessment** approaches - observing how the system might fail and increasingly **based on complex network science** - should be promoted further, also at the regional scale, to complement reliability assessment approaches - focusing more on how the system should work. Despite specific scenarios where the system exhibits poor resilience and robustness performances might be estimated to have small probabilities of occurrence, still they should be identified and considered by the decision-makers for the design and protection of critical infrastructures. As a matter of fact, vulnerability analyses could systematically explore the effects of failures and stresses in order to identify system weaknesses that may be exploited by, perhaps unknown or previously unimagined, threats or hazards.
- Since both **complex network and engineering approaches** have their distinguishing features and might be instrumental to assessing different aspects of electricity security, a **deeper interplay** between the two disciplines is recommended. Some of the most promising areas where complexity concepts applied to power systems have potential for developing sound scientific evidence are: power system evolution scenarios, smart grids, agent-based modelling and interdependent networks.

METHODOLOGICAL FEATURES

- Policy makers and other stakeholders should propose and agree upon **common definitions** of crucial electricity security properties - particularly: **flexibility, resilience and robustness** - which (differently from other attributes like operational security and adequacy) are not consented at the EU level.
- **Cost-benefit analyses** should be preferred **to multi-criteria analyses** whenever viable. As all energy systems deliver some level of security, the primary objective for supply security policy is to strike the balance between the costs of improving security and the benefits from it. One of the main ambitions of the decision maker is to monetise and assess every aspect through cost-benefit analysis. However this approach can hardly be used when there is no thorough knowledge of the features (e.g. magnitude and probability) of the security threat, the outcome of the impact (e.g. severity) and options for a prevention policy [93]. If this information is not available other methods may be used, such as indices or multi-criteria analyses, to support decision making under uncertainty.
- **Multi-criteria analyses** can be used to analyse both qualitative and quantitative aspects. If only quantitative data is evaluated, the ranking weights can be used to construct a complex indicator. As an example, the JRC developed a multi-criteria assessment framework to assess smart grid Projects of Common Interests [266][264]. A kind of multi-criteria method is the analytical hierarchy process,

whereby experts make pairwise comparisons of various aspects, policies or scenarios and rank them individually based on their judgement and a set of predefined criteria.

- **Indicators should be used with care**. Composite indicators, aggregating data - coming from model outputs and/or expert opinions - over time and/or space, are generally easier to communicate to and grasp for policy decision makers. However the aggregation might conceal and/or underestimate specific security properties - like the vulnerability of certain users, components or subsystems - and a single value makes it hard to grasp all the implications for security. Some indices rely on expert opinions to come up with weight factors, whereas others use the same weight factor for all indicators. However, the selection of criteria (e.g. choice of different indicators) and weight factors is usually not transparent or well explained. Additionally, the aggregation rules largely consider threats and other electricity security features as static [93].

- **Sensitivity analyses** should continuously **support security analyses.** Sources of insecurity can be dynamic and change over time but insecurities are in most studies seen as static and independent of the development of the energy system. An option for improvements could be to conduct subsequent valuations with more extensive sensitivity analyses, particularly of factors that are important for security of supply and assumed to be exogenous [93]. Also crucial for validation, sensitivity analyses are needed in order to understand how initial assumptions and boundary conditions (e.g. on meteorological data, renewable energies development, etc.) influence the results of the models [153].

- Energy system/power market **models**, Power market/system models, Static power system/grid models and Dynamic power system/grid models would need to be utilised - and, depending on cases, **soft or hard linked** - in so far as they address complementary electricity security aspects and properties. It is fair to acknowledge that no model could aim at providing the full picture and the details needed to support the policy decision making. This does not mean that models are useless but that they have to be used with care, possibly combining outputs and results of models tailored to target different, complementary issues. However one single model cannot embed and describe all the electricity security aspects because the power system is multi-scale (in both space and time) and multi-physics, is highly nonlinear, and has both discrete and continuous behaviours [157]. Using the models separately and independently may trigger the risks of adopting conflicting assumptions and promoting clashing solutions on how to increase the level of security [93]. Finally, using multiple tools with the same dataset as input, though more time-consuming, improves the quality of the results since helps inputs/models debugging and results benchmarking [249].

- **Flexibility** should be increasingly used as **driver for modelling integration** in the reliability analysis area. As more and more renewable energy is in the system, balancing requirements should be analysed dynamically. One of the questions to answer is: provided that flexibility can be considered as a short-term dimension of adequacy, when/where one has to stop checking flexibility performances in the power system, then stepping into operational security/stability analyses? Since flexibility can be time-wise positioned between operational security and adequacy, its study not only requires a finer evaluation of adequacy aspects but is also bound to steer the integration of stability/operational security studies into the decision making/planning process [281]. Flexibility in power systems is also inherently linked to the regulatory and market rules that help shape operations. An agreed-upon methodology to measure flexibility can help inform policy, assess needed changes to system operations, increase stakeholder acceptance of renewable energy targets, and increase investor confidence that the power system can integrate renewable energy without significant curtailments [136].

- **Probabilistic approaches** should complement and - in specific areas (e.g. flexibility and adequacy of power systems with high penetration of renewable energy sources in particular) - completely supplant the deterministic approaches **when assessing reliability** aspects of the electricity security problem. Reliability analyses - encompassing operational security and flexibility/adequacy analyses - provide crucial input to decision makers although they do not cover the whole spectrum of security events/aspects (even when based on probabilistic techniques).

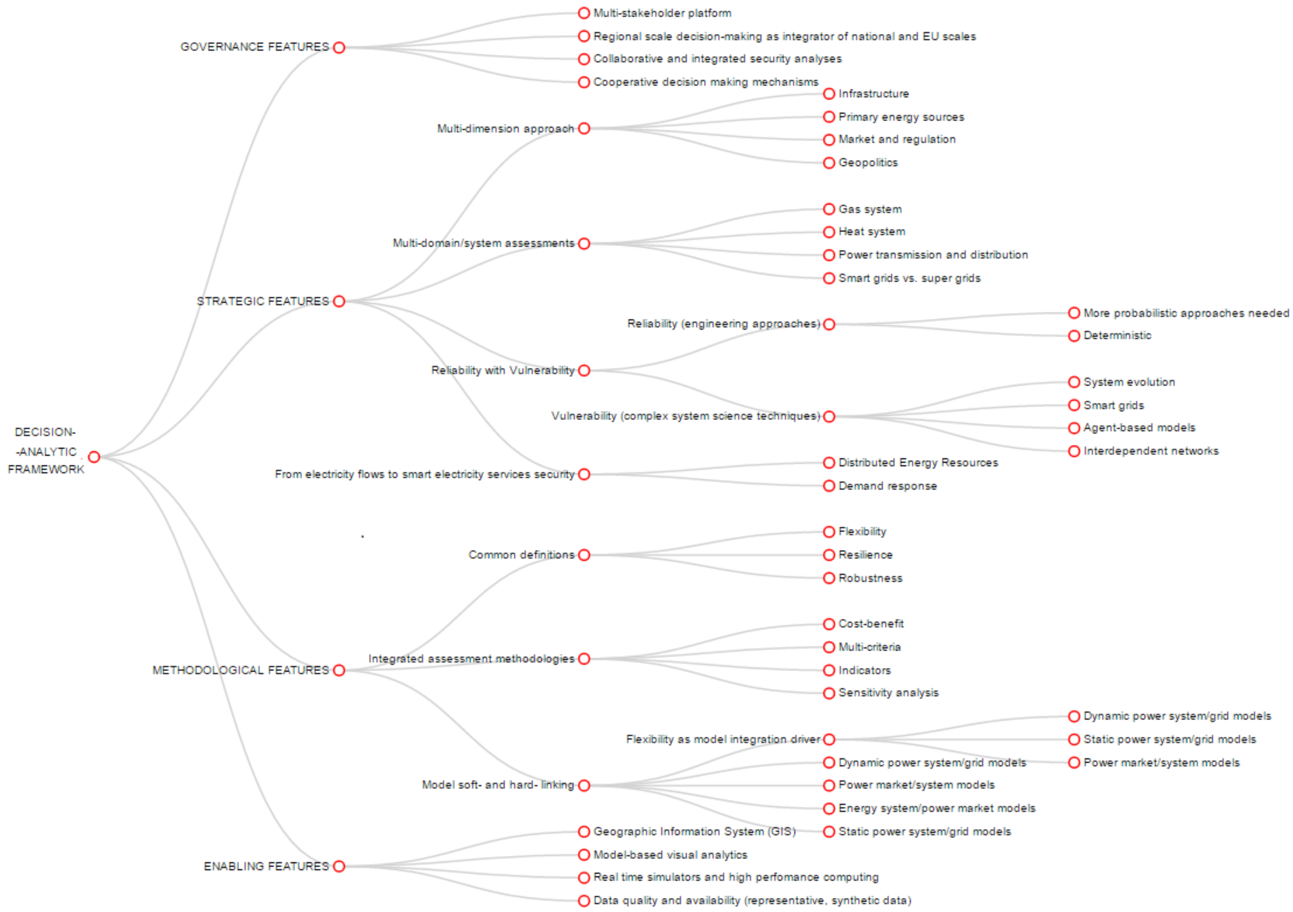


Figure 38 - Conceptual framework for electricity security analyses

ENABLING FEATURES

- Advanced model-based and **Geographic Information System** (GIS)-based **visual analytics** should be pervasively adopted to support the interactions with the policy makers while presenting, analysing and interpreting electricity security scenarios/results. Policymakers indeed need to be fed with concise, visually impacting input so that they can quickly understand the main messages arising from the scientific evidence. Model based analytics, since they can greatly support the decision making and action by performing what-if studies to examine alternate projected scenarios of future grid conditions, are set to become crucial instruments for the system operators.
- Decision makers and analysts should take full advantage of **supercomputers, real time simulators and parallel processing** to develop detailed, full-scale models of the power grids, and possibly make the high performance computing (HPC) technology available for real-time daily operations. These technologies would allow more detailed and accurate system simulation and speed up the response

to adverse situations thus reducing the inability to prevent failures and enabling the integration of dynamic analysis into real-time grid operations. The time is ripe for taking advantage of supercomputers and parallel processing to develop detailed, full-scale models of the power grids, as also recommended in [131][333] and possibly make the HPC technology available for real-time daily operations [132]. These technologies would be especially effective when combined to visual analytic approaches.

- **Reliable, representative datasets** should be **made available** to analysts. A perfect model without accurate data would simply be useless, thus gathering input data for the electricity security models is a critical issue per se. However, most of the data generated in the electricity sector is viewed as proprietary, both because it includes sensitive industrial information about company operations and because it might be used for malicious purposes [157]. Building electricity security models requires huge amounts of data, but in many cases analysts need to make assumptions/simplifications, introducing thus additional high uncertainties in the process (two particularly critical sectors are renewable energy potential and demand forecast) [153]. For this reason, representative, synthetic data that are sufficient to mirror real operations/performances should be provided for future research [157]. First steps and examples in this direction come from ENTSO-E, which began to make available representative static and dynamic models [76] and the JRC, which started a project to build and share representative distribution network models [282]. Also open source data and models started to appear. Some sort of standardisation of some model elements (such as naming or reporting conventions and data) could improve significantly these exchanges, helping to communicate the results. However, maintaining a plurality of model is important, as it allows tailoring models to specific policy questions, as well as benchmarking results for improved robustness [153].

5.4. DECISION-ANALYTIC FRAMEWORK APPLICATIONS

5.4.1. POWER SYSTEM SECURITY AND PLANNING DECISION MAKING

Elements of the current decision framework for electricity security analysis are depicted in Figure 37, where the different spatial scales (EU, regional and national) and the main actors involved in reliability analyses for the planning phase are represented. This representation of course does not capture the whole spectrum of methodologies, actions and actors involved (as an example, aspects more linked to the real time system management are not fully covered by this case study as well as the analyses of the interfaces with the distributed/decentralised domains of the electricity value chain).

In the current situation, one can distinguish two main parallel though interacting decision making processes: the one at the EU-wide scale and the one at the national level, where adequacy and operational security analyses are conducted. The interaction necessarily happens on the regional scale, through actors and via platforms which are only partly formalised and enforced. Thus, this interaction between the EU and the national scales cannot but be limited. It has also to be noted that the security aspects represent just one of the perspectives considered in this electricity system analyses: equally important, the affordability and sustainability aspects are assessed - and possibly monetised - when performing cost-benefit analyses defining investment priorities. The models mostly deployed (from top to bottom) are energy system/power market models, power market/system models and static power system/grid models, since dynamic power system/grid models are currently rarely used in combination with the others for the reliability studies (e.g. the TYNDP does not include specific inputs from stability studies).

The proposed revisited framework for electricity security analysis and policy decision making - based upon an integrated multi-region, multi-stakeholder and multi-model approach - is proposed in Figure 39. Reliability analyses and vulnerability analyses are conducted on two different layers, fundamentally by the same actors and combined through an integrated assessment approach (which can hardly be a cost-benefit analyses given the difficulties in monetising especially some vulnerability aspects and properties).

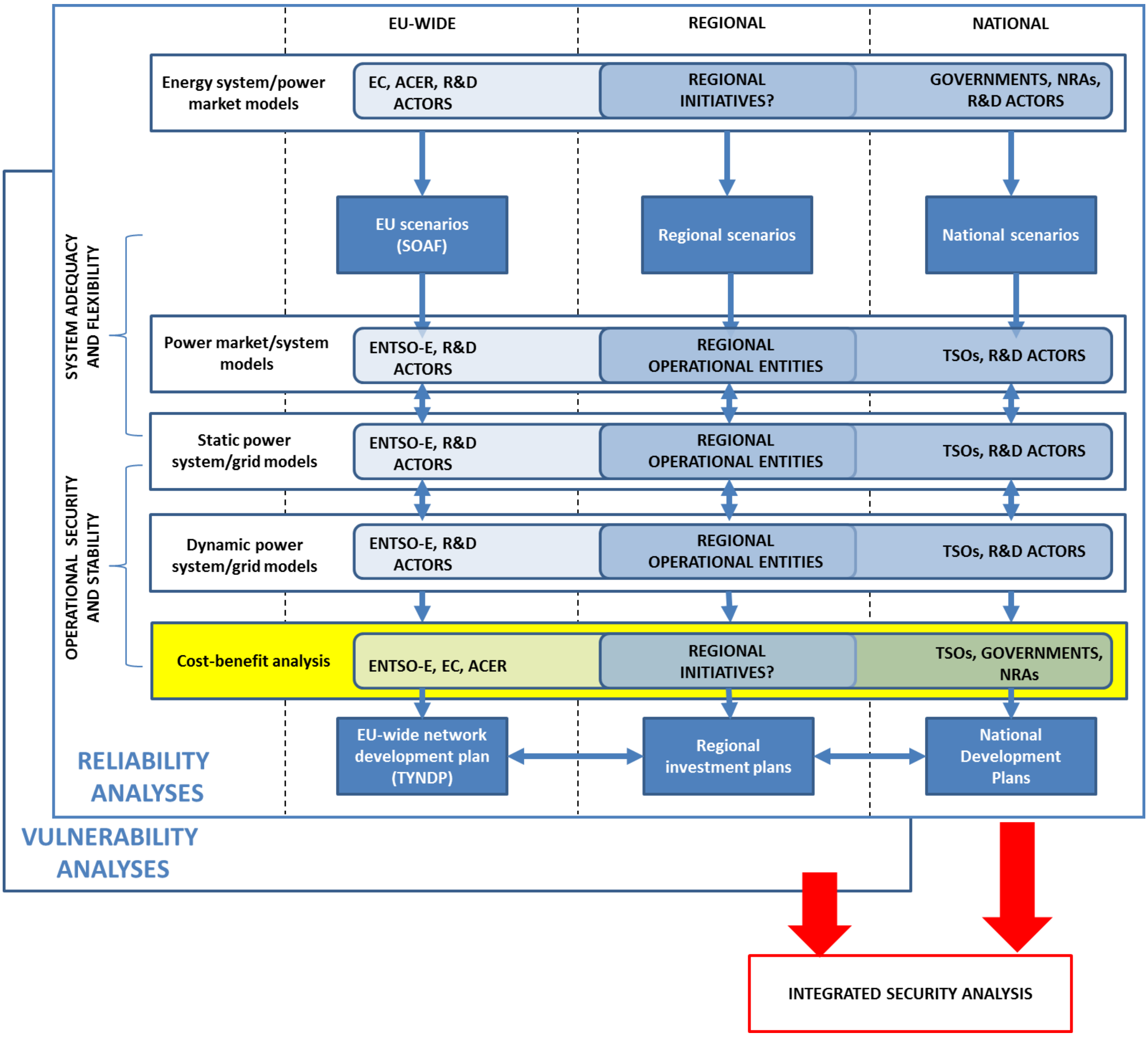


Figure 39 - Perspective framework for electricity security analysis and decision making at the planning level

Looking deeper into the reliability analyses, one can see additional assessment blocks and models introduced. As for the models deployed (from top to bottom), along with the energy system/power market models, power market/system models and static power system/grid models already featuring in the previous framework, also dynamic power system/grid models are utilised for integrated reliability studies. The key point here is the need to study flexibility issues, which requires to go closer to real time to assess the system performances.

5.4.2. TEST CASES FOR NATIONAL, REGIONAL AND EU SECURITY ANALYSES

Also based upon the decision-analytic framework introduced in this Chapter and the electricity security attributes of defined in Chapter 3, we developed the following test cases/proofs of concept (see also Figure 40):

- a **national application,** mainly targeting the infrastructure dimension of electricity security and assessing operational security and robustness features of the Italian transmission grid. The national application features a fully georeferenced model and advanced visualisation tools capable to present in a graphically impacting and effective manner the electricity security simulation outputs.
- a **regional application,** targeting several dimensions of electricity security - infrastructure, source, geopolitical - and testing operational security and adequacy features of the integrated Baltic system power system. The regional application presents an independent extra high voltage/high voltage model of the Baltic power system introducing also preliminary market aspects.
- a proof-of-concept for a potentially **EU-wide** real time simulation **platform** to perform multi-dimension and multi-property integrated security analyses. The prototype EU-wide platform is based on real-time remote interconnection of high-performance computing, data infrastructure and hardware/software components through a dedicated Virtual Private Network.

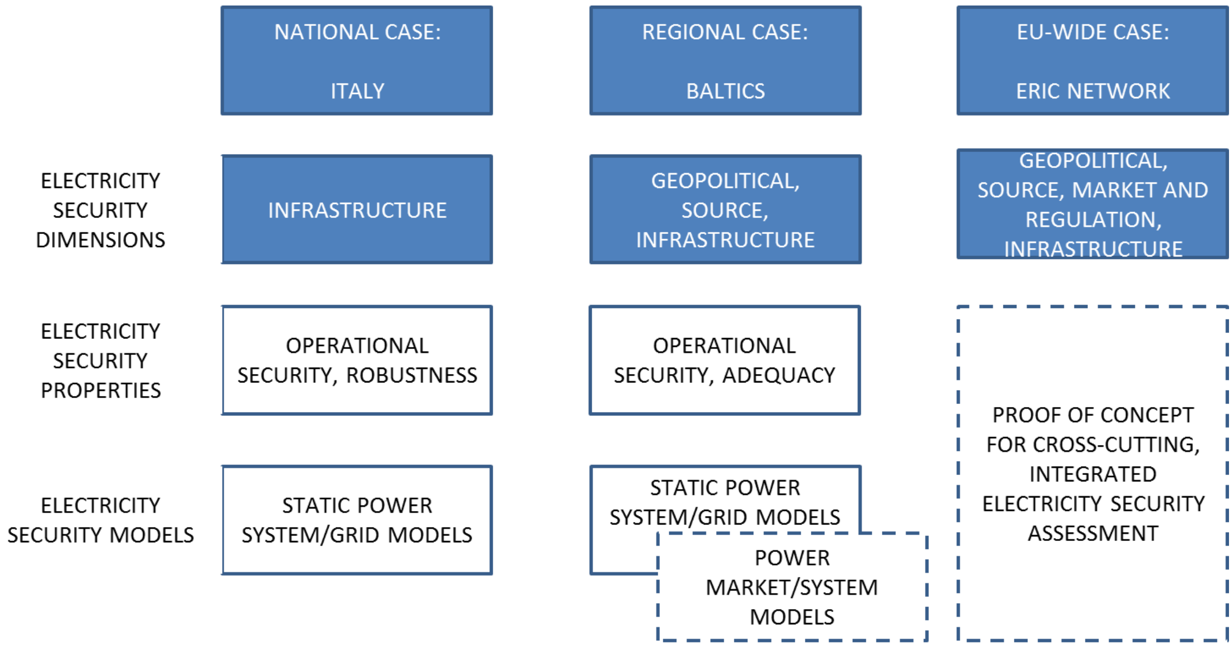


Figure 40 - Overview of electricity security applications in this work

Against this background, and building upon the framework/recommendations described in Chapter 4, the test cases aim to contribute to explain how some of the current gaps in electricity security analysis can be filled:

- the **Italian national application** showed how the decision maker (i.e. the system operator), via Geographic Information System and other visualisation tools, could have quicker awareness of potentially critical system statuses and this would more quickly allow to react accordingly.

- the **Baltic regional application** showed how coordinated security analyses can be conducted across Member States, targeting multiple security properties and dimensions (with a view to a planned expansion to cover market aspects as well) and how the electricity security models can be used to make decisions going well beyond the techno-economic aspects and including the geopolitical sphere.
- The **EU-wide real-time platform** helped to show how computational power and data confidentiality may become manageable problems towards accurate cross-national and cross-regional real time security analyses.

Detailed results and information about the test cases and the proof of concept are presented in the next Chapter.

6. TEST CASES FOR ELECTRICITY SECURITY ANALYSES

"Knowing is not enough. We must apply."

Leonardo Da Vinci, polymath

In this Chapter, test cases and a proof-of-concept fitting in the conceptual framework defined in Chapter 5 are discussed. First the performances of an Italian geo-referenced transmission model, subjected to extreme natural events, are assessed. Then operational security and adequacy analyses on an integrated Baltic power system model are illustrated. Thirdly, a proof-of-concept for a multi-scale and multi-stakeholder platform for real time simulation is demonstrated.

6.1. ITALIAN GRID: OPERATIONAL SECURITY AND ROBUSTNESS ANALYSES

6.1.1. MOTIVATION

As discussed in Chapter 3 and Chapter 4, electricity security analysis is crucial to support policy decision making and particularly operational security analyses are key to help the system operators in addressing and handling impacts on the power system brought about by adverse events of manifold species/origins.

Natural threats can materialise into extreme events that, although rare, may hugely impact the power system operation. The uncertain and variable frequency of natural disasters associated with climate change adds additional complexity to the tasks of assessing and taking actions against such extreme events. Furthermore, given that short run actions can be only to a limited extent effective to respond to natural threats, decision makers (operators in particular) have to be acquainted with natural threats in order to deploy the most effective countermeasures to reduce the risks and mitigate the effects of adverse natural events.

Italy is one of southernmost European countries and it borders with France, Switzerland, Austria, and Slovenia. Landslides, earthquakes, and volcanic eruptions occurred frequently because of its special orography, causing significant damage to people and infrastructure. The Italian territory is for a large fraction mountainous, with the Alpine range in the north and the Apennines running all along the peninsula from north to south. Three active volcanoes named Mount Etna, Stromboli, and Mount Vesuvius, and six dormant volcanoes are located in southern Italy.

The analysis of power systems security against natural threats may greatly benefit from the use of fully georeferenced models of the transmission system where geographic information can be directly combined and compared with network information. Georeferenced models in power systems are used for planning, reinforcing, monitoring, and managing the transmission networks. Sophisticated spatial analysis is greatly useful for formulating scenarios, determining optimum generation potential, studying environmental impact, and managing facility assets. By providing a geographically oriented view of the electric generation and transmission structures, devices, and network, a georeferenced model is not only applied to power system stability, protection and coordination, contingency analysis, economic modelling, but also helps utilities to discover new issues about the investments and risks of building a transmission network, and allows the simultaneous assessment of technical, financial, and environmental factors. Georeferenced model improves visualization of power systems by associating spatial data with transmission assets to display geographically

referenced real time power system data such as the voltage and line loading monitoring. Geographical information is stored in geographical map layers making it easy to integrate relevant information such as weather, vegetation growth, and road networks with relate transmission network conditions with other. Data of real time weather integrated in geographical map of power system increases the operator's situational awareness. For example, with the help of such model, the identification of a natural threat front moving towards a given area enables operators to quickly identify transmission facilities subject to increased risks of disruption [133][283][284].

6.1.2. MODEL AND SCENARIOS

The gross inland electricity consumption in Italy was 310.5 TWh in 2014, 2.5% down over 2013. The 2014 final electricity consumption also shrank by 2.1% compared to 2013. Domestic energy production covered 85.9% of electricity demand, with a 3.4% downward trend relative to 2013; the remaining demand was covered by imports, accounting for 43.7 TWh (3.7% more than in 2013). Gas-fired power plants generated 91.1 TWh, thus covering the lion's share of fossil fuel production (54.5%), followed by coal-fired power plants which produced 39.4 TWh (22.8% of fossil fuel production). Renewables covered 38.9% (it was 35.1% in 2013) of electricity demand, with upward trends especially for bioenergy, hydro and PV. The total net generation capacity was 121,762 MW in 2014, -2.2% compared to 2013, mainly due the retirement of thermal generation plants; PV instead continued to add capacity, exactly 424 MW in 2014 (growing by 2.3% over 2013). The peak demand was 51,550 MW, 4.4% down compared to the 2013 peak (53,942 MW) and much lower than the 56,822 MW maximum ever recorded in 2007. The striking difference between installed generation capacity and peak demand highlights an overcapacity amounting to almost 58% [285].

Starting from commercial, publicly available and in-house databases (including: the ENTSO-E System Study Model - STUM, the data collected with the FP7 Pan European Grid Advance Simulation and state Estimation - PEGASE project, the Platts commercial database, several ENTSOE's and TERNA's statistical data), a fully georeferenced model of the Italian 380 and 220 kV transmission system (see Figure 41) was developed with 4 typical power/demand snapshots of the year 2014, namely: winter peak (15-Jan 11:00), winter off-peak (15-Jan, 03:30), summer peak (17-Jul, 10:00) and summer off-peak (17-Jul, 03:00).

Each snapshot contains the full list of generators (some 240), buses (some 1200) and branches (some 1400 lines and 200 transformers) of the 220-380 kV Italian network, on top of simplified portions of bordering power systems interconnected to the Italian network.

The model was calibrated and validated against 2014 operational data from TERNA, with power flow errors typically below a few percentage points. Being the network snapshots highly similar to those used by TERNA for network operation, the outcomes of the contingency analysis performed through these models are expected to reasonably represent close-to-real statuses of the Italian power system. The PowerWorld tool was used for the simulations [187].

Figure 41 - Georeferenced model of the Italian transmission with administrative map

6.1.3. ANALYSIS AND DISCUSSION

In order to demonstrate the use of georeferenced models to analyse the local and nation-wide impact of natural threats, two different cases were developed and studied:

- The impact of a severe winter storm in the Alps between Italy and Switzerland.
- The impact of a flooding caused by a dam collapse in the hydroelectric Lac Du Mont Cenis reservoir, situated in France close to the Italian border.

The studies were performed resorting to steady state contingency analysis and the impacts of the adverse natural events were assessed through a set of metrics including: overload percentage of lines/transformers, number of violations, number of isolated buses, disconnected load and disconnected generation.

6.1.3.1. EFFECTS OF A SEVERE WINTER STORM ON THE ALPS

The extreme cold winter weather conditions occurring in the Alpine area might bring the temperatures down as low as to - 45°C. The transmission corridor (see Figure 42) hosting two 220 kV lines connecting Switzerland and Italy, one from Riddes (SRIDDE21) to Valpelline (IVALTA21) and another one again from Riddes (SRIDDE21) to Avise IAVITA21, crosses the Alps with an average altitude around 3500 m. Assuming the occurrence of a snowfall in the Alps with a magnitude comparable to the highest one recorded (11.5m), the two 220 KV interconnectors along this corridor with Switzerland are anticipated to be interrupted due to the impact of the accumulated snow/ice on the towers/wires.

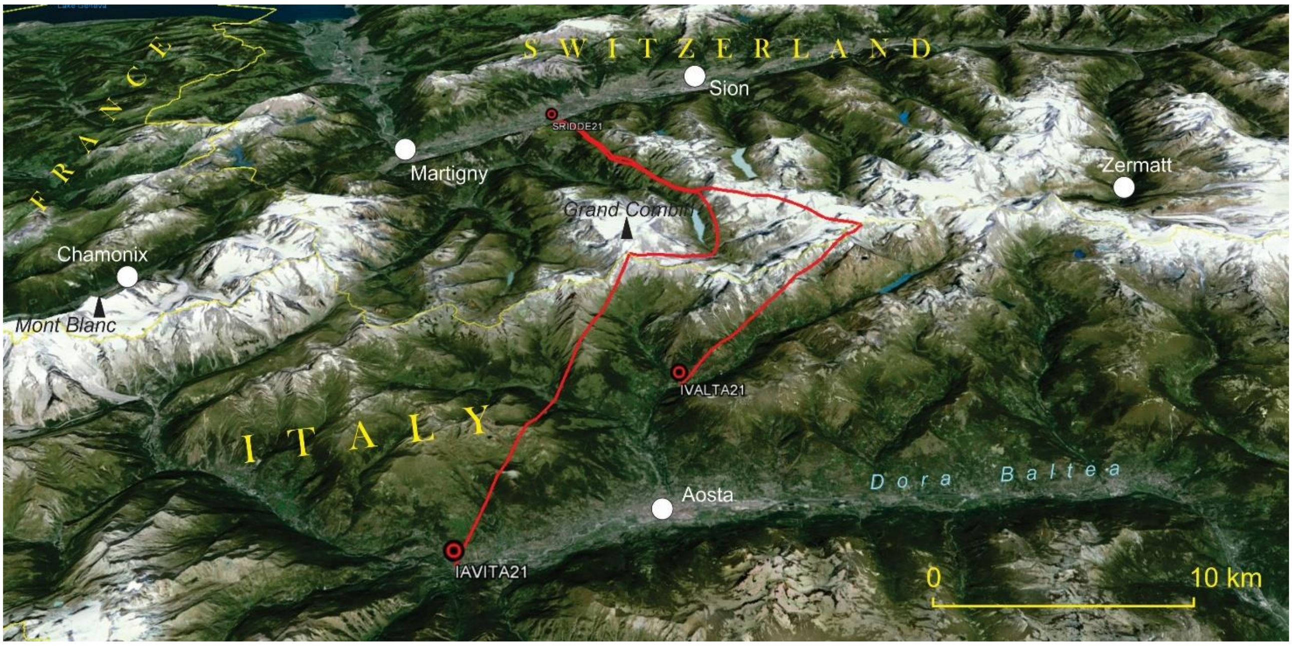


Figure 42 - Targeted Italy-Switzerland electricity transmission corridor

The contingency analysis (see Table 11, line names are intentionally anonymised) shows that - even if there are no isolated buses, disconnected loads or generators - an additional loss of lines can trigger system violations with high potentials to develop a system wide disturbance. As an example, after tripping a 380 KV line in Central Italy, the highest line flow can reach 210.9% of the rated capacity while no voltage violation is observed.

Table 11 - Impacts of top 5 contingencies in terms of branch overloading

Contingency Record	Isolated Bus	Disconnected Load (MW)	Disconnected Generation (MW)	Number of overloaded lines	Branch overload (%)
Line 1	0	0	0	4	210.9
Line 2	0	0	0	10	207.3
Line 3	0	0	0	6	184.4
Line 4	0	0	0	10	153.5
Line 5	0	0	0	4	153.4

Table 12 - Branch overload after tripping of line 1 in Central Italy

Branch	Value (MVA)	Limit (MVA)	Percent (%)
Line A	393.7	186.7	210.87
Line B	464.86	304.8	152.51
Line C	440.95	379.8	116.1

Figure 43 shows, as an example, the visual comparison of the power flows over the network before and after the contingencies. Manifestly, the contingency impacts the central part more severely than the rest of the country.

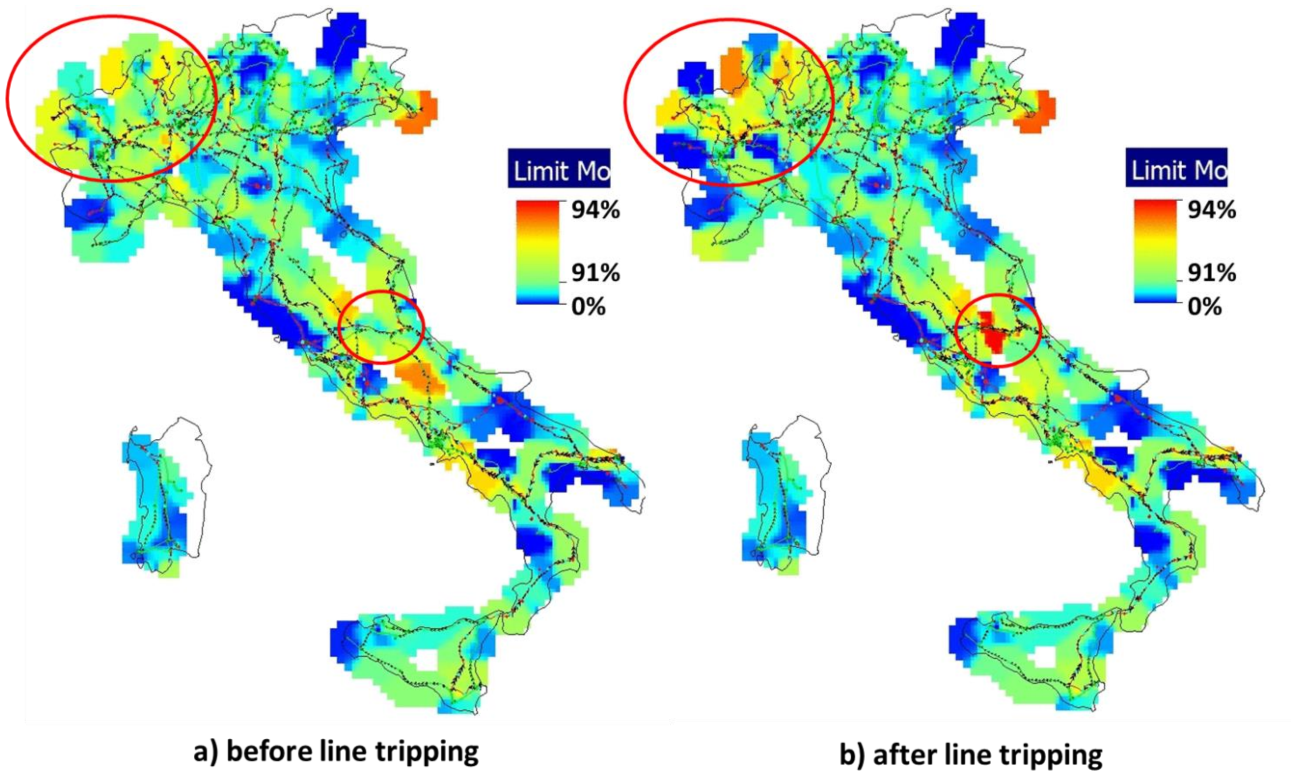


Figure 43 - Comparison of power flow distribution before (a) and after (b) critical line tripping in Central Italy

Besides the above reported severe contingencies, additional potential risks for the transmission tower collapse in the same area may be associated with winter storm. Indeed, after the disconnection of the two considered tie-lines, power flows over the lines in the same area were recorded to decrease, which in turn could further hinder the capability of melting the ice over the transmission lines. Consequently, the ice accumulated could cause those lines' towers collapse. To show this aspect in Table 13, we report the power flow on a nearby 220 kV Italy-Switzerland interconnector, before and after the tripping of the other two disrupted tie-lines, and the corresponding power flow decrease.

Table 13 - Power flow on a third 220 kV IT-CH interconnector before and after the two 220 kV tie-lines disruption

	Before disconnection		After disconnection		Difference	
Line	Line flow (MVA)	Used percentage (%)	Line flow (MVA)	Used percentage (%)	Line flow (MVA)	Used percentage (%)
220 kV IT-CH interconnector	44.14	7.24	26.10	4.28	18.04	2.96

The large geographical exposure of power system in the natural environment indicates the vulnerability of power grids when facing the destructive adverse natural events. They do not only damage the power facilities directly but may also lead to blackout through cascading failures, which brings huge economic loss to society. The climate change even deteriorates the frequency and affected area of the natural threats. Therefore it is necessary to have appropriate approach and models to track the consequences of the climate change, especially in the power systems, through the analyses of the low frequency but high impact threats. A possible way to achieve this is to combine power system and geographical information analyses. Georeferenced models based on the steady state contingency analysis help to plan, design, reinforce and

manage the power system in a comprehensive way. They can also promptly assist to capture the interdependencies among various EU national power systems.

Performing the contingency analysis is the first step to understand and then improve power system's response to natural threats; since operators and decision makers in general can devise other actions to mitigate the damage caused by adverse natural events. For example, emergency plans can be designed and implemented in order to: reduce the disturbance probability, rapidly respond to natural threats and recover a normal operation status after the events occurred.

The contingency analysis shows that an additional loss of lines can trigger system violations with high potentials to develop a system wide blackout. There are no isolated buses, disconnected loads or generators.

6.1.3.2. Effects of a dam collapse in France

In the second case we consider a flood caused by the collapse of the dam of the hydroelectric reservoir of Lac Du Mont Cenis (it lies completely on French territory at the Mont Cenis Pass but close to Italy with total storable volume amounting to about 320 million cubic meters, and a maximum altitude of 1974 m above sea level), which would widely affect densely populated areas of the provinces of Turin, Vercelli, Alessandria, etc.

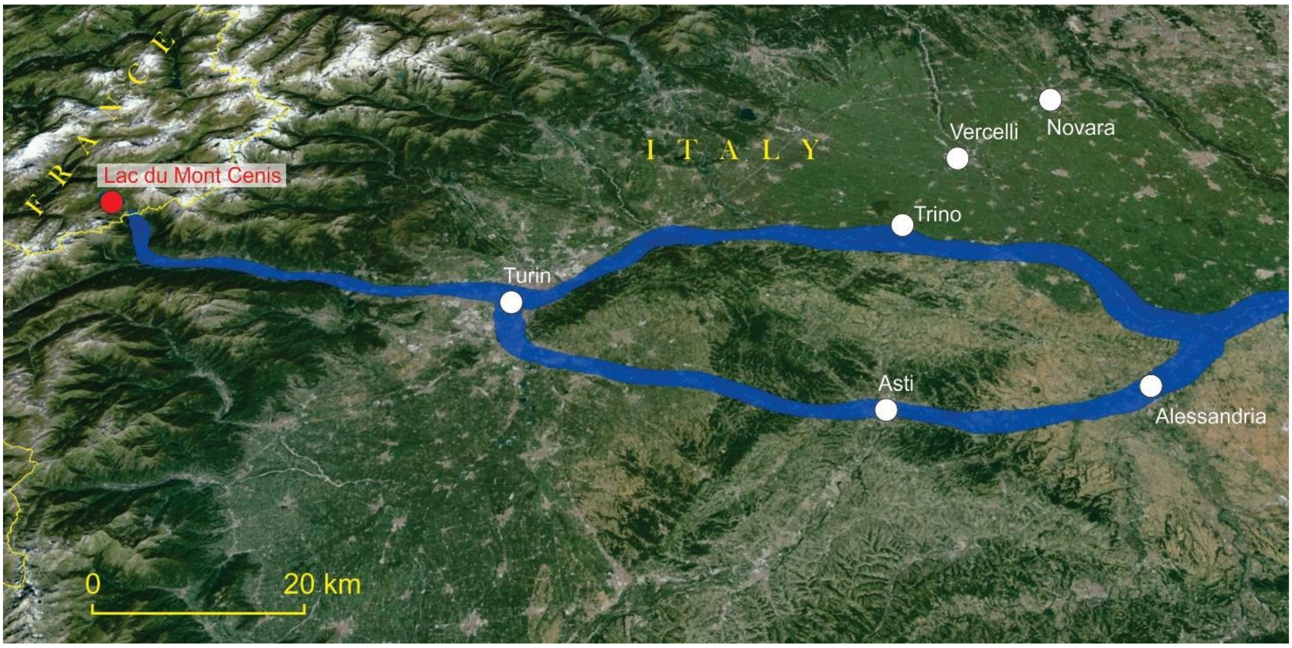


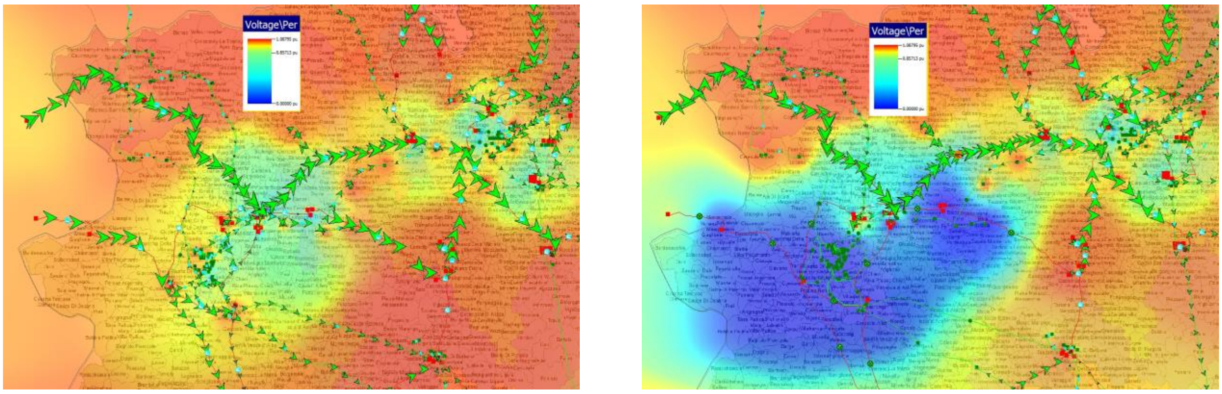
Figure 44 - Areas affected by the flood caused by the collapse of the Lac Du Mont Cenis dam

25 important substations located in the potentially flooded provinces were preliminarily identified in the affected provinces and used to perform contingency analysis. Table 14 reports a set of representative contingencies. The system will suffer from just one line flow violation when disconnecting substation ITONT alone, and the violation reaches 124%. The isolation of all 25 substations disconnects the highest load (1130 MW), generation (1690 MW) and leads to largest set of isolated buses (38 buses). On the other hand, when disconnecting the substations individually, the largest disconnected load reaches 207 MW but with the lowest number of isolated buses (2 buses) when isolating the substation 1, while the largest disconnected generation arrives 740 MW when isolating the substation 2.

Table 14 - Representative contingencies for the collapse of the Lac Du Mont Cenis Dam

No.	Contingency Record	Isolated Bus	Disconnected Load (MW)	Disconnected Generation (MW)	Voltage & line flow violations	Branch overload (%)
1	ALL 25 substations	38	1130	1690	0	0
2	Substation 1	2	207	0	0	0
3	Substation 2	4	77	740	0	0
4	Substation 3	3	68	587	0	0
5	Substation 4	5	3	314	1	124

Figure 45 shows the system voltage changes around the affected area by the flood, and it also implies the geographic coverage of the blackout with the administrative information. It is manifest that the provinces of Turin and Alessandria would be affected more heavily than other towns.



(a) Voltage visualisation around affected area before the event

(b) Voltage visualisation around affected area after the event

Figure 45 - Compared visualisation of voltage profiles in the affected area

In summary, the large geographical exposure of power system in the natural environment indicates the vulnerability of power grids when facing the destructive adverse natural events. They do not only damage the power facilities directly but may also lead to blackout through cascading failures, which brings huge economic loss to society. The climate change even deteriorates the frequency and affected area of the natural threats.

Therefore it is necessary to have appropriate approaches and models to track the consequences of the climate change, especially in the power systems, through the analyses of the low frequency but high impact threats. A possible way to achieve this is to pool together power system analysis and geographical information. Georeferenced model based on the steady state contingency analysis allows us to plan, design, reinforce and manage the power system in a holistic way. It can also promptly at the EU level capture the interdependencies among various states.

Taking the contingency analysis is the first step to improve the ability of power system against the natural threats, next we can take some other actions to minimise the damage brought by adverse natural events. For example, making the emergency plans to control the power flow to decrease the possibilities of blackout when the power system is in unusual condition, and especially for the plans to quick response to natural threats and recover power system after the events happen.

6.2. BALTIC POWER SYSTEM: OPERATIONAL SECURITY AND ADEQUACY ANALYSES

6.2.1. MOTIVATION

As argued in Chapter 3 and Chapter 4, electricity security analysis for policy decision making needs to evolve more towards combined modelling exercises, involving more actors and increasing the spatial scale at a least at a regional (cluster of member states) level.

The energy policy of the Baltic States is integrated in the energy strategy of the European Union (EU) and aims at pursuing three major objectives: competitiveness, sustainable development and security. All the three Baltic power systems are working to fulfil the planned EU technical requirements and to adopt the European regulations, codes and standards, e.g. from ENTSO-E, and from the European Committee for Electrotechnical Standardization (CENELEC). The integration of the Baltic States into the EU energy market has been identified as a strategic priority for all three countries. The main goal of the Baltic Energy Market Interconnection Plan (BEMIP) is to create a Baltic Sea region unified market. The current implementation of a joint wholesale electricity market for the entire Baltic States is the driving force for the energy market development in the Baltic States [40].

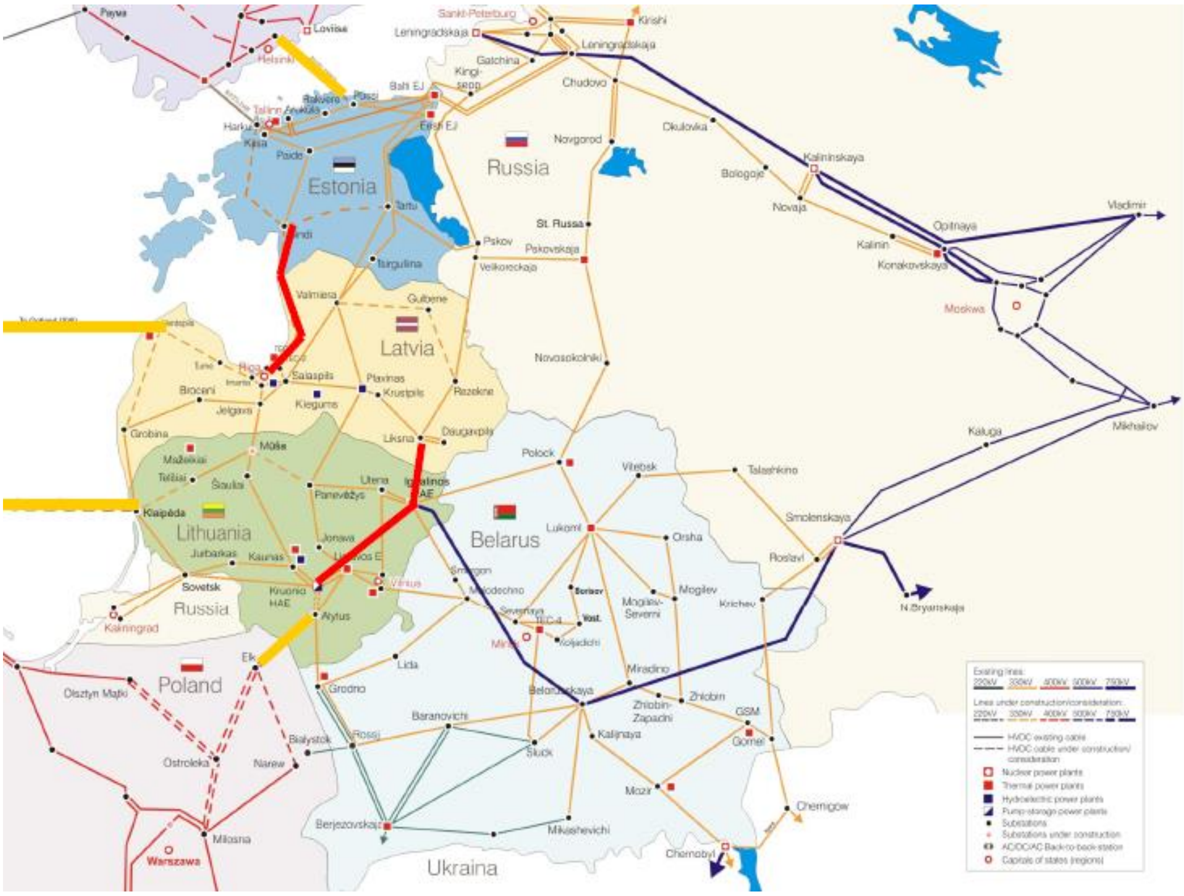


Figure 46 - BRELL (Belarus, Russia, Estonia, Latvia and Lithuania) system [287]

The electricity systems of the Baltic States are tightly interconnected and integrated into the BRELL (Belarus, Russia, Estonia, Latvia, and Lithuania), that operates synchronously with the UPS/IPS zone (see Figure 46). The transmission lines feature voltages spanning from 110 kV to 330 kV and stretch over more than 17000 km. Together with the neighbouring electrical networks of Russia and Belarus, the electrical networks of Estonia, Latvia and Lithuania form the "Baltic Ring", consisting of 330 and 750 kV lines. The 750 kV lines in the integrated power system are generally operated as antenna connections (open-loop) [287]-[290].

The interconnection of the power systems of Estonia, Latvia and Lithuania (Baltic Integrated Power System, BIPS) operates as a synchronous Alternating Current (AC) grid in parallel with the Integrated/Unified Power System (IPS/UPS) of Russia and Belarus. This is performed via a ring created in the early sixties of the last century by interconnecting the power systems of the western part of the former Soviet Union: the Baltic States (Latvia, Lithuania, and Estonia), north-western Russia, Central Russia and Belarus. The Russian power system provides primary power reserves for the frequency regulation to the whole system [288]-[290].

The backbone of the BIPS is formed by 330 kV high-voltage power lines. There are 58 high-voltage transmission lines with a total length of 4137 km, and 32 substations equipped with 54 autotransformers (347/242kV, 330/115kV) with a total capacity of 8665 MVA. The regional transmission network of the Baltic IPS consists primarily of 110 kV lines, with the exception of the Estonian power system, where 220 kV lines are also present. The Baltic power systems still lack adequate electricity connections, both between themselves and to other parts of the EU. However, the situation is improving: recently, the Estlink 1 and 2 connections between Estonia and Finland, the LitPol Link connection between Lithuania and Poland and the Nordbalt connection between Sweden and Lithuania have considerably raised the transfer capacity between the Baltic and the EU electricity markets [288][289][290].

The power generation landscape in the Baltic States changed dramatically at the beginning of 2010, when the Ignalina Nuclear Power Plant (1500 MW) in Lithuania was shut down (in 2009 it produced around 10000 GWh, almost 40% of the overall consumption of the Baltic States). A new nuclear power plant in Visaginas (1350 MW) is under consideration, with an investment of about 7 G€ and a construction time of 10 years. In 2013, generation in Estonia was mainly characterised by large thermal power plants (Eesti, Balti and Iru), with a total generation of 11892 GWh/year and renewable sources, mainly wind power, accounting for 451 GWh/year. In Latvia two main energy resources were exploited: hydro produced 2912 GWh/year (Pļaviņu, Rīgas, Ķeguma, Aiviekstes hydro power stations), and fossil fuels accounted for 2869 GWh/year (Riga Combined Heat and Power plants – CHP-1 and CHP-2). Whereas wood and wind power plants contributed with 119 GWh/year. The Lithuanian generation capacity consisted of hydropower and pumped storage power plants for 1066 GWh/year (Kaunas and Kruonis plants); gas, black fuel or oil for 2615 GWh/year (Vilnius, Mazeikiu, Kaunas and Elektrenai power plants); and wind produced 649 GWh/year [288][289][290].

The availability of primary energy sources for electricity production and the dependence from abroad is different for the various Baltic States. Estonia's energy independence is 90%, whereas the value is 48% for Latvia, and of 19% for Lithuania [288][289][290].

The integration of the Baltic States into the EU energy market has been identified as a strategic priority for all three countries. The main goal is to create a unified market of the Baltic Sea region. Current implementation of a joint wholesale electricity market for the entire Baltic States has boosted energy market development in the Baltic States. So far, "energy-only" markets are established in Estonia, Latvia and Lithuania. The day-ahead (Elspot) and intraday (Elbas) electricity markets have been set up, employing implicit auctioning of cross-border transmission capacity. Baltic States have national balancing markets, which are organised by the national Transmission System Operators in charge of balancing their areas. After the Ignalina nuclear power plant shutdown, a generation surplus arose in the northern part of the Baltic States, while a deficit emerged in the southern part causing power transfers from Estonia to Latvia with the overloading of tie-lines. During summertime, the related congestion causes the market to split into two price-zones, with the exploitation of more expensive local capacity and import from abroad.

The Baltic States are considering how to optimise their mix of generation resources, defining priorities at the individual and common levels with one common goal: greater energy independence. Due to their limited ability to act on their own, especially on large, costly projects, joint efforts are expected.

6.2.2. MODEL AND SCENARIOS

Security analyses were carried out assesses the operational security of the Baltic States for both the current state, and a set of possible future scenarios, in terms of generation capacity, generation mix and network enhancement (both internally and with respect to new tie-lines). These sections are based on the work carried out by JRC in cooperation with the Institute of Physical Energetics in Riga and Politecnico di Torino [286].

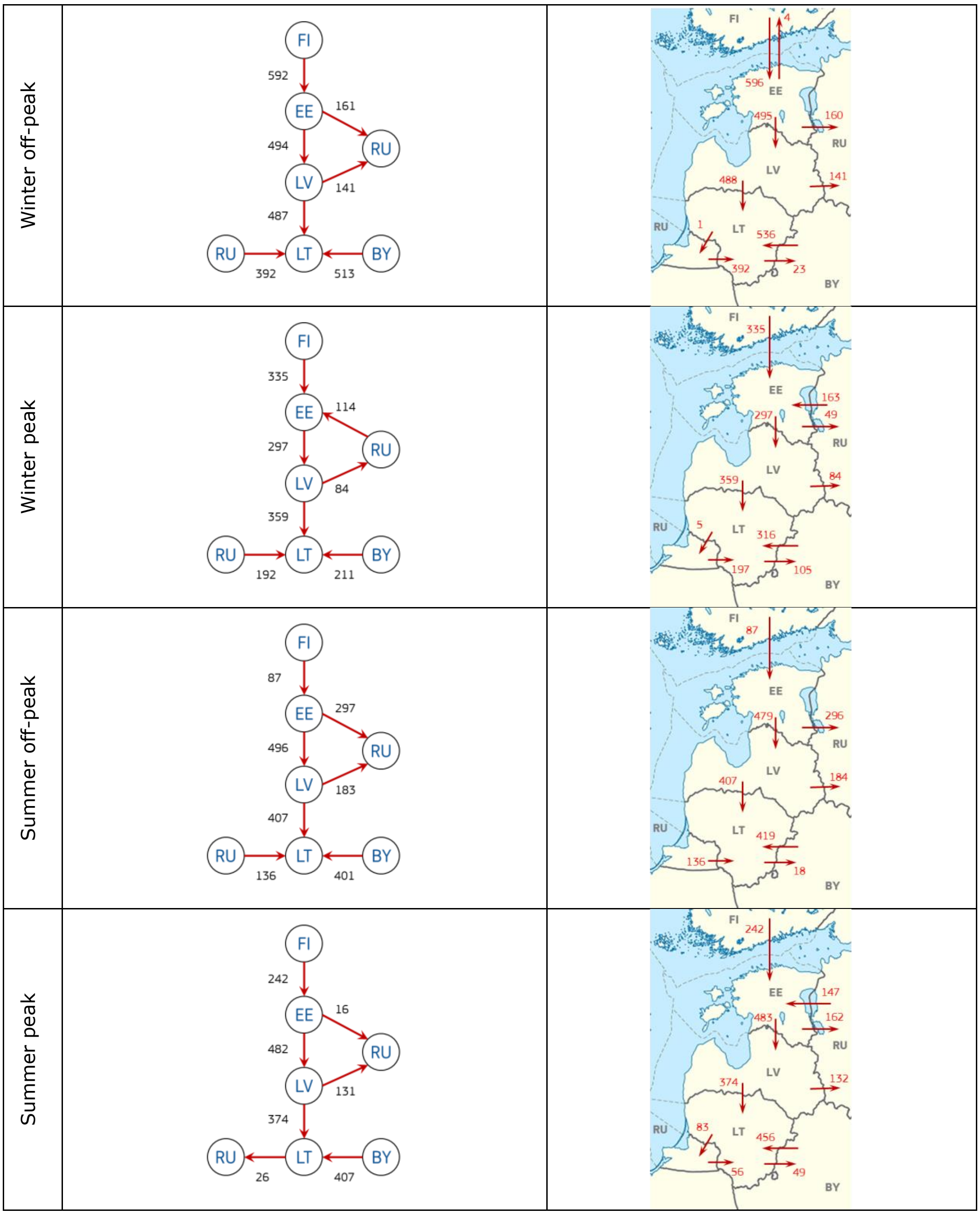


Figure 47 - Reference model validation (left: reference model results, right: ENTSO-E flow snapshots [293])

An in-house power system model of the Baltic States was developed with the purpose of assessing comparative options for a reliable and secure development of the region's electricity system. The model consists of buses with voltage of 110 kV and higher, mainly 110 kV, 220 kV and 330 kV. The 35 kV undersea cables connecting the Estonian mainland and the north-western islands were also included. The model has been calibrated based on the 2014 reference scenario to match the historical records from ENTSO-E. The

cross-border power flows in the Baltic model are close to the recorded ENTSO-E data in winter off-peak load and summer peak load scenarios. Two additional scenarios (winter peak load and summer off-peak load) were examined. Line loading and voltage levels within the Baltic States are within the acceptable range in all 2014 reference scenarios. The PowerWorld tool was used for the simulations [187].

After calibrating the models for the current scenarios, and validating them by the ENTSO-E snapshots, the network models, loads and generation patterns for the future horizons (i.e., 2020 and 2030) were constructed. To achieve this, the original model was modified by:

- adding network reinforcement projects,
- estimating the expected load increase patterns,
- including new generation units.

6.2.3. Analysis and discussion

6.2.3.1. Generation adequacy assessment

The generation adequacy for the three Baltic States is assessed based on the best available public data from the local TSOs, along with Nord Pool Spot's and ENTSO-E's adequacy forecasting [288]-[291]. In fact, the assessment of the actual generation adequacy reflects the ability of the generating units to match demand for an indicative load reference point (peak hour of 16th January 2013). The methodology is based on a deterministic approach, to calculate the Remaining Capacity (RC) that results from the difference between the Reliably Available Capacity (RAC) and the expected peak load [292].

Figure 48 summarises the current generation adequacy perspective for the Baltic States. As may be seen, all countries present RCs higher than the Adequacy Reference Margin (ARM), implying adequate generation supply with a potential for electricity export to third countries. Individually, Estonia presents the highest potential for export (with 660 MW of RC), while Latvia and Lithuania did present very marginal RC.

Among the three Baltic States, Lithuania seems the most vulnerable in terms of generation adequacy as an effect of the Ignalina Nuclear Power Plant (NPP) decommissioning, with a shortage of 150-180 MW generation capacity during the 2014 winter peak, and a 130-160 MW deficit at the summer peak. Even in the case of generation sufficiency, Lithuania would still depend on imports, as 71% of the electricity consumed in 2013 is being imported (50% originated from third countries), due to higher local generation prices. While wind generation in Lithuania can supply 15% of peak demand the volatility of renewable generation and the risk of icing during the winter peak call for further assessment of generation adequacy based on stochastic methodologies. With a 2.6 GW Net Generation Capacity (NGC), the Estonian power system is able to cover the peak loads and also allow net exports to Latvia, Russia and Finland in case of favourable electricity prices, with 32% of the electricity generated in 2013 being exported mainly to Russia and Latvia. Despite the high NGC with respect to the annual load peak demand in Latvia and Lithuania, the RC is clearly limited due to the high share of hydro generation in both countries resulting in significant UC during peak demand. In fact, Latvia's water inflow shortage (mainly in the Daugava River) imposes severe constraints during the first six weeks of the year which, as a consequence, are characterised by inadequate generation adequacy. In terms of exports, Latvia is a net exporter to Lithuania, while it still has considerable dependence on imports from Estonia and Russia, reaching 38% of load in the first semester of 2013.

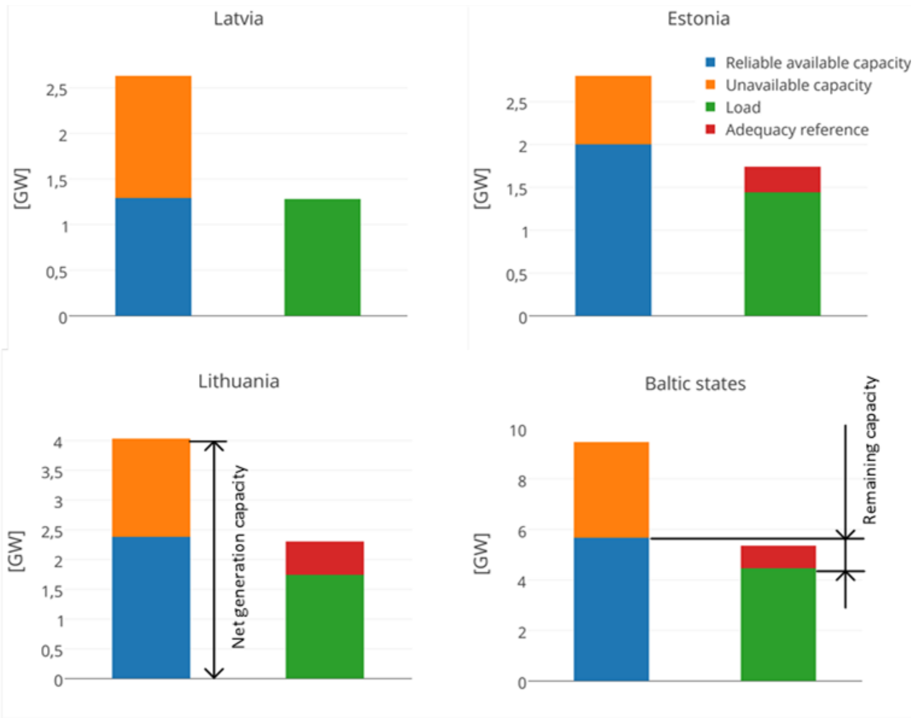


Figure 48 - Generation adequacy in winter peak day

The future of electricity security in the Baltic States greatly depends on the strategic choices that will be implemented both at the infrastructural and operational levels. The crucial elements to be evaluated are (i) the generation side with the development of new generation capacity, and consequently of a new energy mix; (ii) the foreseen infrastructural enhancements, both internal and cross-border; as well as (iii) the possible shift to the autonomous synchronous operation of the Baltic States or a synchronisation to the Continental Europe Network. The load's time variation should be considered as well with changes in structure, operation, and load must be set in a coherent time frame. For this purpose, the current situation is here compared with two alternative time frames: 2020 and 2030.

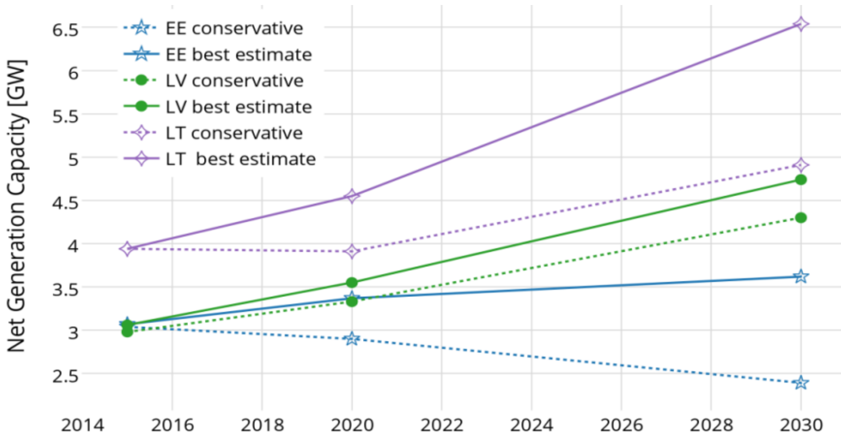


Figure 49 - Net generation capacity evolution scenarios in the Baltic States

In accordance with the ENTSO-E Scenario Outlook and Adequacy Forecast [292], two main scenarios are investigated for the three Baltic States. The two scenarios are built based on a bottom-up approach consisting in a first forecasting exercise from the reference point (January 2013) until 2020, whose results are successively projected onto the 2030 horizon. The first scenario (referred to as a "conservative" one) takes into consideration only confirmed investments, while the second scenario (referred to as the "best estimate" scenario) assumes adequate market incentives and investments credibly deemed as "likely". The

load forecasting for the two scenarios is assumed to be similar up to the year 2020, based on the best available national demand estimates and considering the usual climatic conditions. The two scenario projections diverge on the 2020 to 2030 horizon in terms of load forecasting, mainly due to differing the assumptions of the gross domestic product: hypothesising more favourable economic and financial conditions the best estimate scenario results in higher electricity demand and therefore increased need for generation capacity expansion and network reinforcements.

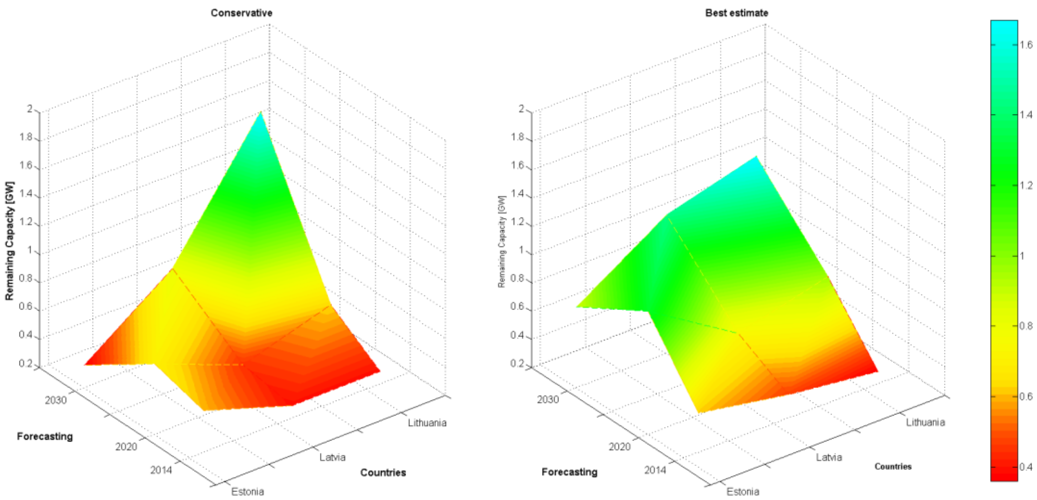


Figure 50 - Reserve capacity under the two scenarios for the three Baltic States

Consistently with the present generation adequacy assessment, the mid- and long-term assessment of the developed scenarios is based on the UCTE methodology, while the data was mainly taken from the ENTSO-E Scenario Outlook and Adequacy Forecast and the forecasts of the member TSOs [292][293]. Figure 50 summarises the Baltic States' generation adequacy evolution in the two assessed scenarios. In both scenarios, all countries achieve adequate generation capacity, with lower predictions for Estonia under the conservative scenario in the 2030 projection. In the following sub-sections, further analyses are developed for each country under the two scenarios.

The main tenet of the conservative scenario is the Estonian generation capacity decrease. In fact, Estonia's strong dependence on fossil sources will be affected starting from 2016, due to emission limitation directive entering into force. However, it is foreseen for both scenarios that Estonia would be nevertheless capable of meeting the load by using its local generation capacity: this is due to the flexibility provided by the Industrial Emissions Directive in granting exemption for power plants part of small isolated networks. Despite the prospect of keeping a few combustion power plants, Estonia is still expecting a noticeable decrease in the installed generation capacity, with 21.4% decrease between 2015 and 2030. Latvia's generation will assist to the highest increase in installed capacity, with 11.74% increase up to 2020 followed by 29.13% increase up to 2030, totalling a whopping 44.30% increase with respect to the 2015 reference year. The newly installed capacity is mainly composed of renewable energy sources, while fossil and hydro generation sources would remain similar to the reference year. For Lithuania's generation capacity, we may assist to a slight decrease by 2020 due to emission limitations, followed by a substantial increase of 25.6% up to 2030 due to the expected commissioning of the Visaginas NPP and the considerable investment in wind energy capacity.

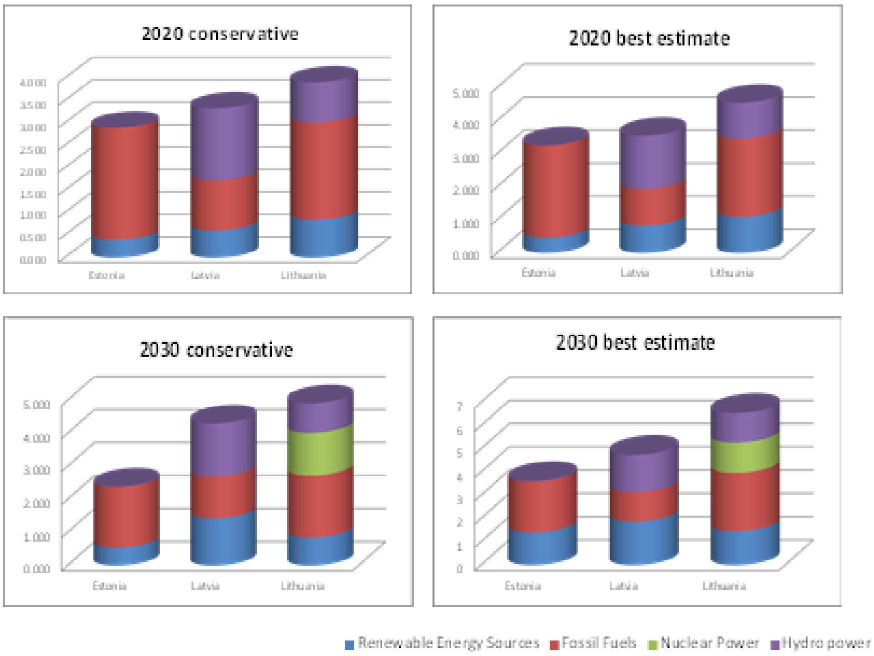


Figure 51 - Electricity generation mix [GW] in the different scenarios

Overall, the three Baltic States are expected to experience to a slight increase in installed capacity by 2020 in comparison to the reference year, followed by a 16% increase of installed capacity on the 2030 horizon, mainly due to Latvia's expected generation capacity investment. For the conservative scenario, the three Baltic States can still individually meet their demand using local capacities, with positive generation RC in 2020 and 2030.

In the conservative scenario, all three Baltic States are expected to be beyond the European 2020 requirement for generation mix, and hence meet the emissions targets. Nonetheless, low penetration scenarios would still require network reinforcement and cross-border transmission investments, in order to efficiently integrate RES and reach 18% of penetration in 2020 (28% target) and 24% in 2030 for all the three Baltic States.

The best estimate scenario, unlike the conservative one, foresees an increase in Estonia's installed capacity. The largest expansion should take place in the share of RES with 15 percentage points (pp): the comparative figures for Latvia and Lithuania are instead 3 pp and 5 pp respectively. Consistently with the conservative scenario, Estonia is expected to satisfy its electricity demand relying on local generation, with positive RC throughout the 2030 horizon.

Latvia features similar patterns to Estonia, with substantially higher installed capacity and adequate RC. Furthermore, its RES share in the generation mix would remain the highest among the three Baltic States for both scenarios, with the due consequences in terms of low RAC.

Finally, Lithuania is expected to achieve a sustained improvement of generation adequacy, all the while presenting the highest load demand increase for both the conservative and the best estimate scenarios, with respectively 35% and 42% load growth in the period 2015-2030. The low share of RES in the Lithuanian electricity mix could be an obstacle in meeting the 2050 roadmap targets for power generation. The best estimate scenario presents higher hydro capacity for Lithuania, with a 42% increase compared to the conservative scenario resulting in the highest level of UC per NGC within the three Baltic States.

In general under both scenarios, all the three Baltic States are facing high demand growth forecasts, clearly above the ENTSO-E average for January 2030. While the generation adequacy assessments for all scenarios are projecting adequate RCs, further need for cross-border interconnections with ENTSO-E members is

clearly expected, in preparation to the higher energy independence from the UPS/IPS. Furthermore, requirements to meet the 2050 roadmap for CO_2 emissions and gradual decommissioning of fossil fuel generation power plants will result in the expected increase of offshore wind farms deployment, requiring an efficient market design and effective power balancing reserves. In this prospect, cross-border transmission capacity would specifically play a crucial role in the security of supply, by balancing the high volatility of wind power resources.

6.2.3.2. Reference scenario economic analysis

In this section, economic and security analyses of the Baltic power systems based on the reference models are reported. The objective of the economic analyses is to understand the competitiveness of the Baltic States among themselves in the electricity markets, while capturing the impacts from the network infrastructures (such as congestions, and voltage limits) on their market merits.

The generation mix for each scenario is defined by the optimal power flow. The objective of the optimal power flow is to minimise generation cost in the electricity system based on the marginal cost of each generator, considering grid constraints such as transmission line limits and voltage ranges. In the following sections the marginal cost for each Baltic country is given in terms of locational marginal cost, so that possible zonal splitting due to grid congestions can be identified. Different zones can also be formed within the same country.

Further, contingency analysis performed on the basis of the four reference models is meant to check for the operational security of the systems, and the adequacy of resources available to the TSO in charge to handle such contingencies. The results can also be used to identify the criticalities of the system under different generation and load conditions. These are ranked by a set of metrics such as maximum overload percentage, maximum voltage violation percentage, number of violations, islanded generation and load, etc.

For the simulated winter off-peak case, the simulation indicated an overall of 1.2 GW import into the Baltic States; however, Estonia and Latvia were net exporting countries (mainly to Russia) with around 63 MW and 132 MW net respectively. Lithuania was the only country with a huge net import of 1392 MW, while the load of Lithuania at that time was 1001 MW; therefore, through the simulation results, we can observe that the Kruonis pump station was pumping water into the reservoir.

In the winter peak case, the overall load increased by more than 50% compared with the winter off-peak case. The power imports of the Baltic States totalled 788 MW, representing a decrease of more than one third compared with the winter off-peak case. Only Latvia kept net export of 146 MW, while Estonia and Lithuania imported 152 and 762 MW, respectively. According to our simulation, the Kruonis pump station was discharging water to satisfy its domestic loads, thus setting a comparatively low marginal cost for Lithuania.

With only 144 MW, the imported power of the Baltic States was low for the summer off-peak case. This amounted to a 90% decrease w.r.t. the winter off-peak case. Estonia and Latvia were exporting countries in this scenario, reaching 706 MW and 94 MW respectively. Lithuania was the only country with a huge net import of around 950 MW, while the load of Lithuania was only around 850 MW. The simulation results indicated that the Kruonis pump station was pumping waters into the reservoir, like in the winter off-peak case.

Compared to the summer off-peak case, the load increased by more than 50% during summer peak, but was around 20% lower than in both the winter cases. In this reference model, the total imported power of the Baltic States was 475 MW, more than three times higher than in the summer off-peak case. Only Lithuania kept net import of 754 MW while Estonia and Latvia exported 256 and 23 MW, respectively.

Figure 52 illustrates the system marginal cost in the four reference models described above. For the winter off-peak case, the marginal cost in Estonia was higher than in the other two countries, while Latvia and Lithuania had similar marginal cost. Latvia can mainly use renewables (hydro and wind) to cover the demand; yet more expensive cogeneration units based on oil/gas were running at their minimum level for district heating. Due to the large amount of import into Lithuania and the maintenance minimum operation requirements of cogeneration plants, the hydro pump storage was operating almost at its maximum. Estonia used many shale oil generators due to the lack of cheaper resources; therefore, its marginal cost was the highest among the three Baltic States.

For the winter peak case, the marginal cost of each state was similar to the winter off-peak case. Combining the results of both cases in winter, it is obvious that Latvia has stronger market advantage compared with the other two Baltic States due to zero marginal cost of hydro power plants. The strategy of Lithuania for using the hydro pump station to shift the generation resources from off-peak to peak loads successfully decreased its marginal cost for domestic generation.

For the summer off-peak case, with low demand the renewable resources cannot be fully exploited due to thermal power plants. For example, not all hydro power plants in Latvia reach their maximum outputs. To balance the import and generation from domestic thermal units in Lithuania, the pump station also worked at its maximum to store water into the reservoir.

For the summer peak case, the locational marginal cost varied from region to region in Latvia and Lithuania. Marginal cost in Latvia's Riga area were driven up to the same level as Estonia by frequent episodes of congestion in that region, whose effects were felt as far as in parts of Lithuania. This is mainly caused by limited maximum power of the hydro power plants in Latvia (50% of the gross electrical capacity) due to low water inflows in the River Daugava during summer season.

For the winter off-peak case, the marginal cost in Estonia was higher than in the other two countries, while Latvia and Lithuania had similar marginal costs. Latvia can mainly use renewables (hydro and wind) to cover the demand; yet more expensive cogeneration units based on foils/gas were running at their minimum level for district heating. Due to the large amount of import into Lithuania and the maintenance requirements of cogeneration plants, no renewable generation was needed and the hydro pump storage was operating almost at its maximum. Estonia used many shale oil generators due to the lack of cheaper resources; therefore, its marginal cost was the highest among the three Baltic States.

For the winter peak case, the marginal cost of each state was similar to the winter off-peak case. Combining the results of both cases in winter, it is obvious that Latvia has stronger market advantage compared with the other two Baltic States. The strategy of Lithuania for using the hydro pump station to shift the generation resources from off-peak to peak loads successfully decreased its marginal costs for domestic generation.

For the summer off-peak case, with low demand the renewable resources cannot be fully exploited due to thermal power plants. For example, not all hydro power plants in Latvia reach their maximum outputs. To balance the import and generation from domestic thermal units in LT, the pump station also worked at its maximum to store water into the reservoir.

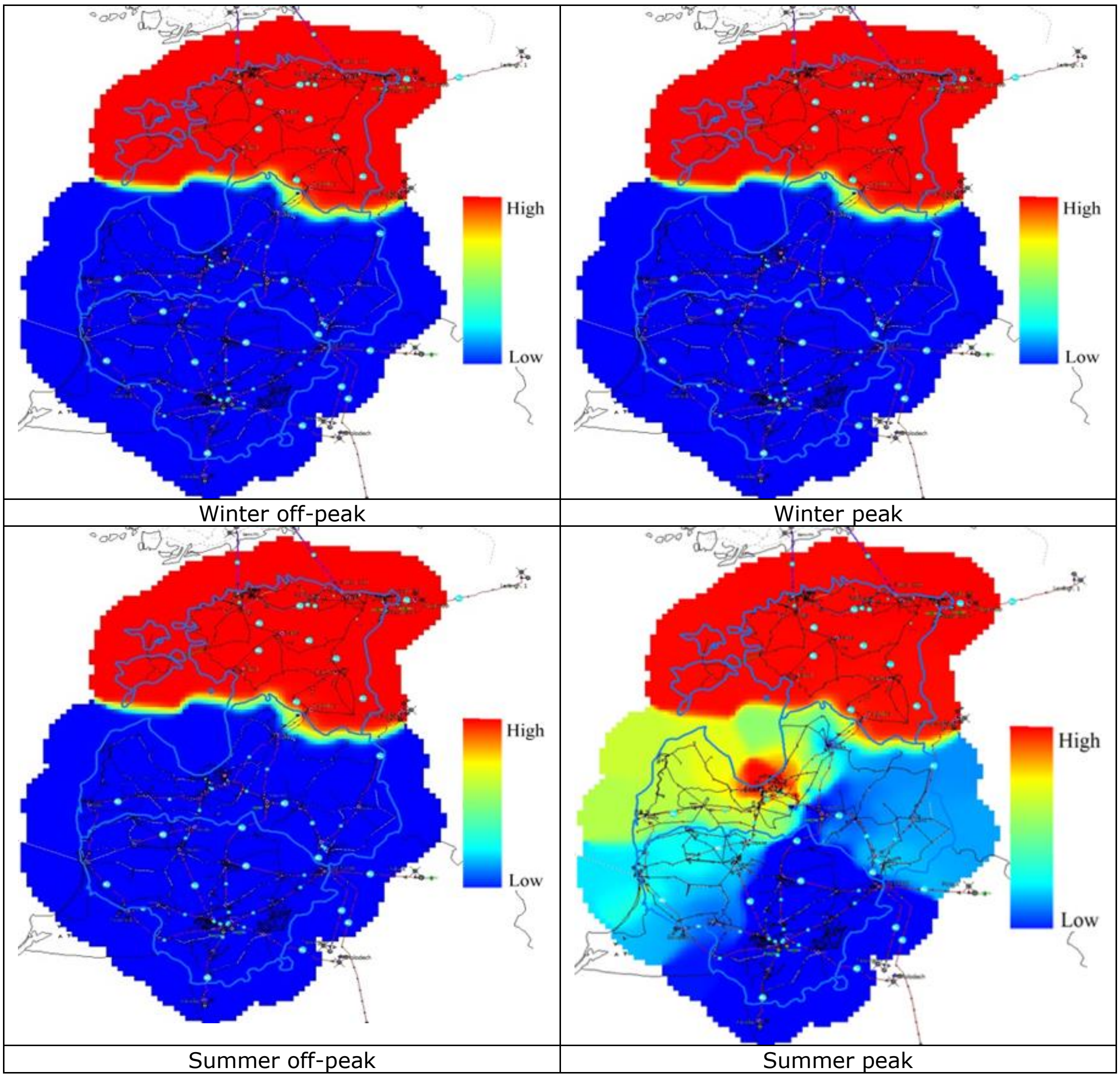


Figure 52 - System marginal costs of the four reference models

For the summer peak case, the locational marginal costs varied from region to region in Latvia and Lithuania. Marginal costs in Latvia's Riga area were driven up to the same level as Estonia by frequent episodes of congestion in that region, whose effects were felt as far as in parts of Lithuania.

6.2.3.3. Reference scenario operational security analysis

Figure 53 shows the system physical features for the four reference models. They were also used as the starting operational points to perform n-1 steady state contingency analysis in the latter part of this subsection.

Under the contingency analysis the participation factors of the automatic generation control of generators in the Baltic States as a whole were set proportional to the installed capacity of the generators. Emergency power reserves for each country are activated when necessary under the contingency analysis.

In the winter off-peak case one of the Estlink cables (Estlink 1 in our simulation) was used to export a very small amount of energy to Finland, while the other one was used to import energy from Finland. As a consequence, Estlink 2 was used up to 96% of its capacity.

For the winter peak case, according to the simulation results, the Estonia's system experienced situation of comparatively low voltage, due to the lack of reactive power support under high demand. However, the voltage was still in the acceptable operational range.

For the summer off-peak case, the system voltage in Estonia was better than for the winter cases because of lower exchanges through the DC lines (Estlink 1 and 2), involving less need for reactive compensation from the system.

For the summer peak case, power flows in the area southeast of Riga reached the operational limits of the transmission lines, with congestion occurring correspondingly. Similarly to the previous cases, voltage in Estonia was affected by the exchange of power on Estlink 1.

Based on the operational points listed in Figure 9 for the four reference models, contingency sets containing each single transmission line, transformer and generator in the models were applied for the steady state security analysis lists the most severe contingencies according to each criterion in Table 15 (the events are intentionally anonymised).

For the winter off-peak case, the most serious contingency was the loss of a branch in contingency 1, which resulted in system-wide disturbance. The loss of component in contingency 3 created the highest overloads in the contingency set and also caused the lowest system voltage. The highest number of violations can be observed when the component in contingency 2 failed; however, the consequences were not so serious. The fault on the component in contingency 4 cut the largest import of 596 MW to the Baltic States; however, no system violations were observed.

For the winter peak case, no system-wide disturbance was witnessed. The worst contingency was to lose the component in contingency 3, which not only caused 2.7 times higher power flow than the maximum allowed flow over some lines, but also heavily lowered system voltage.

For the summer off-peak case, no system-wide disturbance occurred. The system's resilience under this reference case was the highest among all the four cases. The most severe one was the tripping of the component in contingency 7, which can bring 40% excessive flows over other lines. All other contingencies left the system largely unaffected.

For the summer peak case, no system-wide disturbance was observed. The most severe contingency was the loss of the component in contingency 10, which caused about 150% excessive current in a line, which had already been operating near the maximum limit in the normal state. Even though low bus voltage was detected, the consequences were not as serious as the winter peak case.

Obviously, the most critical components in the system were the ones in contingency 1 (which can cause system-wide disturbance in case of high demand) and contingency 3 (whose fault sets off system overload in every reference case). Other faults caused by network components not directly pertaining to our focus are not listed here.

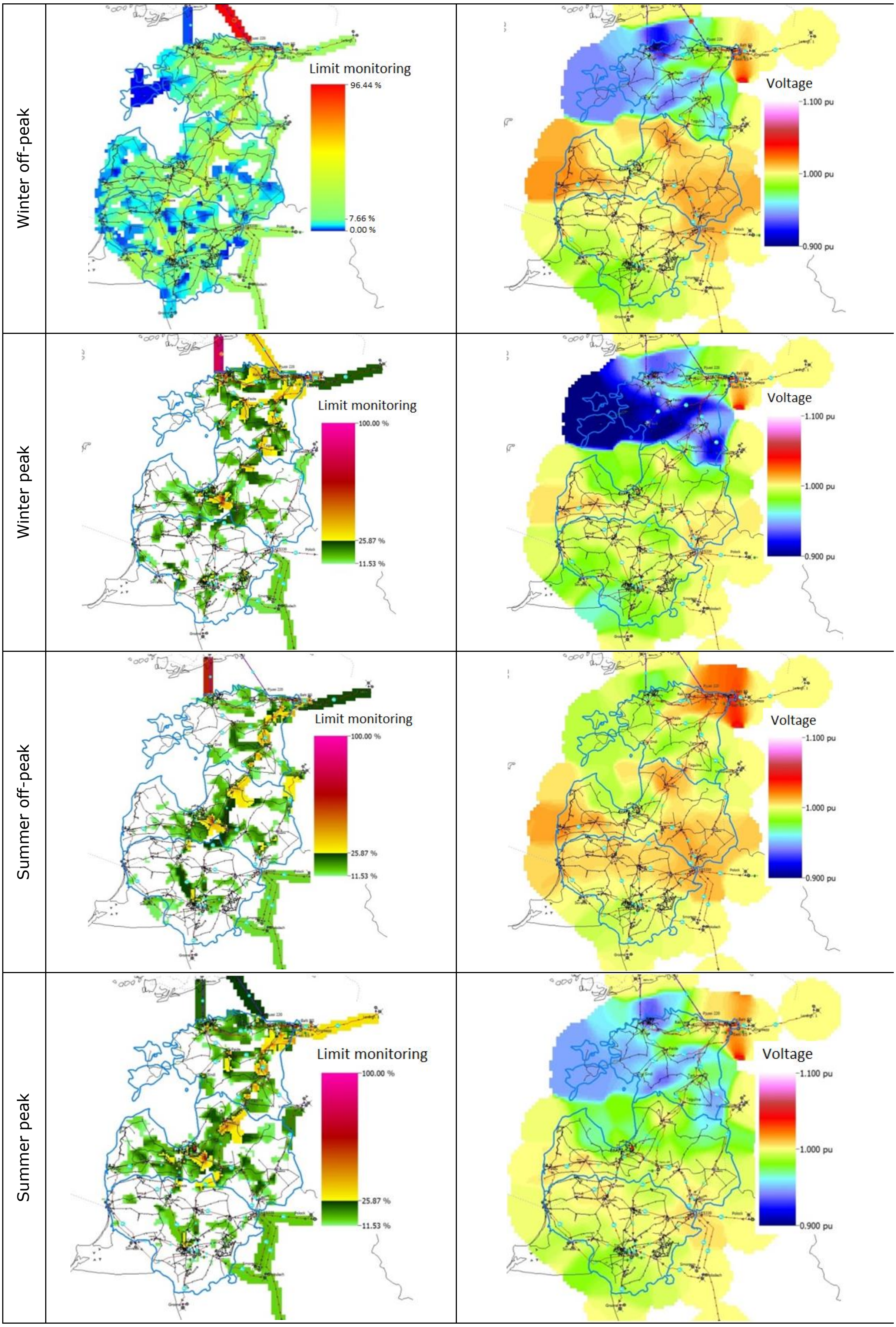


Figure 53 - System performances for the four reference models under normal operation

Table 15 - Selected most critical contingencies according to multiple criteria for the four reference cases

Cases	Contingency Record	Most severe consequence	Violations	Unserved loads (MW)	Disconnected generation (MW)	Maximum overload (%)	Minimum Voltage (p.u.)
Winter off-peak	contingency 1	System wide disturbance	-	-	-	-	-
	contingency 2	Low voltage	43	0	0	-	0.87
	contingency 3	Overload	35	0	0	165	0.84
	contingency 4	Disc. Gen.	0	0	596	-	-
	contingency 5	Uns. loads	0	10.26	0	-	-
Winter peak	contingency 6	Low voltage	114	0	135	109.7	0.792
	contingency 3	Overload	75	0	0	268	0.745
	contingency 4	Disc. Gen.	65	0	200	117.3	0.88
	contingency 5	Uns. loads	65	17	0	116.7	0.879
Summer off-peak	contingency 7	Low voltage	3	0	0	141.3	0.898
	contingency 8	Disc. Gen.	0	0	105.3	-	-
	contingency 5	Uns. loads	0	12.95	0	-	-
	contingency 9	Overload	0	0	0	165	-
Summer peak	contingency 3	Overload	36	0	0	158.7	0.865
	contingency 10	Overload	2	0	0	244.8	-
	contingency 4	Disc. Gen.	2	0	126	126.4	-
	contingency 11	Low voltage	8	0	0	132.7	0.835
	contingency 5	Uns. loads	0	21.12	0	131.3	-

6.2.3.4. 2020 SCENARIO ECONOMIC ANALYSIS

The reference models were extended into the future through the analysis of the 2020 and 2030 horizons. Based on the extended models for 2020, we will briefly discuss in this section the economic and security aspects (with special regard to the system's operational security under a specific scenario of geopolitical security concerning the IPS/UPS network) and the issues concerning energy independency of the Baltic States. To achieve the objectives, a general scenario was assumed: zero electricity exchange between the Baltic States and IPS/UPS. In this scenario zero power flows are with both Russia and Belarus. The Baltic States remain connected with Finland, Poland and Sweden through cross-border transmission lines. Interconnections with Kaliningrad are kept unchanged.

As previously described, the system models do not include a market model for the future scenarios; therefore, cross-border exchange patterns were not derived endogenously, but simply imposed by assumption of the following pecking order for electricity trading: 1) Finland, 2) Sweden, 3) Poland, and 4) Kaliningrad. The order was based on the average costs of the energy mix of each country. Furthermore, in order to study the energy independency of the Baltic States, higher prices were set for the import from outside, while export prices were set to zero.

Figure 10 gives the results of the energy exchanges between neighbouring countries in the Baltic. The results are provided for the four typical cases already seen in the previous sections. It can be noted that energy exchanges with outside countries were practically zero, which indicates that the Baltic States can satisfy their demand locally in 2020 in all four reference cases.

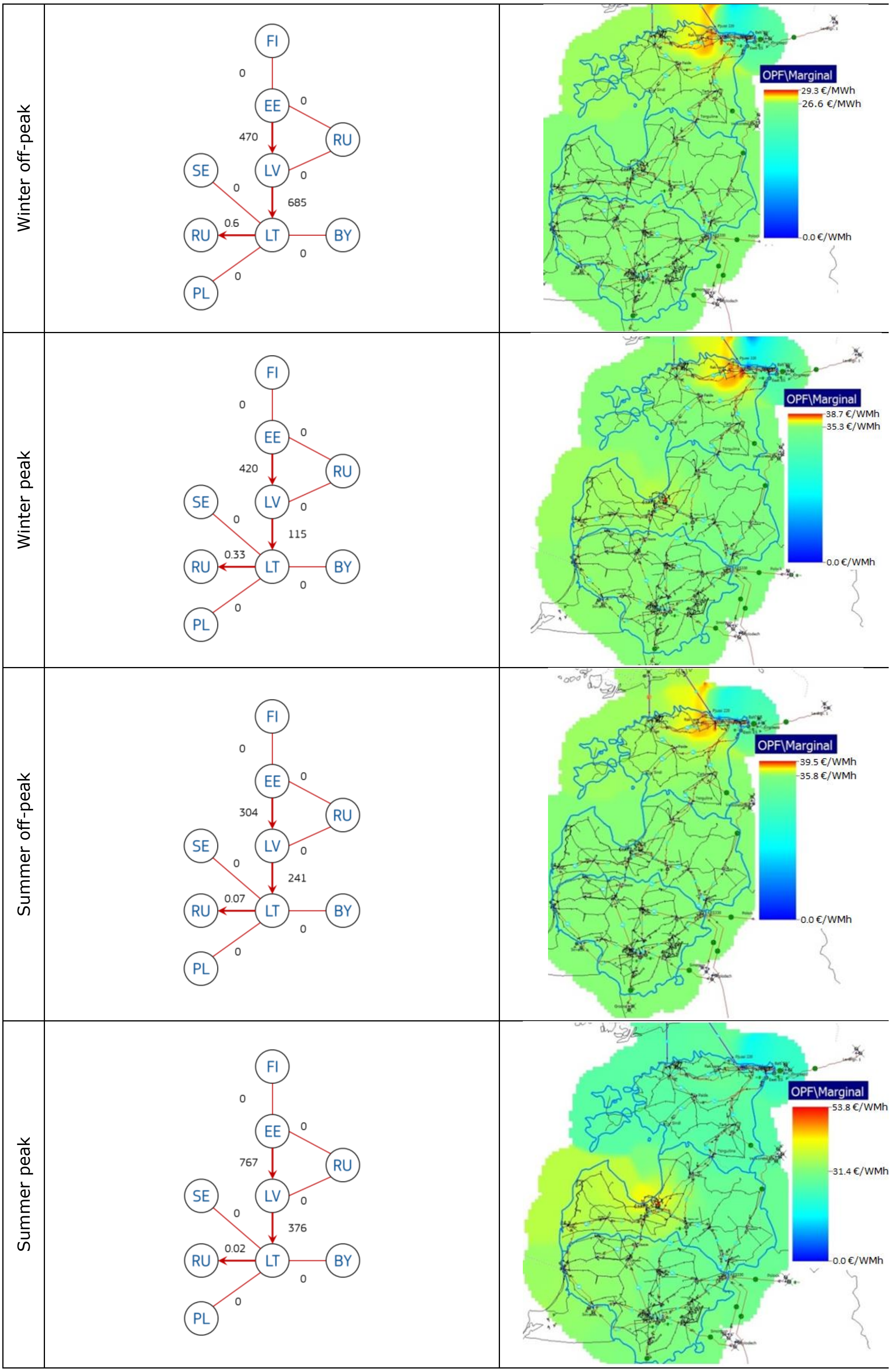


Figure 54 - Energy independence levels and system marginal prices of the Baltic States

For the winter off-peak case, Estonia and Latvia provided 470 MW and 215 MW export to Lithuania as in the previous cases. Due to congestions in the north-eastern part of Estonia, the locational marginal cost varied slightly in that area. The buses' marginal cost ranged from 0 €/MWh to 29.3 €/MWh and the average marginal cost was 26.6 €/MWh with a standard deviation of 1.7 €/MWh.

For the winter peak case, Estonia exported 306 MW and 115 MW to Latvia and Lithuania, respectively. Like in the previous case, congestions can be observed in a small area near Riga and in the northeast of Estonia as well. The buses' marginal cost ranged from 0 €/MWh to 38.7 €/MWh, while the average marginal cost was 35.3 €/MWh with a standard deviation of 2.2 €/MWh. Like in the previous cases, the hydro pump station was discharging the water for generating electricity; therefore, it effectively lowered the costs for the peak hours.

For the summer off-peak case, Estonia exported 63 MW and 241 MW to Latvia and Lithuania, respectively. The buses' marginal cost ranged from 0 €/MWh to 39.5 €/MWh and the average marginal cost was 35.8 €/MWh with a standard deviation of 2.2 €/MWh. The system marginal cost were even higher than that in the winter peak case, due to the fact that the hydro units in Latvia were switched off to reserve water for the peak hours.

The summer peak case presented huge exports from Estonia (767MW) to Latvia (391MW) and Lithuania (376MW). Congestions can be detected at the southeast of Riga, while the north-eastern part of Estonia provided counter-flows to alleviate the congestion. Therefore, cost increases occurred in the western part of Latvia and Lithuania, whereas Estonia maintained comparatively low costs. The buses' marginal cost ranged from 0 €/MWh to 53.8 €/MWh, with an average marginal cost of 31.4 €/MWh and a standard deviation of 4.4 €/MWh.

6.2.3.5. 2020 SCENARIO OPERATIONAL SECURITY ANALYSIS

Figure 55 shows the system's physical features for the four extended models for 2020. These were also used as the starting points to perform n-1 steady state contingency analysis in the latter part of this sub-section.

Under the four simulated configurations of load and generation, network system voltages were in quite acceptable ranges during normal operation. System congestions can be mainly spotted in the northeast of Estonia and the vicinities of Riga. As in the four reference models, the voltage of Estonia was generally lower than in the other two countries. Based on the operational points listed in Figure 55 for the four extended models of 2020, contingency sets containing each single transmission line, transformer and generator in the models were applied for steady state security analysis. Table 16 lists the most severe contingencies (intentionally anonymised) according to several criteria described in the first row.

As can be gleaned from Table 16, the system's operational security levels were not as severe as for the reference cases. No element able to cause system-wide disturbance has been detected.

For the winter off-peak case, the most serious contingency was the loss of the component in contingency 3, which created the highest number of violations and the highest overloads in the contingency set. The failure of the component in contingency 11 caused the lowest system voltage.

For the winter peak case the worst contingency was the failure of component in contingency 3, which not only caused 2.8 times higher power flows than the maximum allowed over other lines, but also heavily lowered the system voltage. The loss of the component in contingency 2 brought the largest number of violations; however, the consequences were not as serious as what followed the fault of the component in contingency 3.

For the summer off-peak case the system displayed the highest resilience among all the four cases. The most severe case was the tripping of the component in contingency 14, which is able bring about 39% of excess flows.

For the summer peak case the most severe contingency was the loss of the component in contingency 3, which caused about 69% excessive current over a line in the system.

The most critical components in the system were still the component in contingency 3 (which resulted in system overload in most cases if it had fault). Of course, there are other network components that are critical as well. For the sake of spaces, we do not list them.

Table 16 - Most critical contingencies according to multiple criteria for the four extended models in 2020

Cases	Contingency Record	Most severe consequence	Violations	Unserved loads (MW)	Disconnected generation (MW)	Maximum overload (%)	Minimum Voltage (p.u.)
Winter off-peak	contingency 12	Disc. Gen.	0	0	12.17	-	-
	contingency 11	Low voltage	5	0	0	-	0.848
	contingency 3	Overload	32	0	0	167.3	0.872
	contingency 5	Uns. loads	0	15.42	0	-	-
Winter peak	contingency 3	Num. violations	60	0	0	129	0.826
	contingency 3	Overload	13	0	0	279	0.755
	contingency 11	Low voltage	9	0	0	-	0.702
	contingency 5	Uns. loads	0	24.59	0	-	-
	contingency 13	Disc. Gen.	0	0	19.33	-	-
Summer off-peak	contingency 14	Overload	2	0	0	139	-
	contingency 15	Overload	3	0	0	132.1	-
	contingency 3	Disc. Gen.	0	0	12.11	-	-
	contingency 5	Uns. loads	0	13.17	0	-	-
Summer peak	contingency 3	Overload	34	0	0	168.6	0.865
	contingency 13	Disc. Gen.	0	0	18.89	-	-
	contingency 11	Low voltage	6	0	0	-	0.826
	contingency 5	Uns. loads	0	21.48	0	-	-

A common goal of the Baltic States is greater energy supply independence through the diversification of primary energy sources. Due to the countries' limited ability to act on their own – especially on large, costly projects – joint efforts are needed.

The present study gives an insight in the ability of the Baltic States to operate their electricity systems independently of the neighbouring countries. The results show that by 2020 and 2030 the dependency of the Baltic States on the outside generation resources is fairly low, following current electricity system development trends.

This study represented a first building block contributing to the process of scientific support to policy decision making within the BEMIP platform. The preliminary techno-economic analyses in the current study pave the ground for more detailed market analyses, expected to be conducted with tailored market/power dispatch tools to support electricity system development policies and initiatives in the Baltic States. As an example, re-dispatch actions could be considered after each congestion event to assess the costs of such security actions on the integrated power system under study.

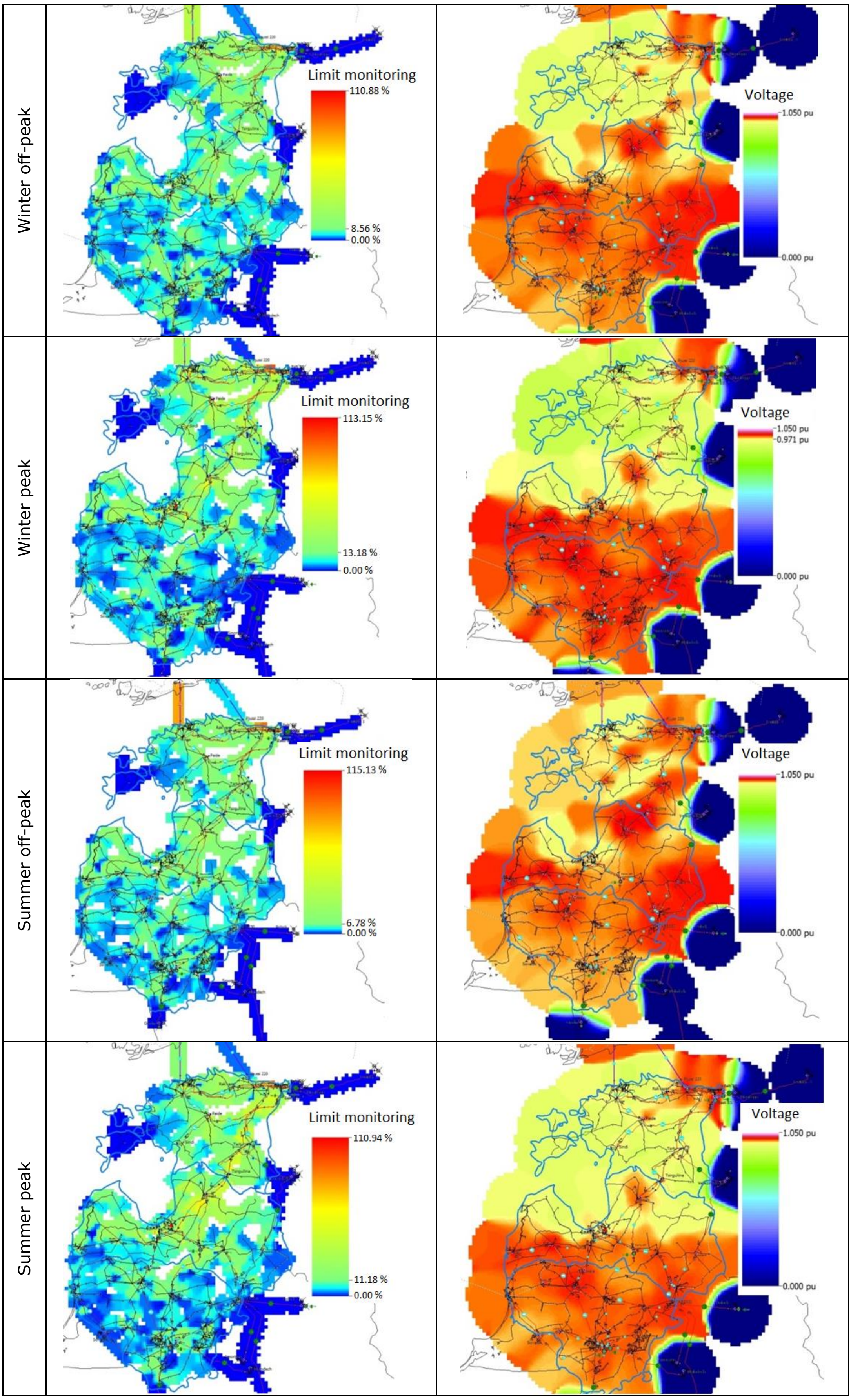


Figure 55 - System performances for the four cases in 2020 under normal operation

The final ideal target would be to deploy an integrated modelling approach by combining static power system/grid models with dynamic power system/grid models and power market/system models, as called for by the Baltic stakeholders, hence addressing more electricity security properties - from stability to adequacy - in support of the policy decision making.

Different geo-political options and scenarios for higher security of energy supply and energy independence are in the process of being defined and assessed with the relevant actors, particularly in the BEMIP context.

6.3. A MULTI-STAKEHOLDER PLATFORM FOR REAL TIME SECURITY ANALYSES

6.3.1. MOTIVATION

As discussed in Chapter 3 and Chapter 4, a number of challenges, especially linked to the increased variability of generation sources, call for in-depth analyses with increased time/spatial granularity and ideally closer to real time studies. This on its turn poses several challenges: the computational resources required are remarkable, operators cannot risk putting the real system in danger to test what-if options, and realistic models cannot be built without sharing high-quality confidential data.

Performing much needed security analyses with increased time/spatial granularity and ideally closer to real time, poses several challenges: the computational resources required are remarkable, operators cannot risk putting the real system in danger to test what-if options, and realistic models cannot be built without sharing high-quality confidential data. The time hence seems ripe for taking advantage of real time simulators and co-simulation arrangements to address these challenges: sharing parallel, distributed resources through co-simulation can dramatically increase the computational capability, allowing developing detailed, full-scale models of the power grids; real time simulators could be coupled to real time operations providing a safe test-bed where mimicking real system conditions; sensitive models/data could be stored in geographically distributed and protected servers and only input/output data for the modelling interfaces would be shared [133][157].

6.3.2. MODEL AND SCENARIOS

As demonstration case, four laboratories in Germany (RWTH Aachen), Italy (PoliTO, Torino and JRC, Ispra) and the Netherlands (JRC, Petten) were interconnected to develop a multi-site real time co-simulation platform for power system analysis.

As a test case, the multi-site real-time lab performed a co-simulation of an interconnected transmission and distribution system: the transmission system was simulated in a first lab (Aachen, Germany) and the Medium Voltage distribution grid in a second lab (Turin, Italy). The behaviour of the prosumers on the distribution grid was captured by a dedicated consumer/prosumer behaviour model in a third lab (Petten, Netherlands). In addition a monitoring system, in a fourth lab (Ispra, Italy), analysed data and simulation results through a cloud system.

Figure 56 gives an overview of the 4 interconnected laboratories sharing resources over the cloud and their interfaces for the demonstration of an EU Federation of labs. The connection architecture is based on a server-cloud where local computers or machines interact across laboratories through dedicated VPNs (Virtual Private Network) over the GEANT network (the pan-European research and education network that interconnects Europe’s National Research and Education Networks [295]). The local VPN servers bridge the local simulation platform at each site and the cloud ensuring security of data exchange while offering a better coordination of the communication and the multi-point connection.

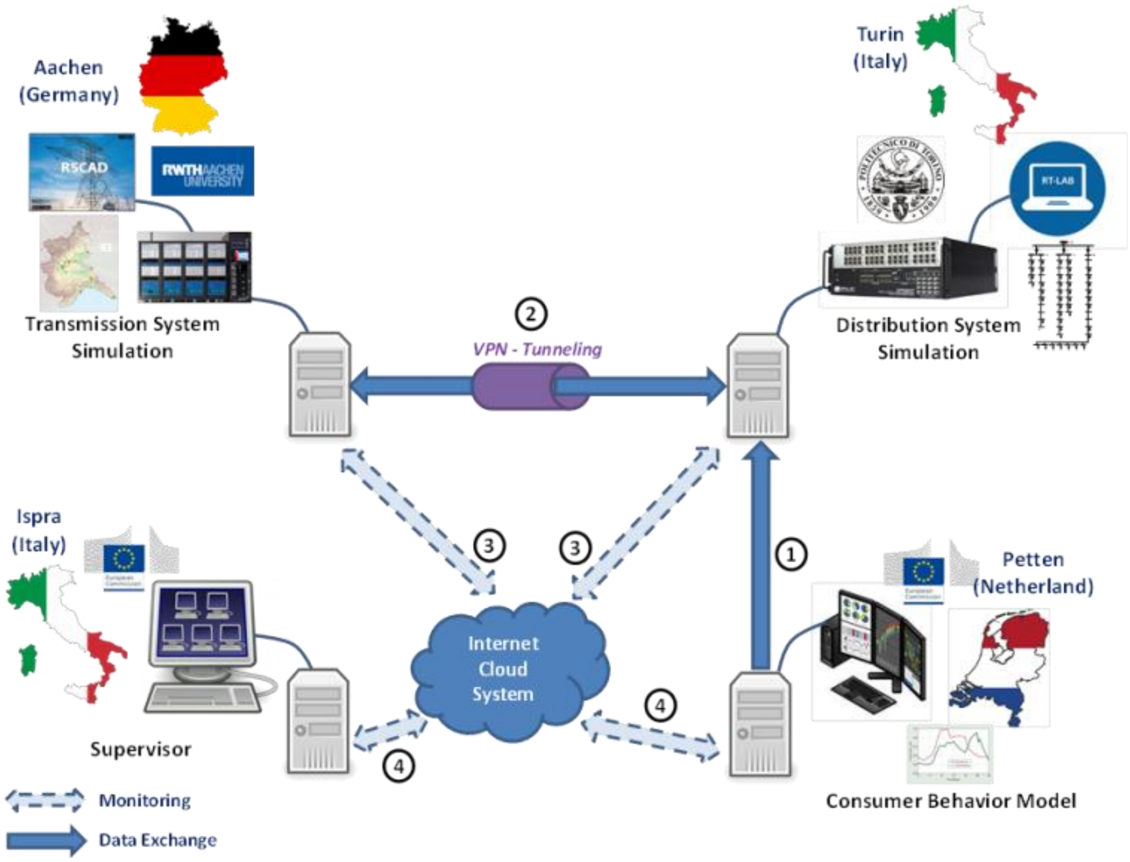


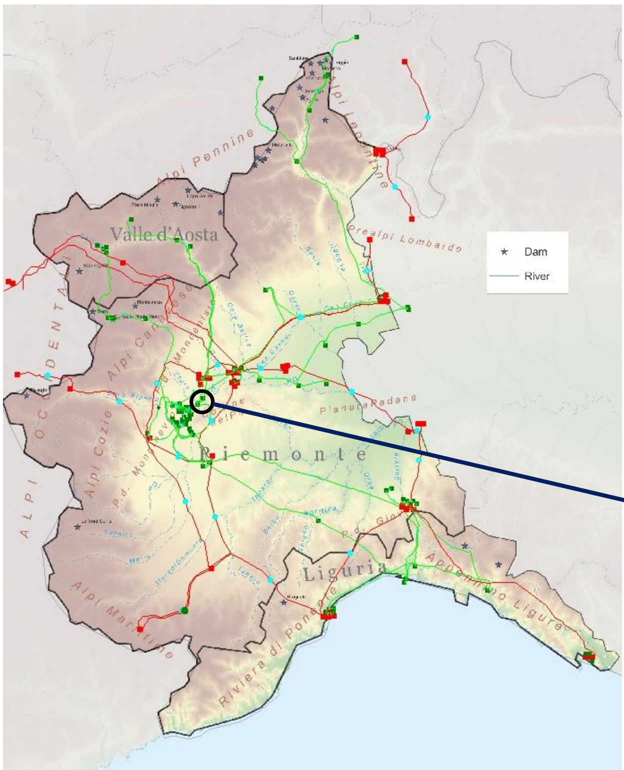
Figure 56 - Real-time laboratories interconnection architecture

The specific scenario designed for the demo was an interconnected transmission and distribution grid (see Figure 57); however, alternative scenarios (e.g. the interconnection of several transmission systems over a regional or a pan-European scale) can be envisaged and implemented.

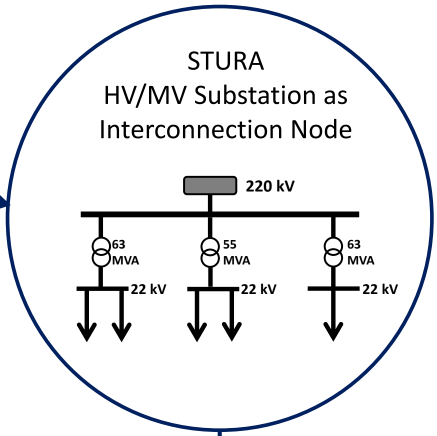
The whole transmission layer consisted of 86 buses, 110 lines, 20 generators, and 54 equivalent loads for the Medium Voltage (MV) substations. This HV grid was interconnected with the MV network (modelled in a different lab) through one of its HV/MV substations, where the data exchange between the two real-time simulators takes place. Electric current values measured in the distribution network at its HV/MV main bus were transferred to the transmission model through an interface (fundamental frequency phasor or dynamic phasors with higher components) to update an equivalent current controlled source representing the whole distribution system on the HV model. Similarly, the voltage quantity on the HV side is measured and sent to the distribution side to update the values of an equivalent voltage controlled source.

The portion of the MV network consisted of a primary substation with three 22 kV busbars, each of which was fed by a 220/22 kV transformer and 5 MV lines departing from the HV/MV substation. For the simulation of the transmission system adopted for this study, 4 RTDS racks were utilised since a single RTDS rack can simulate of a power system with up to 66 nodes (22 buses). The real-time platform RT-LAB developed by OPAL-RT was used for simulating the distribution system (12 cores operating at 3.46 GHz).

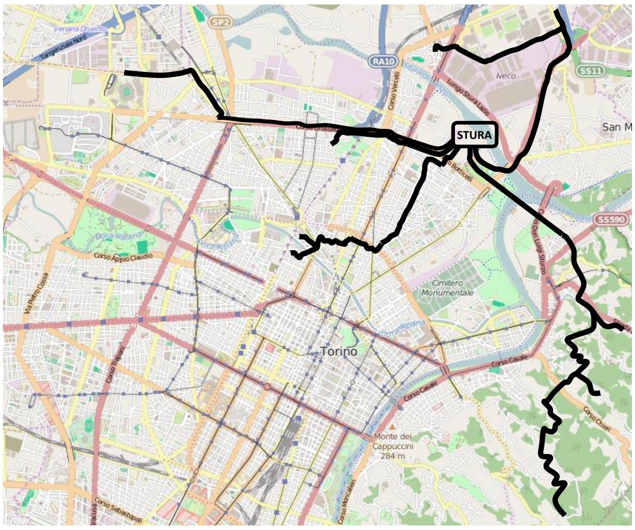
TRANSMISSION SYSTEM 380 – 220 KV PIEDMONT REGION - ITALY

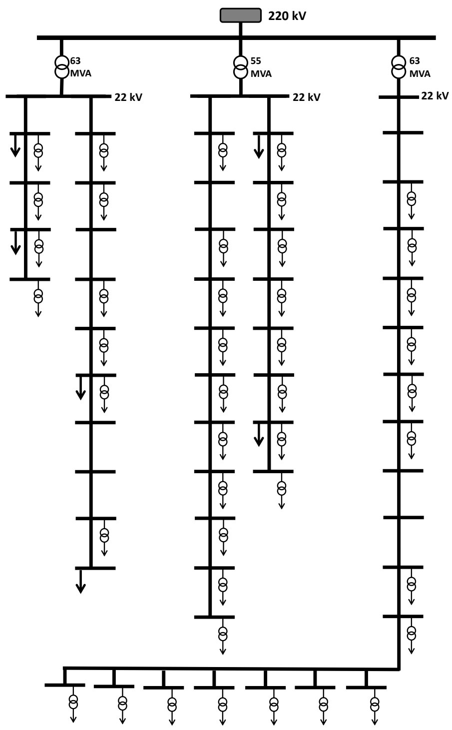


Number of 380 kV buses	26
Number of 220 kV buses	60
Number of generators	20
Number of lines	110
Number of loads	54
Maximum total active capacity [MW]	10291
Maximum total reactive capacity [Mvar]	4338



DISTRIBUTION SYSTEM 22 KV – A PORTION OF TURIN CITY - ITALY





Number of MV buses	49
Number of lines	49
Total length of lines [km]	38.54
Number of MV/LV transformers	40
Number of LV customers	742 mono phase, 8293 three phase
Total contractual load [MW]	37.056
Number of equivalent LV models	40
Number of MV customers	6

Figure 57 - Transmission-distribution network scheme for real-time simulation

On October 29th 2015, at Ispra (Italy), at the inauguration of the European Interoperability Centre for Electric Vehicles and Smart Grids, the demo of the real-time integrated co-simulation platform was presented.

A power system scenario with high penetration of distributed generation was under study (see Figure 58 and Figure 59). The system was assessed in a summer day around 5 pm, when demand was high, since people are back from work and a large number of EVs are plugged in for charging.

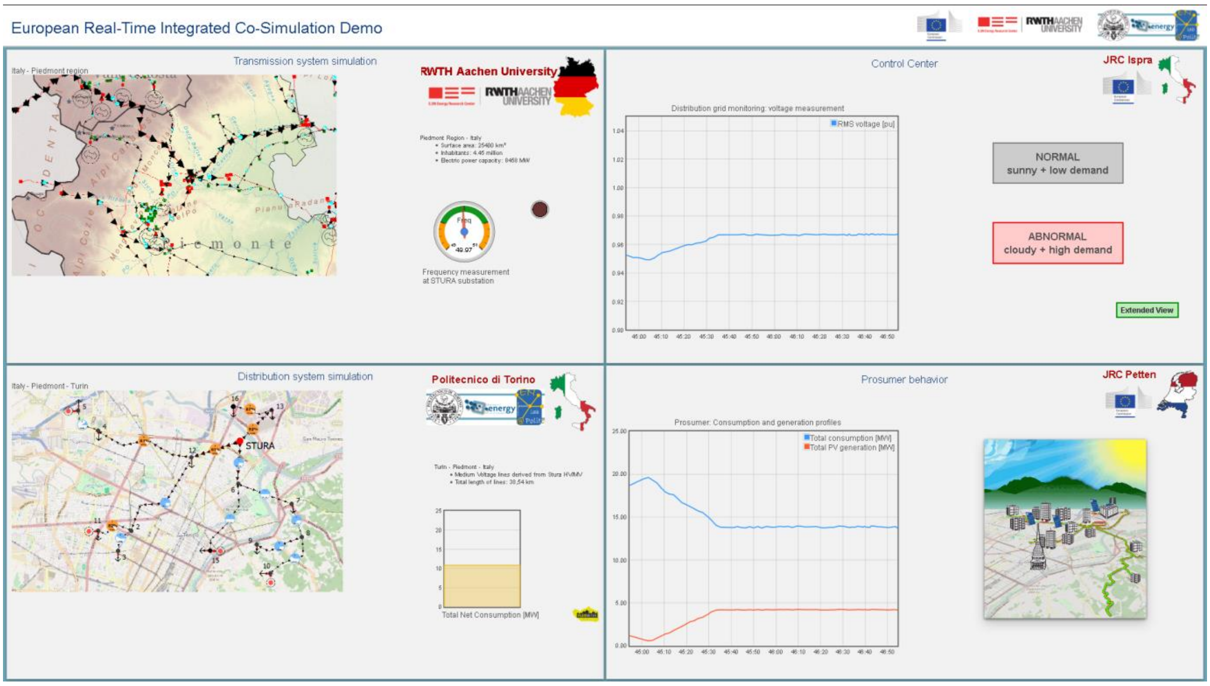


Figure 58 - Demo graphical interface - conceptual layout

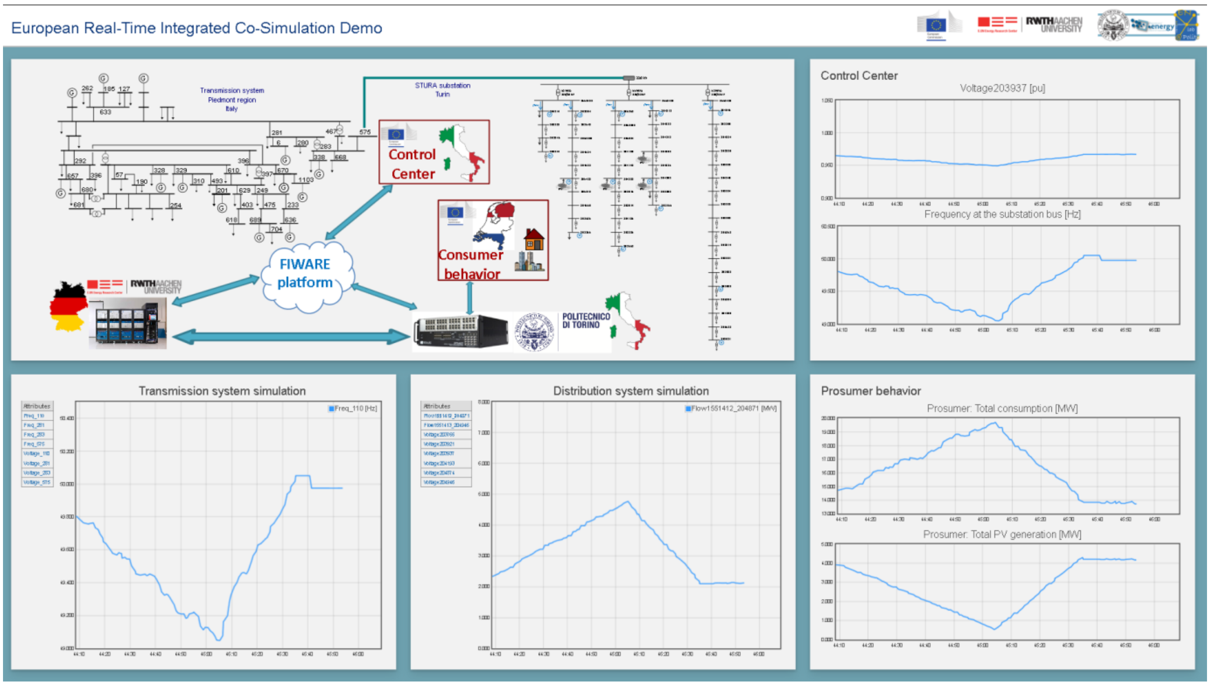


Figure 59 - Demo graphical interface - technical layout

At a certain point, local PV generation was assumed drastically dropping due to an abrupt change in weather conditions from sunny to cloudy. These resulted in a sudden increase in power absorption from the substation connected to the transmission system. Consequent voltage drops in the distribution system and frequency perturbations in the transmission grid were observed when performing co-simulation. From the technical layout, two measurements were selected and shown in Figure 60 and Figure 61.

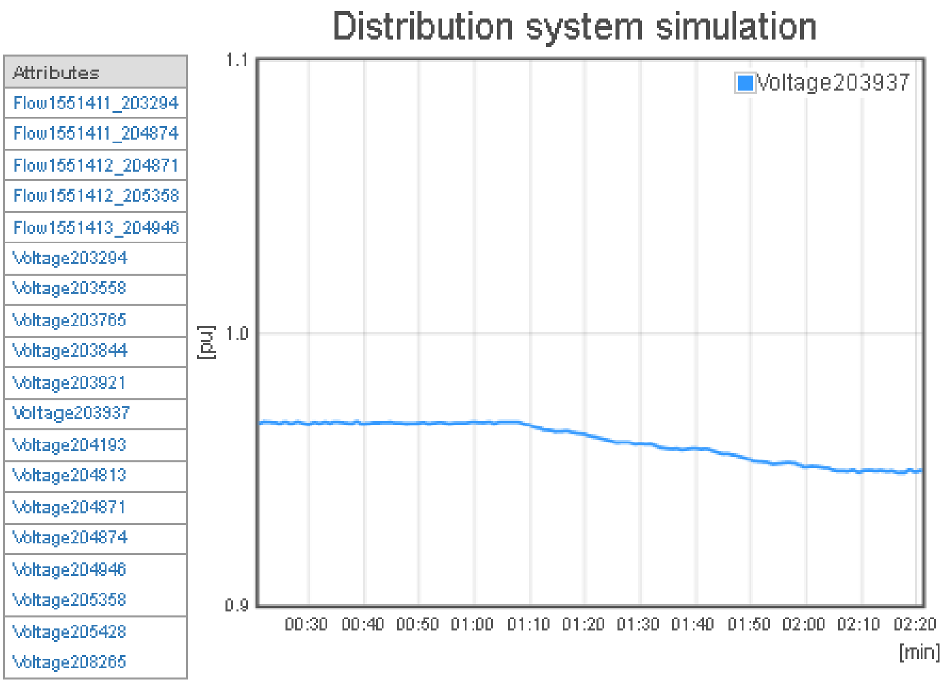


Figure 60 - Distribution system real time monitoring - measured voltage drop at a feeder's end

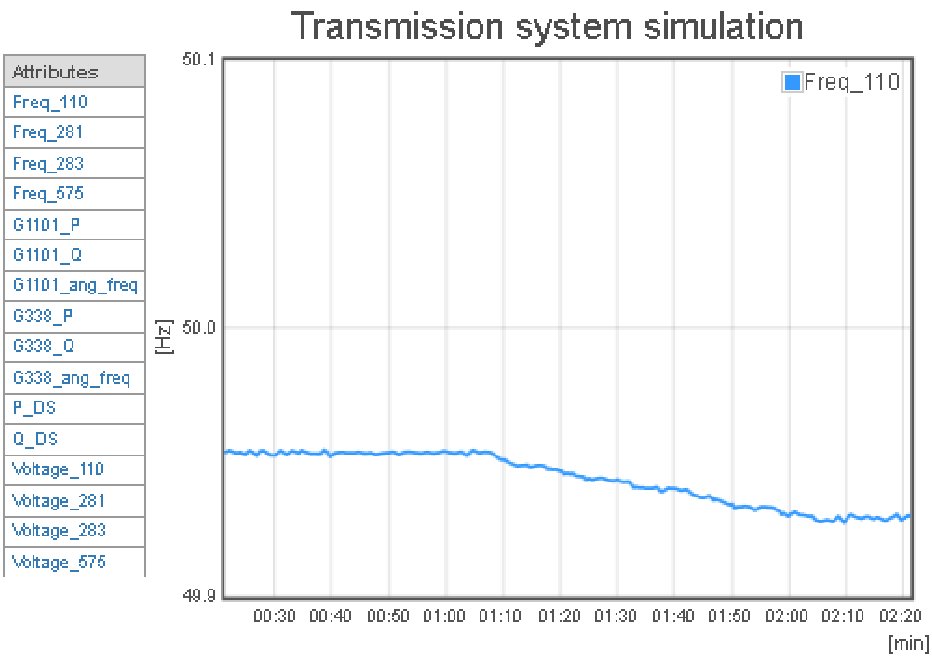


Figure 61 - Transmission system real time monitoring - measured frequency drop

Figure 60 indicates voltage drop at the end of the longest MV feeder in the distribution system caused by the described event. Web application provides a customized set of selections of different measurements for monitoring, like flow of lines, voltage at some buses. One measurement selected from transmission system is

shown in Figure 61. It refers to frequency measurement at one of the neighbouring buses to the substation where distribution system is connected. Although the rotating inertia of the large conventional generators mitigates fluctuations in the studied scenario, high penetration of PV generators could eventually have a significant impact on the transmission grid.

6.3.3. ANALYSIS AND DISCUSSION

This proof of concept demonstrated the potentials of a federation of laboratories located in different member states and sharing hardware/software capabilities and resources across the EU. Regarding power system analysis, the integrated laboratory enables real time, detailed modelling of power grids via remote access to software and equipment based on multiple locations. Such an infrastructure can support remote testing of devices, enhance simulation capabilities for large multi-scale and multi-layer systems, while also achieving soft-sharing of expertise in a large knowledge-based virtual environment. Particularly interesting, sensitive data, models and algorithms may be kept confidential as only boundary variables among individual simulations need to be shared.

As recalled throughout this work, even though each stakeholder has its own competence area (e.g. each EU Member State is in charge of their security of supply assessment and safeguard), a key to improve energy security relies on a greater cooperation and a more collective approach, since national choices have cross-EU security and market implications. This kind of simulation platform might support all actors who need to take decisions in the power system area. This includes national and local authorities, regulators, network operators and utilities, manufacturers, consumers/prosumers.

7. CONCLUSIONS

The electricity sector, globally and, particularly in the EU, over the last years has been facing fascinating developments and critical challenges, linked to the techno-economic trends and socio-political dynamics.

A lively political, academic, regulatory and industrial debate is ongoing on to how keep the electricity system secure - put it simply, on how to keep the lights on - in the face of several trends and issues including: the integration beyond the connection of massive quantities of variable renewable energy resources, the changing role of less variable nuclear and fossil fuel-fired power plants, the growing attention on peaking and cycling capabilities of all sort of generators, the promises kept by pumped hydro and the hopes attached to several types/sizes of storage devices, the convergence needs of market dynamics/transactions and grid operations/flows, the readiness of distributed generation to support market/system operations, the disruptive potential of demand side response at all system levels, the tensions or synergies between the super grid evolution vs. the smart grid (r)evolution.

An increasingly diversified number of actors is involved and affected by the energy system transition and has a stake in the energy and electricity security issues.

Policy decision makers, at all levels, are confronted with crucial questions: is there an optimal combination of security of supply, affordability and sustainability objectives to be sought or shall some ingredient be sacrificed to the benefit of the others? Is there an optimal level of security of supply and an optimal mix of different generation technologies to be pursued? What are the overall more (environmentally and financially) sustainable solutions? To what extent the lack of competitiveness of traditional generation technologies is linked to wrong market design or intended system transition? Will energy-only markets always be able to deliver the right generation capacity mix? Shall domestic generation be promoted or interconnection capacity further exploited? To what extent emerging resources - storage and demand response in particular - shall be considered to replace/supplement large scale generators in adequacy/flexibility services provision? Is a smoother load profile something which shall be attained with an optimal mix of different balancing technologies? When and how security related investment shall be carried out? Who should take action and who should bear the costs?

System operator as well face critical questions - trickling down at more technical/economic level from the policy ones illustrated above - when operating, designing and planning the electricity system.

Policy decision makers and operators, although perhaps the most visible ones, are not the only decision makers and stakeholders: regulators, market operators, generation companies, asset owners, aggregators, manufacturers, consumers, emerging actors (offering new services and/or proposing new business models), all play a role in the security of supply problem definition and solution.

A structured platform for cooperative governance and decision making is therefore crucial to ensure that electricity security objectives and actions are discussed, agreed and implemented in a transparent, effective and fair way.

This work aimed to contribute at bringing together scientific advice with policy making in the power system security field. This was mainly done via: a revised taxonomy of energy and electricity security properties, a critical review of models and methodologies for electricity security analyses and a novel decision-analytic framework for electricity security. Aspects for the practical application of the framework at national (Italian), regional (Baltic) and EU scales were analysed and discussed.

What presented in this thesis reflects activities on energy security, systems and markets conducted at the JRC, the in-house scientific branch of the European Commission, providing scientific advice to the EU policy making. Additional relevant work was not included due to time, resource and sensitivity constraints. As an

example, the assessment of electricity security at distribution system level would deserve an entire separate report. The interested reader can consult the website of the JRC Smart Electricity Systems research group [282] to get abreast with the progress in integrating power system models in the regional dimension (e.g. in the Baltic, Cyprus and other regions), mapping emerging smart grid solutions and functionalities across Europe (releasing the periodic outlook of smart grid projects), testing the interoperability of electric vehicles and smart grids (in cooperation with US twin laboratories) etc.

As amply discussed, currently, each EU Member State is still largely in charge of their own energy security assessment and safeguard; however, as pointed out by the European Commission, a key to improve energy security relies on a greater cooperation and a more collective approach, since national choices and decisions over energy markets, sources and infrastructure have immediate cross-EU security implications. The electrons do not stop at the border of two power systems and sometimes it might be overall more secure to let them flow.

Drawing also upon my experience across these years (first in power transmission industry/regulation and then in the energy research/policy areas), I would supplement such recommendation for increased cooperation among EU governments with an advice for growing interaction and collaboration among all those parties - having formal/informal roles, defined stakes or specific competences and skills - who could help creating the knowledge and the understanding required to address the energy security conundrum in the evolving EU's energy system.

The transition to a new energy and power system is beyond the scope of any single person or entity and is at the same responsibility of all the stakeholders. Only by promptly reaching a certain level of collective knowledge and collaboration society can benefit from - someone argues can successfully survive - these changes.

Finally, a few comments about the quotes I have used in this thesis.

"The universal utilization of water power and its long-distance transmission will supply every household with cheap power and will dispense with the necessity of burning fuel. The struggle for existence being lessened, there should be development along ideal rather than material lines" (Nikola Tesla) I like it twice. Firstly for the long term vision on renewables and grid infrastructure coupling; on a personal note I sense that the centralised vs. decentralised competition will not have an absolute winner: the future I feel is not transmission vs distribution but transmission with distribution; the second reason concerns the ideal lines, and it is also linked to the second quote: *"Energy is the golden thread that connects economic growth, social equity, and environmental sustainability" (Ban Ki-moon)*: hopefully emerging energy solutions would increasingly be enablers of equity, fairness and inclusion and ensure wider access to affordable, reliable, sustainable energy.

In *"Smart grids could become Europe's shale gas" (Maroš Šefčovič)* I do read a promise for economic growth through innovation as well as a warning: smart grids may well suffer the same ups and downs of shale gas owing to geo-political and socio-economic dynamics. Nevertheless, electricity security is also a lot about emergence triggering changes: *"People only accept change in necessity and see necessity only in crisis" (Jean Monnet).*

The difficult and much needed interaction between science and policy I think is effectively described by *"The purpose of computing is insight, not numbers" (Richard Hamming)* and *"Politics is more difficult than physics" (Albert Einstein).* Only finding the right way to communicate and apply it, scientific knowledge might be an effective policy support instrument: *"Knowing is not enough. We must apply" (Leonardo Da Vinci).*

A. REFERENCES

[1] United Nations Development Programme

[2] European Commission, COM(2015) 80, Energy Union Package, A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy

[3] European Commission, COM(2014) 15 final, A policy framework for climate and energy in the period from 2020 to 2030

[4] E. Bompard, G. Fulli, M. Ardelean, M. Masera, "It's a Bird, It's a Plane, It's a...Supergrid!: Evolution, Opportunities, and Critical Issues for Pan-European Transmission", IEEE Power and Energy Magazine, vol. 12, no. 2, pp. 40-50, March-April 2014

[5] IEA, World Energy Outlook 2015

[6] European Commission, EU energy statistical pocketbook

[7] European Commission, Eurostat, Energy statistics

[8] World Bank, Open Data

[9] European Commission, COM(2014) 330 final, European Energy Security Strategy

[10] European Commission, SWD(2014) 330 final/3, In-depth study of European Energy Security, accompanying COM(2014) 330 final

[11] European Commission, Eurostat, Europe 2020 indicators - climate change and energy

[12] European Commission, COM(2015) 574 final, Assessment of the progress made by Member States towards the national energy efficiency targets for 2020 and towards the implementation of the Energy Efficiency Directive 2012/27/EU

[13] European Commission, Heating and Cooling

[14] European Commission, COM (2014) 21/2, Energy prices and costs report

[15] European Commission, COM(2015) 293 final, Renewable energy progress report

[16] European Commission, Climate and energy priorities for Europe: the way forward, Presentation to the European Council 2014

[17] ACER/CEER 2013 Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets, issued in 2014

[18] ACER/CEER 2012 Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets, issued in 2013

[19] B. Caldecott, J. McDaniels, "Stranded generation assets: Implications for European capacity mechanisms, energy markets and climate policy", SSEE, University of Oxford, Working Paper, 2014

[20] ENTSO-E, ENTSO-E at a glance, 2014

[21] Eurelectric, Power Distribution in Europe Facts & Figures, 2013

[22] European Commission, Energy Strategy

[23] ENTSO-E, Statistical Factsheet 2014, released in 2015

[24] European Commission, EU energy trends to 2030, 2009-2010

[25] European Commission, EU energy, transport and GHG emissions, Trends to 2050, Reference scenario 2013, 2013

[26] European Commission, COM(2011) 885 final, Energy Roadmap 2050

[27] European Commission, SWP, SEC(2011)1565/1, Energy Roadmap 2050 Impact Assessment Part 1 including Part I of Annex 1 'Scenarios - assumptions and results'

[28] European Commission, SWP, SEC(2011)1565/1, Energy Roadmap 2050 Impact Assessment Part 2 including Part II of Annex 1 'Scenarios - assumptions and results' and Annex 2 'Report on Stakeholders scenarios'

[29] European Commission, E3MLab/ICCS at National Technical University of Athens, PRIMES Model 2013-2014

[30] IEA, World Energy Model

[31] IEA, Gas Medium-Term Market Report 2015, Market Trends and Projections to 2020

[32] European Commission, COM(2015) 572 final, State of the Energy Union

[33] European Commission, COM(2015) 572 final, State of the Energy Union, Annex 1: Updated roadmap for the Energy Union

[34] European Commission, COM(2015) 572 final, State of the Energy Union, Annex 2: Guidance to Member States on national energy and climate plans as part of the energy union governance

[35] Energy Research Institute, China 2050 High Renewable Energy Penetration Scenario And Roadmap Study, 2015

[36] European Commission, C(2015) 8052 final Annex 1 to Commission Delegated Regulation amending Regulation (EU) 347/2013 as regards the Union list of projects of common interest

[37] European Commission, SWD(2015) 247 final accompanying the Commission Delegated Regulation amending Regulation (EU) 347/2013 as regards the Union list of projects of common interest

[38] European Commission, COM(2015) 82 final, Achieving the 10% electricity interconnection target, Making Europe's electricity grid fit for 2020

[39] ENTSO-E, Ten Year Network Development Plan, 2014

[40] European Commission, Baltic Energy Market Interconnection Plan

[41] North Seas Countries' Offshore Grid Initiative

[42] European Commission, High Level Group on Interconnections for South-West Europe

[43] G. Strbac, N. Hatziargyriou, J. P. Lopes, C. Moreira, A. Dimeas, D. Papadaskalopoulos, "Microgrids: Enhancing the Resilience of the European Megagrid", IEEE Power and Energy Magazine, vol. 13, no. 3, pp. 35-43, May-June 2015

[44] C.-F. Covrig, M. Ardelean, J. Vasiljevska, A. Mengolini, G. Fulli, E. Amoiralis, "Smart Grid Projects Outlook 2014", JRC Scientific and Policy Report, 2014

[45] I. Colak, S. Sagiroglu, G. Fulli, M. Yesilbudak, C.-F. Covrig, "A survey on the critical issues in smart grid technologies, Renewable and Sustainable Energy Reviews", Volume 54, February 2016, Pages 396-405

[46] EPRI, "The integrated grid - realizing the full value of central and distributed energy resources", 2014

[47] Treaty of Lisbon amending the Treaty on European Union and the Treaty establishing the European Community, signed at Lisbon, 13 December 2007 and ratified on 13 November 2009

[48] United Nations Conference on Climate Change, 2015 COP21, Paris Climate Conference

[49] European Parliament and Council of the European Union, Directive 2001/80/EC on the limitation of emissions of certain pollutants into the air from large combustion plants

[50] European Parliament and Council of the European Union, Directive 2005/89/EC concerning measures to safeguard security of electricity supply and infrastructure investment

[51] Council of the European Union Directive 2008/114/EC on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection

[52] European Commission, COM(2006) 786 final, European Programme for Critical Infrastructure Protection

[53] European Commission, SWD(2013) 318 final, new approach to the European Programme for Critical Infrastructure Protection - Making European Critical Infrastructures more secure

[54] European Parliament and Council of the European Union, Directive 2009/28/EC on the promotion of the use of energy from renewable sources

[55] European Parliament and Council of the European Union, Directive 2009/72/EC concerning common rules for the internal market in electricity

[56] European Parliament and Council of the European Union, Regulation 714/2009 on conditions for access to the network for cross-border exchanges in electricity

[57] European Commission, Regulation (EU) 2015/1222 establishing a guideline on capacity allocation and congestion management

[58] European Commission, Implementing Decision (EU) 2015/1960 on the establishment of the annual priority lists for 2016 for the development of network codes and guidelines

[59] ENTSO-E, Network Code Operational Security

[60] ENTSO-E, Network Code Operational Planning & Scheduling

[61] ENTSO-E, Network Code Load Frequency Control & Reserves

[62] ENTSO-E, Network Code Emergency and Restoration

[63] ENTSO-E, Network Code (Binding Guideline) Capacity Allocation & Congestion Management

[64] ENTSO-E, Network Code on Forward Capacity Allocation

[65] ENTSO-E, Network Code Electricity Balancing

[66] European Parliament and Council of the European Union, Regulation 347/2013 on guidelines for trans-European energy infrastructure

[67] European Parliament and Council of the European Union, Regulation (EU) 1316/2013 establishing the Connecting Europe Facility

[68] COoRdination of Electricity System Operators (Coreso), Brussels (BE)

[69] Transmission System Operator Security Cooperation (TSC), Munich (DE)

[70] Security Coordination Centre (SCC), Belgrade (RS)

[71] ENTSO-E, ENTSO-E Vision the Energy Union ahead

[72] ENTSO-E, Regional Security Coordination Service Providers

[73] European Commission, Ecorys, ECN, DNV GL, Options for future European Electricity System Operation, 2015

[74] ENTSO-E, Response to the EC study "Options for Future European Electricity System Operation", 2015

[75] European Commission, COM(2015) 340 final, Launching the public consultation process on a new energy market design

[76] ENTSO-E website

[77] Pentalateral Energy Forum (PLEF), Second Political Declaration, 8 June 2015

[78] ENTSO-E, Target Methodology for Adequacy Assessment, Updated Version after Consultation, 14 October 2014

[79] ENTSO-E, Scenario Outlook & Adequacy Forecast 2015

[80] ENTSO-E, Guidelines for Cost Benefit Analysis of Grid Development Projects, 2015

[81] ENTSO-E, Regional Investment Plan Continental South West, 2014

[82] ENTSO-E, Regional Investment Plan Continental Central South, 2014

[83] ENTSO-E, Regional Investment Plan Continental South East, 2014

[84] ENTSO-E, Regional Investment Plan Continental Central East, 2014

[85] ENTSO-E, Regional Investment Plan Baltic Sea, 2014

[86] ENTSO-E, Regional Investment Plan North Sea, 2014

[87] IEA, Re-powering Markets - Market design and regulation during the transition to low-carbon power systems, 2016

[88] J. Watson, "Is the move toward energy security at odds with a low-carbon society?" In: Giddens A, Latham S, Liddle R, editors. Building a low-carbon future the politics of climate change. London, Policy Network, 2009

[89] J.P. Deane, F. Gracceva, A. Chiodi, M. Gargiulo, B. P.Ó. Gallachóir, "Assessing power system security. A framework and a multi model approach", International Journal of Electrical Power & Energy Systems, Volume 73, December 2015, pp. 283-297

[90] B. Han, E. Bompard, F. Profumo, Q. Xia, "Paths Toward Smart Energy: A Framework for Comparison of the EU and China Energy Policy," in IEEE Transactions on Sustainable Energy, vol. 5, no. 2, pp. 423-433, April 2014

[91] CEN-CENELEC-ETSI Smart Grid Coordination Group, Smart Grid Reference Architecture, 2012

[92] C. Winzer, "Conceptualizing energy security", Energy Policy, Volume 46, July 2012, Pages 36-48

[93] A. Månsson, B. Johansson, L. J. Nilsson, "Assessing energy security: An overview of commonly used methodologies", Energy, Volume 73, 14 August 2014, pp. 1-14

[94] International Electrotechnical Vocabulary (IEV numbers 191-02-05, 191-21-01, 191-21-03, 617-01-01, 617-01-03)

[95] E. Bompard, T. Huang, Y. Wu, M. Cremenescu, "Classification and trend analysis of threats origins to the security of power systems", International Journal of Electrical Power & Energy Systems, Volume 50, September 2013, pp. 50-64

[96] IEC/TR 62351-12 Resilience and security recommendations for power systems with Distributed Energy Resources (DER) cyber-physical system

[97] CNN, U.S. investigators find proof of cyberattack on Ukraine power grid

[98] The Guardian, Power cuts, travel chaos and more flood warnings issued as Storm Frank hits UK

[99] IEA, Saving electricity in a hurry, 2005

[100] UNEP, Impacts of summer 2003 heat wave in Europe

[101] F. Gracceva, P. Zeniewski, "A systemic approach to assessing energy security in a low-carbon EU energy system", Applied Energy, Volume 123, 15 June 2014, pp. 335-348

[102] K. Thywissen, "Core terminology of disaster reduction: A comparative glossary". In: J. Birkmann, editor, "Measuring vulnerability to natural hazards: Towards disaster resilient societies", United Nations University Press, Hong Kong 2006

[103] S. Hosseini, K. Barker, J.E. Ramirez-Marquez, "A Review of Definitions and Measures of System Resilience", Reliability Engineering and System Safety, 2016, 145, pp. 47-61

[104] J. Johansson, H. Hassel, E. Zio, "Reliability and vulnerability analyses of critical infrastructures: Comparing two approaches in the context of power systems", Reliability Engineering & System Safety, Volume 120, December 2013, pp. 27-38

[105] A. Estebsari, "Models and tools to support the decision making for electricity security", Doctoral dissertation, 2015, Politecnico di Torino, Torino

[106] Å. J. Holmgren, "Quantitative vulnerability analysis of electric power networks", Doctoral Thesis, Royal institute of Technology, Stockholm, 2006

[107] President’s Commission on Critical Infrastructure Protection, "Critical foundations - Protecting America's infrastructures", The Report of the President’s Commission on Critical Infrastructure Protection, 1997

[108] United Nations International Strategy for Disaster reduction (UN/ISDR), "Living with Risk: A global review of disaster reduction initiatives", United Nations publications, Geneva, 2004

[109] W. Kröger, E. Zio, "Vulnerable Systems", Springer, London 2011

[110] T. Aven, "On some recent definitions and analysis frameworks for risk, vulnerability, and resilience", Risk Analysis, 2011 Apr; 31(4):515-22

[111] L. Cuadra, S. Salcedo-Sanz, J. Del Ser, S. Jiménez-Fernández, Z.W. Geem, "A Critical Review of Robustness in Power Grids Using Complex Networks Concepts", Energies 2015, 8(9), 9211-9265

[112] ACER, Opinion 05/2013 on Capacity markets

[113] European Commission, Energy: New market design to pave the way for a new deal for consumers, Fact Sheet, 15 July 2015

[114] European Commission, Eurostat, EU Electricity production, consumption and market overview website, May 2015

[115] European Commission, COM(2012) 586 final, the EU approach to resilience: learning from food security crises

[116] European Commission, DG Migration and Home Affairs, Critical Infrastructure

[117] NERC, Glossary of Terms Used in NERC Reliability Standards, 2016

[118] NERC, Definition of Adequate Level of Reliability, 2007

[119] NERC, Severe Impact Resilience: Considerations and Recommendations Severe Impact Resilience Task Force Board of Trustees Accepted: May 9, 2012

[120] NERC, Special Report: Potential Reliability Impacts of Emerging Flexible Resources, 2010

[121] ENTSO-E, Continental Europe Operation Handbook

[122] IEA, Making the energy sector more resilient to climate change, 2015

[123] IEA, Learning from the blackout, 2005

[124] IEA, Harnessing variable renewables: a guide to the balancing challenge, 2011

[125] IEA, The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems, 2014

[126] European Commission, SWD (2015) 243 final, Monitoring progress towards the Energy Union objectives - Concept and first analysis of key indicators, accompanying COM(2015) 572 final

[127] European Commission, C(2013) 7243, Delivering the internal electricity market and making the most of public intervention

[128] European Commission, SWD(2013) 438 final, Generation Adequacy in the internal electricity market - guidance on public interventions - Accompanying the Communication C(2013) 7243

[129] European Commission, SWD(2013) 442 final, Incorporating demand side flexibility, in particular demand response, in electricity markets - Accompanying the Communication C(2013) 7243

[130] European Commission, Climate and energy priorities for Europe: the way forward, 2014, presentation

[131] European Commission, Consultation paper on generation adequacy, capacity mechanisms and the internal market in electricity, 2012

[132] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, V. Vittal, "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions" IEEE Transactions on Power Systems, vol. 19, no. 3, pp. 1387-1401, Aug. 2004

[133] Z. Huang, J. Nieplocha, "Transforming power grid operations via high performance computing", Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, Pittsburgh, PA, 2008, pp. 1-8

[134] IEEE Power Systems Engineering Committee, "Reliability Indices for Use in Bulk Power Supply Adequacy Evaluation," in IEEE Transactions on Power Apparatus and Systems, vol. PAS-97, no. 4, pp. 1097-1103, July 1978

[135] EPRI, Metrics for Quantifying Flexibility in Power System Planning, 2014

[136] J. Cochran, M. Miller, O. Zinaman, M. Milligan, D. Arent, B. Palmintier, M. O'Malley, S. Mueller, E. Lannoye, A. Tuohy, B. Kujala, M. Sommer, H, Holttinen, J. Kiviluoma, S.K. Soonee, "Flexibility in 21st Century Power Systems", 21st Century Power Partnership, 2014

[137] IEEE PES Computer and Analytical Methods Subcommittee, Task Force on Understanding, Prediction, Mitigation and Restoration of Cascading Failures, "Vulnerability Assessment for Cascading Failures in Electric Power Systems", 2009

[138] National Academies, 2012. Disaster Resilience: A National Imperative. Washington, DC: The National Academies Press

[139] CEER, Security of Electricity Supply Report 2004

[140] Eurelectric, Security of Electricity Supply - Roles, responsibilities and experiences within the EU, 2006

[141] Eurelectric, "Flexibility and Aggregation requirements for their integration in the market", 2014

[142] Smart Grid Task Force, Expert Group 3, "Regulatory Recommendations for the deployment of flexibility", 2015

[143] ACER, Opinion 08/2014 on the National Ten-Year Electricity Network Development Plans

[144] ACER, Opinion 01/2015 on the ENTSO-E draft Ten-Year Network Development Plan 2014

[145] ACER, Regional Initiatives status review report 2014

[146] ACER, Regional Initiatives status review report 2012

[147] CEER, Assessment of electricity generation adequacy in European countries, 2014

[148] CEER, Benchmarking Report 5.2 on the Continuity of Electricity Supply, 2015

[149] ENTSO-E response to ACER's European Energy Regulation - A Bridge to 2025, 2014

[150] ENTSO-E, Where the Energy Union starts: regions - Vision Package, 2015

[151] A. L'Abbate, G. Fulli, F. Starr, S.D. Peteves, "Distributed Power Generation in Europe: technical issues for further integration", JRC Scientific and Technical Report, 2007

[152] I. Colak, G. Fulli, S. Bayhan, S. Chondrogiannis, S. Demirbas, "Critical aspects of wind energy systems in smart grid applications", Renewable and Sustainable Energy Reviews, Volume 52, December 2015, Pages 155-171

[153] I. Hidalgo González, P. Ruiz Castello, A. Sgobbi, W. Nijs, S. Quoilin, A. Zucker, C. Thiel, "Addressing flexibility in energy system models", JRC Science and Policy Report, 2015

[154] MIT, The future of electric grids, 2011

[155] J. Cochran et al, "Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience. Golden, CO: National Renewable Energy Laboratory", NREL, 2012

[156] J. Cochran, M. Miller, et al. "Market Evolution: Wholesale Electricity Market Design for 21st Century Power Systems", NREL, 2013

[157] National Academies of Sciences, Engineering, and Medicine. 2016. Analytic Research Foundations for the Next-Generation Electric Grid. Washington, DC: The National Academies Press

[158] C. Brancucci Martínez-Anido, "Electricity Without Borders. The need for cross-border transmission investment in Europe", Next Generation Infrastructures Foundation, 2013, PhD Thesis TU Delft

[159] M. Panteli, P. Mancarella, "The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience", IEEE Power and Energy Magazine, vol. 13, no. 3, pp. 58-66, May-June 2015

[160] D.N.P. Murthy, E.Y. Rodin, "A comparative evaluation of books on mathematical modelling", Mathematical Modelling, Volume 9, Issue 1, 1987, pp. 17-28

[161] A. Zucker, T. Hinchliffe; A. Spisto, "Assessing Storage Value in Electricity Markets", JRC Scientific and Policy Report, 2013

[162] D. Möst, D. Keles, "A survey of stochastic modelling approaches for liberalised electricity markets", European Journal of Operational Research, Volume 207, Issue 2, 1 December 2010, pp. 543-556

[163] J. McCalley, S. Asgarpoor, L. Bertling, R. Billinion, H. Chao, J. Chen, J. Endrenyi, R. Fletcher, A. Ford, C. Grigg, G. Hamoud, D. Logan, A. P. Meliopoulos, M. Ni, N. Rau, L. Salvaderi, M. Schilling, Y. Schlumberger, A. Schneider, C. Singh, "Probabilistic security assessment for power system operations", Power Engineering Society General Meeting, 2004. IEEE, 2004, pp. 212-220 Vol.1

[164] A.M. Foley, B.P. Ó Gallachóir, J. Hur, R. Baldick, E.J. McKeogh, "A strategic review of electricity systems models", Energy, Volume 35, Issue 12, December 2010, pp. 4522-4530

[165] M. Aien, A. Hajebrahimi, M. Fotuhi-Firuzabad, "A comprehensive review on uncertainty modeling techniques in power system studies", Renewable and Sustainable Energy Reviews, Volume 57, May 2016, pp. 1077-1089

[166] E. Bompard, C. Gao, M. Masera, R. Napoli, A. Russo, A. Stefanin, F. Xue, Approaches to the security analysis of power systems: defence strategies against malicious threats, JRC Report, 2007

[167] R. Allan, R. Billinton, "Probabilistic assessment of power systems", Proceedings of the IEEE, vol. 88, no. 2, pp. 140-162, Feb. 2000

[168] A. M. Rei, M. T. Schilling, A. C. G. Melo, "Monte Carlo Simulation and Contingency Enumeration in Bulk Power Systems Reliability Assessment", PMAPS 2006. International Conference on Probabilistic Methods Applied to Power Systems, Stockholm, 2006, pp. 1-6

[169] E. Bompard, D. Wu, E. Pons, SESAME Project, "Complex Science Application to the Analysis of Power Systems Vulnerabilities", 2012

[170] M. Rosas-Casals, S. Bologna, E. Bompard, G. D'Agostino, W. Ellens, G.A. Pagani, A. Scala, T. Verma, "Knowing power grids and understanding complexity science", International Journal of Critical Infrastcrutures, 2015, Vol. 11, pp. 4–14

[171] P. Söderholm, "Fuel flexibility in the West European power sector", Resources Policy, Volume 26, Issue 3, September 2000, pp. 157-170

[172] M. Ventosa, Á. Baíllo, A. Ramos, M. Rivier, "Electricity market modeling trends", Energy Policy, Volume 33, Issue 7, May 2005, pp. 897-913

[173] ENTSO-E, Initial Dynamic Model Instruction manual V6.1, 2015

[174] A. Semerow, S. Höhn, M. Luther, W. Sattinger, H. Abildgaard, A. Diaz Garcia, G. Giannuzzi, "Dynamic Study Model for the interconnected power system of Continental Europe in different simulation tools", PowerTech, 2015 IEEE Eindhoven, Eindhoven, 2015, pp. 1-6

[175] FP7 PEGASE (Pan European Grid Advanced Simulation And State Estimation) Project

[176] D. Fabozzi, A. S. Chieh, B. Haut, T. Van Cutsem, "Accelerated and Localized Newton Schemes for Faster Dynamic Simulation of Large Power Systems", IEEE Transactions on Power Systems, vol. 28, no. 4, pp. 4936-4947, Nov. 2013

[177] OPAL-RT Technologies, OPAL-RT

[178] RTDS Technologies, RTDS simulator

[179] M.B. Cain, R.P. O'Neill, A. Castillo, History of Optimal Power flows and Formulations, FERC, 2012

[180] Tractebel Engineering, EUROSTAG

[181] Siemens, PSS Netomac

[182] Mathworks, MatLab Power system simulation and optimization

[183] Mathworks, Simulink

[184] Neplan AG, NEPLAN

[185] Siemens, PSSE

[186] DigSILENT, PowerFactory

[187] Powerworld Corporation, Powerworld

[188] GE, PSLF

[189] Sintef, EMPS - SAMNETT and SAMLAST programs

[190] CESI, SPIRA

[191] LCG Consulting, Energyonline UPLAN

[192] RTE, ANTARES

[193] Energy Exemplar, Plexos

[194] J. Kiviluoma, E. Rinne, N. Helistö, M. Azevedo, VTT, Modelling framework for power systems, 2014

[195] WILMAR

[196] Balmorel

[197] Powersim Software AS, Powersim

[198] CESI, PROMED

[199] ABB, PROMOD

[200] L.D. Costa, F.A. Rodrigues, G. Travieso, P.R. Villas Boas, "Characterization of complex networks: A survey of measurements", Advances in Physics, Volume 56, pages 167 - 242, Issue 1, 2007

[201] B. Bollobás, Random Graphs, Cambridge: Cambridge University Press, 2001

[202] D. J. Watts, S. H. Strogatz, "Collective dynamics of 'small-world' networks", Nature 393, 440-442, 1998

[203] A.L. Barabasi, R. Albert, "Emergence of scaling in random networks", Science, Vol. 286, Issue 5439, pp. 509-512, 1999

[204] P. Hines, E. Cotilla-Sanchez, S. Blumsack, "Do topological model provide good information about electricity infrastructure vulnerability?", Chaos, 2010, 20(033122), pp. 1–5

[205] dena Grid Study I, "Summary of the Essential Results of the Study Planning of the Grid Integration of Wind Energy in Germany Onshore and Offshore up to the Year 2020", 2005

[206] dena Grid Study II, "Integration of Renewable Energy Sources in the German Power Supply System from 2015 – 2020 with an Outlook to 2025", 2010

[207] P. Denholm, M. Hand, Grid Flexibility and Storage Required to Achieve Very High Penetration of Variable Renewable Electricity, Energy Policy, vol. 39, pp. 1817-1830, 2011

[208] J.P. Deane,G. Drayton, B. Ó. Gallachóir, "The impact of sub-hourly modelling in power systems with significant levels of renewable generation", Applied Energy, Volume 113, January 2014, pp. 152-158

[209] R. A. Duncan, G. E. Seymore, D. L. Streiffert, D. J. Engberg, "Optimal Hydrothermal Coordination for Multiple Reservoir River Systems," in IEEE Transactions on Power Apparatus and Systems, vol. PAS-104, no. 5, pp. 1154-1159, May 1985

[210] A. Merlin, P. Sandrin, "A new method for unit commitment at Electricité de France," IEEE Trans. Power App. Syst., vol. PAS-102, pp. 1218–1225, May 1983

[211] A. Rudolf, R. Bayrleithner, "A genetic algorithm for solving the unit commitment problem of a hydro-thermal power system", IEEE Transactions on Power Systems, vol. 14, no. 4, pp. 1460-1468, Nov 1999

[212] P. Palchak, P. Denholm, Impact of Generator Flexibility on Electric System Costs and Integration of Renewable Energy, NREL, 2014

[213] IAEA, Wien Automatic System Planning (WASP) Package

[214] NREL, Regional Energy Deployment System (ReEDS)

[215] T. Mai, E. Drury, K. Eurek, N. Bodington, A. Lopez, A. Perry, "Resource Planning Model: An Integrated Resource Planning and Dispatch Tool for Regional Electric Systems," NREL, 2013

[216] T. Mai, M. M. Hand, S. F. Baldwin, R. H. Wiser, G. L. Brinkman, P. Denholm, D. J. Arent, G. Porro, D. Sandor, D. J. Hostick, M. Milligan, E. A. De Meo, M. Bazilian, "Renewable Electricity Futures for the United States," IEEE Transactions on Sustainable Energy, vol. 5, no 2, pp 372-278, 2014

[217] G. Migliavacca, M. Benini, M. Gallanti, E. Bompard, E. Carpaneto, G. Ciwei, "LREMS: a long term electricity market simulator based on game theory", Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES, Atlanta, GA, 2006, pp. 1333-1340

[218] IEA-ETSAP, TIMES

[219] IEA-ETSAP, MARKAL

[220] M. Chaudry, P. Ekins, K. Ramachandran, A. Shakoor, J. Skea,G. Strbac, X. Wang, J. Whitaker, UKERC, Building a resilient UK energy system, Research Report, 2011

[221] A. Kanudia, R. Gerboni, R. Loulou, M. Gargiulo, M. Labriet, E. Lavagno, R. De Miglio, L. Schranz, G. Tosato, Modelling EU-GCC energy systems and trade corridors: Long term sustainable, clean and secure scenarios, International Journal of Energy Sector Management, 7:2 , 243-268, 2013

[222] R. Baldick et al., "Initial review of methods for cascading failure analysis in electric power transmission systems" IEEE PES CAMS task force on understanding, prediction, mitigation and restoration of cascading failures, Power and Energy Society General Meeting, 2008 IEEE, Pittsburgh, PA, 2008, pp. 1-8

[223] I. Dobson, B. A. Carreras, D. E. Newman, "A loading dependent model of probabilistic cascading failure", Probability in the Engineering and Informational Sciences, vol. 19, pp. 15-32, Jan. 2005

[224] Restructured Transmission Reliability Evaluation for Large-Scale Systems (TRELSS), 2001, EPRI

[225] I. Dobson, B. A. Carreras, V. E. Lynch, and D. E. Newman, "An initial model for complex dynamics in electric power system blackouts," 34th Hawaii Intl. Conference on System Sciences, HI, pp. 710–718, Jan. 2001

[226] B. A. Carreras, V. E. Lynch, I. Dobson, D.E. Newman, "Critical points and transitions in an electric power transmission model for cascading failure blackouts," Chaos, vol. 12, pp. 985-994, Dec. 2002

[227] H. Ren, I. Dobson, B. A. Carreras, "Long-Term Effect of the n-1 Criterion on Cascading Line Outages in an Evolving Power Transmission Grid," IEEE Transactions on Power Systems, vol. 23, no. 3, pp. 1217-1225, Aug. 2008

[228] B.A. Carreras, D.E. Newman, I. Dobson, N.S. Degala, "Validating OPA with WECC Data", System Sciences (HICSS), 2013 46th Hawaii International Conference on, Wailea, HI, USA, 2013, pp. 2197-2204

[229] S. Mei, F. He, X. Zhang, S. Wu and G. Wang, "An Improved OPA Model and Blackout Risk Assessment", IEEE Transactions on Power Systems, vol. 24, no. 2, pp. 814-823, May 2009

[230] S. Mei, Yadana, X. Weng, A. Xue, "Blackout model based on OPF and its self-organized criticality", Proceedings of the 25th Chinese Control Conference, pp. 7–11, 2006

[231] S. Mei, Y. Ni, G. Wang, S. Wu, "A Study of Self-Organized Criticality of Power System Under Cascading Failures Based on AC-OPF With Voltage Stability Margin", IEEE Transactions on Power Systems, vol. 23, no. 4, pp. 1719-1726, Nov. 2008

[232] J. Qi, S. Mei, F. Liu, "Blackout model considering slow process", IEEE Transactions on Power Systems, vol. 28, pp. 3274–3282, Aug. 2013

[233] M. A. Rios, D. S. Kirschen, D. Jawayeera, D. P. Nedic, R. N. Allan, "Value of security: modeling time-dependent phenomena and weather conditions", IEEE Transactions on Power Systems, vol. 17, pp. 543–548, Aug. 2002

[234] D. S. Kirschen, D. Jawayeera, D. P. Nedic, R. N. Allan, "A probabilistic indicator of system stress", IEEE Transactions on Power Systems, vol. 19, pp. 1650–1657, Aug. 2004

[235] D.P. Nedic, I. Dobson, D.S. Kirschen, B.A. Carreras, V.E. Lynch, "Criticality in a cascading failure blackout model", International Journal of Electrical Power & Energy Systems, Volume 28, Issue 9, November 2006, pp. 627-633

[236] E. Bompard, A. Estebsari, T. Huang, G. Fulli, "A framework for analyzing cascading failure in large interconnected power systems: A post-contingency evolution simulator", International Journal of Electrical Power & Energy Systems, Volume 81, October 2016, pp. 12-21

[237] R. Hu, W. Hu, Z. Chen, "Review of power system stability with high wind power penetration," Industrial Electronics Society, IECON 2015 - 41st Annual Conference of the IEEE, Yokohama, 2015, pp. 003539-003544

[238] H.F. Latorre, M. Ghandhari, "Improvement of power system stability by using a VSC-HVdc", International Journal of Electrical Power & Energy Systems, Volume 33, Issue 2, February 2011, Pages 332-339

[239] J. O'Sullivan, A. Rogers, D. Flynn, P. Smith, A. Mullane, M. O'Malley, "Studying the Maximum Instantaneous Non-Synchronous Generation in an Island System - Frequency Stability Challenges in Ireland," IEEE Transactions on Power Systems, vol. 29, no. 6, pp. 2943-2951, Nov. 2014

[240] H. Holttinen et al., "The Flexibility Workout: Managing Variable Resources and Assessing the Need for Power System Modification", IEEE Power and Energy Magazine, vol. 11, no. 6, pp. 53-62, Nov.-Dec. 2013

[241] E. Lannoye, D. Flynn, M. O'Malley, "Evaluation of Power System Flexibility", IEEE Transactions on Power Systems, vol. 27, no. 2, pp. 922-931, May 2012

[242] A. Capasso, A. Cervone, M.C. Falvo, R. Lamedica, G.M. Giannuzzi, R. Zaottini, "Bulk indices for transmission grids flexibility assessment in electricity market: A real application", International Journal of Electrical Power & Energy Systems, Volume 56, March 2014, Pages 332-339

[243] J. Ma, V. Silva, R. Belhomme, D. S. Kirschen and L. F. Ochoa, "Evaluating and planning flexibility in sustainable power systems", Power and Energy Society General Meeting (PES), 2013 IEEE, Vancouver, BC, 2013, pp. 1-11

[244] N. Schlag, A. Olson, E. Hart, A. Mileva, R. Jones (E3), C. Brancucci Martinez-Anido, B.-M. Hodge, G. Brinkman, A. Florita, D. Biagioni (NREL), Western Interconnection Flexibility Assessment, 2015

[245] G. Strbac, M. Aunedi, D. Pudjianto, P. Djapic, F. Teng, A. Sturt, D. Jackravut, R. Sansom, V. Yufit, N. Brandon, "Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future", Report for Carbon Trust, 2012

[246] European Commission, DG Competition, Capacity Mechanisms Working Group, High level comparison of capacity mechanism models and compatibility with state aid guidelines, 30 June 2015

[247] European Commission, DG Competition, Capacity Mechanisms Working Group, High level comparison of capacity mechanism models and compatibility with state aid guidelines, 22 January 2015

[248] C. Brancucci Martínez-Anido, M. Vandenbergh, L. de Vries, C. Alecu, A. Purvins, G. Fulli, T. Huld, Medium-term demand for European cross-border electricity transmission capacity, Energy Policy, Volume 61, October 2013, pp. 207-222

[249] Pentalateral Energy Forum Support Group 2, Generation Adequacy Assessment, 2015

[250] D.G. Dessavre, J.E. Ramirez-Marquez, K. Barker, "Multidimensional approach to complex system resilience analysis", Reliability Engineering & System Safety, Volume 149, May 2016, pp. 34-43

[251] K. Barker, J. Emmanuel Ramirez-Marquez, C.M. Rocco, "Resilience-based network component importance measures", Reliability Engineering & System Safety, Volume 117, September 2013, pp. 89-97

[252] H. Baroud, K. Barker, J.E. Ramirez-Marquez, C.M. Rocco, "Inherent costs and interdependent impacts of infrastructure network resilience", Risk Analysis. 2015 Apr; 35(4):642-6

[253] J.C. Jansen, A.J. Seebregts, "Long-term energy services security: What is it and how can it be measured and valued?", Energy Policy, Volume 38, Issue 4, April 2010, pp. 1654-1664

[254] Y.Y. Haimes, K. Crowther, B.M. Horowitz, "Homeland security preparedness: balancing protection with resilience in emergent systems", Systems Engineering, 2008, Volume 11, number 4, pp. 287-308

[255] G. O'Brien, A. Hope, "Localism and energy: Negotiating approaches to embedding resilience in energy systems", Energy Policy, Volume 38, Issue 12, December 2010, pp. 7550-7558

[256] M. Ouyang, L. Dueñas-Osorio, X. Min, "A three-stage resilience analysis framework for urban infrastructure systems", Structural Safety, Volumes 36–37, May–July 2012, pp. 23-31

[257] Cardiff University, CGEN (Combined gas and electricity network) model

[258] J.M. Yusta, G.J. Correa, R. Lacal-Arantegui, "Methodologies and applications for critical infrastructure protection: state-of-the-art", Energy Policy, Volume 39, Issue 10, October 2011, pp. 6100-6119

[259] S. M. Rinaldi, J. P. Peerenboom, T. K. Kelly, "Identifying, understanding, and analyzing critical infrastructure interdependencies", IEEE Control Systems, vol. 21, no. 6, pp. 11-25, Dec 2001

[260] P. Crucitti, V. Latora, M. Marchiori, "A topological analysis of the Italian electric power grid", Physica, 2004 A: Statistical Mechanics and its Applications, Volume 338, Issues 1–2, 1 July 2004, Pages 92-97

[261] B.A. Carreras, V. Lynch, I. Dobson, D.E. Newman, Complex dynamics of blackouts in power transmission systems, Chaos, 14, 643-652, 2004

[262] E. Bompard, R. Napoli, F. Xue, "Analysis of structural vulnerabilities in power transmission grids", International Journal of Critical Infrastructure Protection, Volume 2, Issues 1–2, May 2009, pp. 5-12

[263] D. Sarewitz, Jr R. Pielke, M. Keykhah, Vulnerability and risk: some thoughts from a political and policy perspective, Risk Analysis, 2003

[264] J. Vasiljevska, A. Lucas, "Establishment Of The Second List Of Union Projects Of Common Interest", JRC Science for policy Report, 2015

[265] K. Forsten et al., "The integrated grid - A Benefit-Cost Framework", EPRI, 2015

[266] V. Giordano, J. Vasiljevska, S. Vitiello, "Evaluation of Smart Grid projects within the Smart Grid Task Force Expert Group 4", JRC Scientific and Policy Report, 2013

[267] P. Kaderjak, K. Andzsans-Balogh et al., Security of energy supply in Central and South-East Europe. Budapest, REKK, 2011

[268] C. Brancucci Martínez-Anido, R. Bolado, L. De Vries, G. Fulli, M. Vandenbergh, M. Masera, "European power grid reliability indicators, what do they really tell?", Electric Power Systems Research, Volume 90, September 2012, pp. 79-84

[269] K. Poncelet, E. Delarue, J. Duerinck, D. Six, W. D'haeseleer, "The Importance of Integrating the Variability of Renewables in Long-term Energy Planning Models", KU Leuven, 2014

[270] K. Poncelet, A. van Stiphout, E. Delarue, W. D'haeseleer and G. Deconinck, "A Clustered Unit Commitment Problem Formulation for Integration in Investment Planning Models, KU Leuven" 2014

[271] L. Buzna, L. Issacharoff, D. Helbing, "The evolution of the topology of high-voltage electricity networks, International Journal of Critical Infrastructures", 2009, 5(1/2), pp. 72-85

[272] G.A. Pagani, M. Aiello, "The Power Grid as a complex network: A survey", Physica A: Statistical Mechanics and its Applications, Volume 392, Issue 11, 1 June 2013, pp. 2688-2700

[273] S.F. Railsback, V. Grimm, "Agent-based and Individual-based Modeling: A Practical Introduction"

[274] D. E. Newman, B. Nkei, B. A. Carreras, I. Dobson, V. E. Lynch and P. Gradney, "Risk Assessment in Complex Interacting Infrastructure Systems", System Sciences, 2005. HICSS '05. Proceedings of the 38th Annual Hawaii International Conference on, 2005, pp. 63c-63c

[275] S.V. Buldyrev, R. Parshani, G. Paul, H.E. Stanley, S. Havlin, "Catastrophic cascade of failures in interdependent networks", Nature, 464, pp. 1025-1028, 2010

[276] J. Portugal-Pereira, M. Esteban, "Implications of paradigm shift in Japan's electricity security of supply: A multi-dimensional indicator assessment", Applied Energy, Volume 123, 15 June 2014, Pages 424-434

[277] T. Koljonen, A. Lehtilä, "Modelling pathways to a low carbon economy for Finland," in Informing Energy and Climate Policies Using Energy Systems Models, Springer, 2015

[278] P. Rodilla, C. Batlle, "Security of electricity supply at the generation level: Problem analysis", Energy Policy, Volume 40, January 2012, Pages 177-185.

[279] V. Šucha, "Five Plus Four Ingredients for the Effective Use of Science to Inform Policy", World Science Forum, Budapest, Hungary, 6 November 2015

[280] R.H.E.M. Koppelaar, J. Keirstead, N. Shah, J. Woods, "A review of policy analysis purpose and capabilities of electricity system models", Renewable and Sustainable Energy Reviews, Volume 59, June 2016, pp. 1531-1544

[281] A. Henriot, J.M. Glachant, "Capacity remuneration mechanisms in the European market: now but how?", EUI Working Paper, 2014

[282] JRC Smart Electricity Systems and Interoperability research group

[283] J. Giri, M. Parashar, J. Trehern, V. Madani, "The Situation Room: Control Center Analytics for Enhanced Situational Awareness", IEEE Power and Energy Magazine, vol. 10, no. 5, pp. 24-39, Sept.-Oct. 2012

[284] D.V. Nga, O.H. See, N. Quang, C.Y. Xuen, L.L. Chee, "Visualization Techniques in Smart Grid, Smart Grid and Renewable Energy", 2012, 3, 175-185

[285] TERNA (Italian TSO), Dati Statistici sull'energia elettrica

[286] T. Huang, A. Purvins, E. Bompard, G. Fulli, C.F. Covrig, A. Chaouachi, E. Carpaneto; R. Jian Pi, A. Mutule, I. Oleinikova, A. Obushevs, "The Baltic power system between East and West interconnections", JRC Science and Policy Report, 2016

[287] M. Landsberg, BALTSO Development WG, Baltic grid 2025 conclusions & recommendations, 2006

[288] Elering (Estonian TSO)

[289] AST (Latvian TSO)

[290] LitGrid (Lithuanian TSO)

[291] Nord Pool Spot

[292] ENTSO-E, Scenario Outlook & Adequacy Forecast (SO&AF) 2014-2030

[293] ENTSO-E, Monthly Statistics Reports, Overview of National Electricity Consumption

[294] ERIC - European Real-time Integrated Co-simulation laboratory

[295] GEANT network

B. GLOSSARY

Adequacy Reference Margin (ARM): is the part of Net Generating Capacity that should be kept available at all times to ensure the security of supply on the whole period each reference point is representative of. It serves to assess generation adequacy in most of the situations. The Adequacy Reference Margin in an individual country is equal to the sum of the Spare Capacity and the Margin against Seasonal Peak Load.

Adverse event: a materialised **threat**.

Aggregator: new entity in the electricity market that act as mediator/broker between users and the utility operator. Aggregators possess the technology to perform **Demand Response.**

Ant Colony Optimization: probabilistic technique for solving computational problems which can be reduced to finding good paths through graphs. This algorithm is a member of the Ant Colony Algorithms family, in **swarm intelligence** methods, and it constitutes some **metaheuristic** optimisations.

Artificial intelligence: study of how to create computers and computer software that are capable of intelligent behaviour.

Artificial Neural Network: mathematical or computational model based on human neural networks. It consists of a number of simple nodes connected together to form either a single layer or multiple layers. The connections between nodes are called weights that should be adjusted to reach the desired target, making them adaptive to inputs and capable of learning. It is used to solve complex power system monitoring and control problems including security analysis, load identification/modelling, forecasting and fault diagnosis.

Boolean logic: is a form of logic in which the values of the variables are the truth values 1 (true) and 0 (false).

Cascading failure: sequence of dependent failures of individual components that successively weakens the power system.

Contingency: the unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, switch, or other electrical element.

Demand response: change in the power consumption of an electric utility customer to better match the demand for power with the supply.

Disturbance: an unplanned event that produces an abnormal system condition.

Energy dependency rate: proportion of energy that an economy must import. It is defined as net energy imports divided by **Gross Inland Energy Consumption** plus fuel supplied to international maritime bunkers, expressed as a percentage. A negative dependency rate indicates a net exporter of energy while a dependency rate in excess of 100% indicates that energy products have been stocked.

Economic Dispatch describes a variety of formulations to determine the least-cost generation dispatch to serve a given load with a reserve margin, but these formulations simplify or sometimes altogether ignore power flow constraints (see also **Optimal Power Flow**).

Electricity security: power system capability to withstand disturbances - i.e. events or incidents producing abnormal system conditions - and contingencies - i.e. failures or outages of system components - with minimum acceptable service disruption.

Energy Management System (EMS): is a system of computer-aided tools used by operators of electric utility grids to monitor, control, and optimize the performance of the generation and/or transmission system. These monitor and control functions are known as **SCADA**.

Europe Union's 2020 energy targets: 20% **final energy consumption** covered by renewable sources by 2020, 20% greenhouse gas emissions reduction (compared with 1990 levels) and 20% more energy efficiency (compared with the 2020 energy use projections).

Final energy consumption: total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself.

Flow-based allocation method: instead of calculating aggregated **Net Transfer Capacity** per bidding zone, determines physical margins on each "critical grid element" (transmission lines which are likely to become congested) and their influencing factors (how each critical grid element is affected or affects another critical grid element). This normally allows an increase in cross-border transmission capacity where it is most needed because it more accurately reflects the actual situation on the grid.

Fuzzy Logic: is a form of many-valued logic in which the truth values of variables may be any real number between 0 and 1, considered to be "fuzzy" (see, by contrast, **Boolean logic**). It is used to study power system performances (e.g. stability properties) by handling imprecise or vague information.

General Algebraic Modelling System (GAMS) is a high-level modelling system for mathematical programming and optimisation.

Game theory: is the formal study of decision-making where several players make choices that potentially affect the interests of other players. It is applied to liberalised power systems and markets, where emphasis is given to benefit maximisation from the perspective of participants rather than maximisation of system wide benefits.

Gross electricity generation: is measured at the outlet of the main transformers, i.e. it includes consumption in the plant auxiliaries and in transformers**.**

Gross national electricity consumption: includes the total gross national electricity generation from all fuels (including auto-production), plus electricity imports, minus exports.

Gross inland energy consumption: total energy demand of a country or region. It represents the quantity of energy necessary to satisfy inland consumption of the geographical entity under consideration. Gross inland energy consumption mainly covers: consumption by the energy sector itself; distribution and transformation losses; final energy consumption by end users; statistical differences. Gross inland consumption does not include energy (fuel oil) provided to international maritime bunkers. It is calculated as follows Gross inland consumption does not include energy (fuel oil) provided to international maritime bunkers. It is calculated as follows: primary production + recovered products + net imports + variations of stocks – bunkers.

Hazard: is the source of a risk in a harmless state (see also **Threat**).

Heuristic: strategies that use readily accessible information for problem solving in machines and human beings.

Locational Marginal Price (or Nodal Price): is the marginal cost of supplying, at least cost, the next increment of electric demand at a specific location (node) on the electric power network, taking into account both supply bids and demand offers and the physical aspects of the transmission system including transmission and other operational constraints.

Loop flow: a physical flow caused by an electricity exchange within one bidding zone (see also **Transit flow**).

Metaheuristic: is a higher-level procedure or **heuristic** designed to find, generate, or select a **heuristic** technique that may provide a sufficiently good solution to an optimisation problem, especially with incomplete or imperfect information or limited computation capacity.

Net Transfer Capacity (NTC): is the maximum total exchange program between two adjacent control areas compatible with security standards applicable in all control areas of the synchronous area, and taking into account the technical uncertainties on future network conditions.

Optimal Power Flow (OPF) is an optimisation method determining the "best" way to instantaneously operate a power system. Usually "best" = minimizing operating cost. OPF considers the impact of the transmission system (see also **Economic Dispatch**)

Primary energy consumption: equals the **gross inland energy consumption** excluding all non-energy use of energy carriers (e.g. natural gas used not for combustion but for producing chemicals). This quantity is relevant for measuring the true energy consumption.

Primary energy production: is any extraction of energy products in a useable form from natural sources. This occurs either when natural sources are exploited (for example, in coal mines, crude oil fields, hydro power plants) or in the fabrication of biofuels. Transforming energy from one form into another, such as electricity or heat generation in thermal power plants (where primary energy sources are burned), or coke production in coke ovens, is not primary production.

Reliably Available Capacity (RAC): is the difference between **Net Generating Capacity** and **Unavailable Capacity**. The Reliably Available Capacity is the part of Net Generating Capacity which is actually available in the power system to cover the load at a respective Reference Point in normal (average) conditions.

Remaining Capacity (RC) is the difference between **Reliably Available Capacity** and Load at reference point. Remaining Capacity is the part of Net Generating Capacity left on the power system to cover any unexpected load variation and unplanned outages at a Reference Point and in normal (average) conditions (the Remaining Capacity is calculated by ENTSO-E including Load Management, which increases the amount of Remaining Capacity).

Residual Load is the actual load minus wind, solar and must-run generation within a defined (e.g. hourly) time interval.

Risk is the *likelihood* of being injured by the **threat** caused by the **hazard.**

Smart grid is an electricity network that can integrate in a cost efficient manner the behaviour and actions of all users connected to it, including generators, consumers and those that both generate and consume, in order to ensure an economically efficient and sustainable power system with low losses and high levels of quality, security of supply and safety.

State Estimator: network real-time model used to confirm that the monitored electric power system is operating in a secure state by simulating the system both at the present time and one step ahead. This model is extracted at intervals from snapshots of real-time measurements (both analogue and status). With the use of a state estimator and its associated contingency analysis software, generally used in the **Energy Management Systems,** system operators can review each critical contingency to determine whether each possible future state is within reliability limits.

Swarm intelligence: is the collective behaviour of decentralised, self-organised systems, natural or artificial. The concept is employed in work on **artificial intelligence.**

Threat: is any circumstance with the *potential* to adversely impact a system. It is the source of a **risk** in harmful state (see also **Hazard**).

Transit flow: the physical flow resulting from an electricity exchange between two bidding zones (see also **Loop flow**).

Unavailable Capacity is the part of **Net Generating Capacity** that is not reliably available to power plant operators due to limitations of the output power of power plants. It is calculated by adding Non-Usable Capacity, Maintenance and Overhauls, Outages and System Services Reserves.

Unscheduled Flow: the difference between a schedule and a physical flow. It is also the sum of unscheduled **transit flows** and **loop flows** over a border.

C. ABBREVIATIONS AND ACRONYMS

ACER	Agency for the Cooperation of Energy Regulators
ARM	Adequacy Reference Margin
ASIFI	Average System Interruption Frequency Index
BEMIP	Baltic Energy Market Interconnection Plan
BRELL	Belarus, Russia, Estonia, Latvia and Lithuania
CACM	Capacity Calculation and Congestion Management
CCGT	Combined Cycle Gas Turbine plant
CEER	Council of European Energy Regulators
CHP	Combined Heat and Power
CIP	Critical Infrastructure Protection
CGM	Common Grid Model
CRM	Capacity Remuneration Mechanisms
DER	Distributed Energy Resources
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DSM	Demand Side Management
DSO	Distribution System Operator
EC	European Commission
ECOST	Expected Customer Outage Cost
EENS	Expected Energy Not Supplied
EHV	Extra High Voltage
ENTSO-E	European Network of Transmission System Operators for Electricity
EPCIP	European Programme for Critical Infrastructure Protection
FACTS	Flexible Alternating Current Transmission System
FCR	Frequency Containment Reserves
FRR	Frequency Restoration Reserves
GA	Generation Adequacy
GAA	Generation Adequacy Assessment
GHG	Greenhouse Gas
GPC	Gigahertz Processor Card
HPC	High Performance Computing
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICT	Information & Communication Technology
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IEM	Internal Energy Market

IAEA	International Atomic Energy Agency
IPS/UPS	Integrated Power System/Unified Power System
ISO	Independent System Operator
KCL	Kirchhoff`s Current Law
KVL	Kirchhoff`s Voltage Law
LFC	Load-Frequency Control
LOEP	Loss of Energy Probability
LOLE	Loss of Load Expectation
LOLP	Loss of load probability
MCO	Market Coupling Operator
MV	Medium Voltage
NEMO	Nominated Electricity Market Operators
NERC	National Energy Regulatory Commission
NRA	National Regulatory Authority
NTC	Net Transfer Capacity
OECD	Organisation for Economic Co-operation and Development
OPF	Optimal Power Flow
PCIs	Projects of Common Interest
PMSG	Permanent Magnet Synchronous Generator
PST	Phase- Shifting Transformer
p.u.	per unit
RCR	RES Curtailment Risk
REPI	RES Energy Penetration Index
RES	Renewable Energy Sources
RLPI	RES Load Penetration Index
RL	Residual Load
RM	Reserve Margin
ROC	Regional Operational Centre
RR	Restoration Reserves
RSCI	Regional Security Coordination Initiative
RSCSP	Regional Security Coordination Service Provider
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control And Data Acquisition system
SGAM	Smart Grid Architecture Model
SO&AF	Scenario Outlook and Adequacy Forecast
TFEU	Treaty on the Functioning of the European Union
TSO	Transmission System Operator
TYNDP	Ten Year Network Development Plan
VOLL	Value of Lost of Load
VPN	Virtual Private Network