Summary

Electricity system of the European countries are strongly interconnected via high-voltage AC and DC interconnections. This feature provides an opportunity for the national/regional market operators, as well as the system operators, to strengthen their coordination and collaboration on managing the electricity system in Europe-wide scale, with the aim of enhancing energy security, sustainability, and affordability. European countries have already established some degree of regional cooperation in market, reserve provision, resource adequacy, risk preparedness and security analysis levels. Enhancing cooperation among the countries necessitates the increase of physical integration among regions and harmonization of the national and regional regulations.

The present thesis aims at investigating the potential impacts of enhancing the integration among the European electricity systems from market operation and network management perspectives. In particular, this thesis focuses on three main integration scenarios in Europe, already planned by the European Commission, as:

1. Enhancing the integration of the Baltic States to the EU electricity systems, following their joining to the Union.

2. Integrating electricity markets in Europe, towards establishing a single Europe-wide day-ahead and intraday electricity market.

3. Enhancing cooperation among the neighbouring countries in preparing risk preparedness plans, to manage abnormal situations more efficiently.

The above scenarios are investigated individually in this thesis, in three chapters (Chapter 3-5). Accordingly, the main contributions of this thesis can be listed as follows:

1. Developing a Europe-wide integrated market analysis tool, covering 34 European countries and in line with the EU target model, with the following specifications:

    - Zonal pricing approach with one or several market zones per country;

- Network-constrained market model with implicit allocation of inter-zonal network capacities;
- Auction-based intraday market modelling;
- Monte-Carlo stochastic optimization approach, taking into account the uncertainty of wind/solar production and load, due to the day-ahead forecast errors;
- Co-optimization of energy and operating reserves' provision, including FCR and FRR reserves, according to the current European regulations regarding reserve provision in different synchronous areas;
- Modelling market participation of hydro pumped-storage technologies, with the ability to generalize the model to other storage technologies, as well as demand response programs.

2. Developing a decision-making algorithm for risk preparedness planning in multi-regional level, with network and security constraints.

3. Proposing a multi-regional assisted rotational load shedding approach for managing crisis in interconnected regions.

In what follows, the research questions which are dealt with in this thesis are briefly elaborated.

- Which Baltic-EU synchronization scheme is the best option from market perspective?

Baltic de-synchronization from Russia and synchronization to EU electricity system has been assessed by comparing three prospective scenarios, proposed by ENTSO-S: i) Baltic synchronization to Nordic countries via Estonia-Finland interconnection; ii) Baltic synchronization to continental Europe via Lithuania-Poland interconnection; and iii) autonomous synchronous operation of the Baltic States. The scenarios are modelled through market participation of the Baltic countries in a Europe-wide integrated day-ahead market model, followed by a national redispatch market within each Baltic State to manage the potential transmission network constraints. To do so, the model applies the detailed transmission network model of the Baltic power system and the zonal model of the EU power system, connected through inter-zonal transmission capacities, in 2030. Comparing the results of the three scenarios led us to the key conclusion that Baltic synchronization with the Continental European Network is the most preferred option form market performance perspective, resulting in the highest generation surplus, lowest redispatch cost, and adequate reserve capacity within the Baltics. This outcome, even if driven from different results, is in line with previous technical analyses.

- What is the impact of integrating European adjustment markets under high share of renewables?

While the European integrated day-ahead market model has been widely studied, there are still many open questions about the potential impacts of integrating intraday markets. In this thesis, the current option of regional intraday market has been compared with the option of an integrated Europe-wide one, with reference to three European test cases, including the Iberian market, the Italian market, and the German market. The integrated intra-day market is modelled through stochastic Monte-Carlo optimization approach, considering the uncertainty of wind/solar production and electricity demand. The simulation results for a market scenario of 2030 led us to the following key findings:

- Intraday market integration reduces the surplus of conventional generator companies, while providing economic benefits for the customers.
- Integrating electricity markets in Europe, together with market participation of hydro pumped-storage generators, succeeds in converging day-ahead and intraday market prices, as well as diminishing RES curtailment in the market.
- Network expansion increases the total generators' surplus within Europe, while it reduces the total operation cost of the system.
- Flexibility provided by hydro pumped storage units reduces the potential benefits of market integration on market performance. Due to the fact that there are other novel flexibility options to support system operation under high penetration of renewables, e.g. demand response programs, a more rigorous cost-benefit analysis is strongly recommended to assess the economic justification of intraday market integration.

- What are the potential benefits of increasing cooperation among countries to manage abnormal situation?

Currently, European countries implement national rules for preventing, preparing for, and managing crisis situations and behave very differently under crisis circumstance. However, the recent European Commission's proposal on risk preparedness in the electricity sector sets out how member states should cooperate to prevent and manage crisis situations, while ensuring that even under crisis, the electricity is delivered where it is most needed. This thesis provides a mathematical model for analysing the impact of crisis in one region, within an interconnected multi-regional system, under different levels of cooperation among the regions. The

model is formulated as a decision making algorithm to manage crisis, aiming at continuous supply of protected demands and essential reliability services, i.e. reserves in this study, at minimum cost and with the least social impact on non-protected consumers. The simulation results on a 3-zone test case (IEEE RTS-96 system) led to the following key findings:

- Multi-regional cooperation among the interconnected regions to manage potential electricity crises operates effectively in continuous supply of sensitive loads and provision of reserves within the region under crisis.
- Rotational curtailment of the interruptible loads on different buses of the affected and supporting regions leads to reduction of interruption duration on each customer and minimizes the socio-economic impacts of crisis.
- The capability of the neighbouring regions to provide support to the affected region depends on both the available interconnection capacity and the initial state of the affected region in terms of being electricity exporter or importer. Furthermore, making wrong decisions in ceasing the support provision to the affected region, through preventing energy exports to this region, may lead to adverse results on the operation of the interconnected regions.