Simulation Framework for Analysis of the European Transmission System under a Wide Range of Operating Conditions

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Abstract: The lack of a complete AC load flow model dataset for the European Transmission System and an increasing need for Europe-wide coordination of future system developments provide a motivation to create a flexible simulation framework. The process of modelling and simulation of the European Transmission system is automated such that usage of the framework requires minimal user input. At the same time, the framework is able to generate four levels of system representation and corresponding results: DC load flow, market model with dispatch schedule, AC load flow and dynamic simulation. The capability to easily readjust simulation conditions, such as demand or weather profiles, enables the framework to investigate the influence of different factors on the system behavior. Several results of system studies are presented in the paper to demonstrate the extensive capabilities of the framework.

Keywords: European Transmission System modelling, simulation framework for European Transmission System

1 Introduction

New challenges are currently faced by the European transmission system due to changing generation structure, growth of demand and political goals towards green energy. The old network supplied end consumers using dispatchable generation located near to demand centers. The transmission system was seen as a backbone of the entire network, acting above other network levels as a main regulator of power flow volumes and stability provision. As a result of recent HVDC interconnections and the inclusion of new countries within the synchronous region, the European network has become more complex and meshed. Modern ambitions to obtain energy infeed from renewable resources have become stronger. Figure 1 shows the evolution of renewable energy penetration in the ENTSO-E generation capacity mix, where the share of renewable capacity is expected to increase by 60% in the period between 2014 and 2025 and will reach 51% (608 GW) by 2025. Such a significant infeed from renewable sources affects not only the distribution level, where the majority of RES are being installed, but also the behavior of the transmission system, due to the reverse power flows that occur when local load is exceeded by RES infeed. Moreover, the weather dependent nature of RES is probabilistic. Therefore, the entire generation schedule becomes less controllable. Load patterns are also transforming because of initiatives provided by demand-side management programs to decrease peak loads and increase system flexibility.

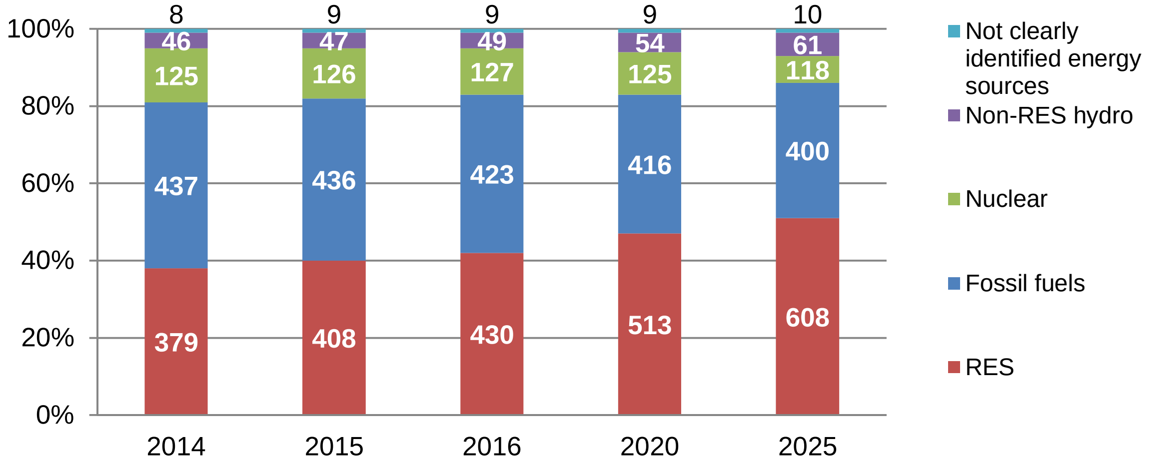


Fig. 1 ENTSO-E total Net Generation Capacity breakdown per fuel type in % and GW (all years; Scenario B; January 7 p.m.) [11]

The above described developments imply that the definition of a 'worst case' scenario to examine system operation will become less clear. While traditionally the entire spectrum of system operating conditions was represented by cases of high- and low-demand, such an approach may become inadequate in the near future. Multiple combinations of various demand, weather, economic and control conditions may represent the 'worst case' for operation of the modern European power network. Such cases may occur in any season and time of day and may not necessarily correlate with extreme system loadings. An example of a worst case can be a situation with a shortage of rotating inertia in the system. In the past, reduced inertia could be experienced during times of low loading due to the decrease of necessary generator output. Currently, high renewable infeed causes the reduction of energy production from conventional generators and thus, reduction of the system inertia even during times of high demand. Therefore, a flexible simulation environment to generate multiple operating conditions and adjust system structure is necessary to realistically assess the system performance and provide an adequate response to the previously described issues.

The conducted research has shown that multiple models of the European Transmission System (ETS) and its regions have been published in the literature during recent years. However, these models do not provide the required flexibility to simulate different scenarios and their applications are usually limited by the scope of the projects for which they were established. Possible explanations to the latter problem may be that institutes try to simplify a model to a level that is sufficient to meet the project aims in order to reduce model creation efforts; or that they have an unwillingness to disclose (commercially) sensitive data. However, a broader statement of a project goal and utilization of estimation algorithms with corresponding validation could solve the described issues.

Taking into account the aforementioned challenges for modelling and simulation, the following paper presents a simulation framework for flexible analysis of the ETS. The framework is capable to produce results of DC load flow, energy market, AC load flow or dynamic simulations for the ETS and therefore investigate the system during both normal and abnormal conditions.

To present the concept of the flexible simulation framework, the paper is structured as follows. Section 2 provides the insight into the state of the art of the existing ETS models and analyses their features. Section 3 describes the method of model creation, providing details on developed interdependencies between representations (DC – AC – dynamic) and on the framework organization. Section 4 presents examples of results obtained for the ETS using a range of simulation methods. Further, an overview of the potential area of framework applications is provided. Section 5 concludes the paper with a summary of significant features of the framework.

2 Literature Review in the EU System Modelling

It is widely stated in scientific papers, such as [1] and observed during research conducted for this work that there is a lack of a complete, flexible and publically available AC model of the ETS. For the sake of confirmation of this statement, five existing models of the ETS are analyzed from different viewpoints in this section. The models and corresponding documentation publications are the following:

- Benchmark system of J. Bialek [1],
- ELMOD market model of TU Dresden [2],
- Transmission system model of Energynautics [3],
- Model of DIW Berlin [4],
- ENTSO-E Initial Dynamic Model of Continental Europe [7].

Table 1 summarizes the information about the selected models.

It is shown that the system representations provided in models 1, 2, and 4 have a high level of details. Location of nodes and line corridors can be considered accurate because mapping of these elements was done involving sources with geographical information. However, these models are DC representations of the system [9]. That is a crucial limiting factor for the majority of system-related studies. DC load flow (LF) models cannot be relied upon to provide realistic results in simulations, because reactive power flows and voltage differences between nodes are neglected in the linearized DC form of power flow equations. This fact was studied and analyzed in [8], in which the level of error in the DC LF calculation as a function of system parameters is explored in detail.

In contrast, model 3 includes sufficient reactive power compensation to facilitate AC load flow (AC LF) calculations. However, there are several approximations used in this model that potentially limit the accuracy of the simulation results. Firstly, the model is a simplified version of the real network. This means that for example, power interchanges between countries can be modeled. However, the optimal location of a new line cannot be exactly determined using such a model. Secondly, reactive power compensation was provided only to facilitate the convergence of the AC LF calculation and is not claimed to reflect real locations of these devices.

Finally, model 5 of the ENTSO-E can be seen as the most detailed, facilitating dynamic calculations for the ETS due to provision of standard dynamic models for generators and their appropriate control devices. However, all geographical information is encoded for the model and line and transformer limits are unified. This complicates modification of the model to examine multiple operation cases. Therefore, its application is also limited.

Table 1. Summary of characteristics of 5 ETS models

Model	Characteristics		
	Year of creation	Dedication	Dimensions
1. Benchmark system of J. Bialek [1]	2005	DC load flow calculations for cross-border trades analysis	1st synchronous UCTE region (18 countries); 1254 nodes, 378 generators (no RES included); 220 – 750 kV
2. ELMOD market model of TU Dresden [2]	2006	Market simulations (DC model)	16 western European countries; 2120 nodes, generators >100 MW capacity; 110, 220, 380 kV
3. Transmission system model of Energynautics [3]	2011	DC and AC load flow and optimal load flow calculations for analysis of scenarios of the future network development	200 nodes represent the aggregation of generation, consumption and main transmission corridors; HVDC lines included; 220 – 380 kV
4. Model of DIW Berlin [4]	2013	Market simulations (DC model)	3216 nodes, 4724 power plants; generator capacities >10 MW; HVDC lines included 220 – 380 kV
5. ENTSO-E Model [7]	2015	Dynamic (transient) analysis for 2020 peak load case	26 synchronous countries of continental Europe; 21382 nodes, 10829 generators with dynamic characteristics;

There are a number of other models developed by different institutes. However, the research conducted to find a detailed AC LF model for flexible application in various simulations gave negative results. This provides a motivation to establish such a model and a framework to apply the model within a range of simulations.

3 Method of the ETS Model Simulations

3.1 Definitions

Before introducing the functionalities and features of the simulation framework, basic definitions should be stated for clarity of further description.

The term *Scenario* is chosen to characterize the elementary system representation that includes: network topology, available power plant fleet, peak loads per country and installed capacities of known equipment (synchronous generators, renewable sources).

Another relevant term is a *Profile Case*. The *Profile Case* defines yearly active power profiles for load, PV and wind sources, yearly reactive power profiles for load (or expressed as a function of active power). Any other profile or functional dependence for yearly change of an operating point of a model element can be also considered as a *Profile Case* and used to distinguish between simulations (for example, hydro storage schedule dependent on availability of water). Time resolution for profiles is 1 hour (15 minutes step is planned in the future). The profiles are expressed in two ways: as historical records (from the ENTSO-E database [13]) and as synthetically generated data sets with a desired weather/demand pattern. Concentrated data is distributed over NUTS2 regions.

Finally, the term *Quasi-Stationary* (QS) model is used within the framework to highlight that a system representation includes operation limits of its elements such that a successful LF time-series calculation for a selected *Profile Cases* is guaranteed.

The introduced definitions are summarized in Table 2.

Table 2. Framework definitions

Definition	Description
Scenario	• Topology (year) • Peak load for every country • Installed capacities of PV and Wind • Power plant fleet
Profile Case	Historical/ synthetic yearly profiles of P_{load}, Q_{load}, P_{PV}, P_{wind}, etc.
Quasi-stationary (QS) model	Model with operation limits of elements that guarantee a successful time-series LF calculation.

3.2 Structure and Functionalities of the Simulation Framework

The simulation framework involves two capabilities: model generation and simulation. As a primary model of the ETS, the structure presented in [5] is considered. This is a QS AC LF model of the synchronous continental part of the ENTSO-E system with geographically mapped locations of substations, generators and line corridors. It includes over 6000 buses (including almost 900 conventional generators) that are connected by over 7000 lines and about 1700 transformers. Figure 2 gives an overview of dimensions and the level of complexity of the developed ETS representation. The model was expanded with governor and exciter characteristics as well as dynamic generator models to accomplish various dynamic calculations as demonstrated in [6]. The process of development of this model was extended and set up as an automated process. This has become a base of the framework. As a result, the following system representations can be generated within the framework: DC model, market model, AC LF model and dynamic model.

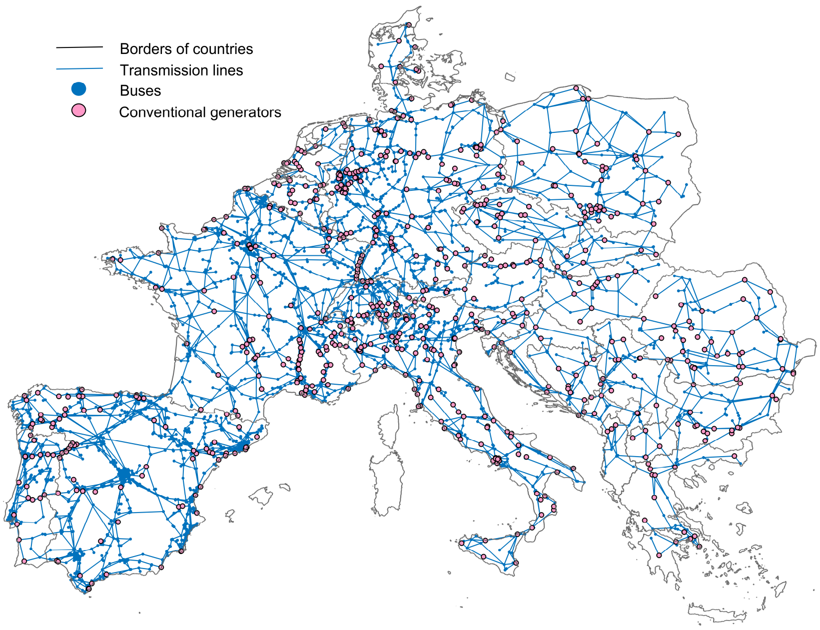


Fig. 2 Topology of the European Transmission System and conventional generation for 2012 scenario

A stepwise transition between system representations is accomplished within the framework. To implement this feature, a set of necessary parameters is defined for each model type.

From simulation point of view, the framework provides desired operation points of a system as results of market simulation, AC LF calculation for a particular loading case, or of a selected dynamic analysis.

To simplify the flow process of the framework, two functional modules were derived according to the type of a model/simulation: quasi-stationary and dynamic. Detailed descriptions of the modules are presented in the following sections.

3.2.1 Module 1

Module 1 is responsible for preparation of quasi-stationary models of the ETS and execution of analysis for a system operation under normal conditions. Figure 3 depicts the components and processes involved within Module 1. Each step of the module (A to E) is described below.

A+B) Initialization of Parameters and Base Model

To initialize a calculation for a new scenario, active power demand or weather situation, these parameters should be provided as corresponding year and *Profile Cases* of interest. Such a combination of parameters formulates a so called base model, which is suitable for DC LF calculations.

C) Market Model and Market Simulation

Further addition of cost characteristics for conventional generation (fuel cost), PV and wind sources (feed-in incentive cost) facilitates a market simulation for the system. Storage locations and capacities can be also included to the model because the capability of storages to provide energy at low cost during demand peaks or times of low renewable infeed has a direct impact on the power supply management in a network. Another point is to consider a distribution system in the simulation. It makes power flow distribution in a system more realistic.

It should be mentioned that market simulations are implemented based on DC Optimal Power Flow (OPF) calculations, where the cheapest total costs of power generation in the system are ensured and transmission line flow limits are not exceeded. The result of this step is an economic power dispatch schedule for a year. However, power losses and reactive flows are not considered in the calculation due to the limitations of the DC OPF formulation.

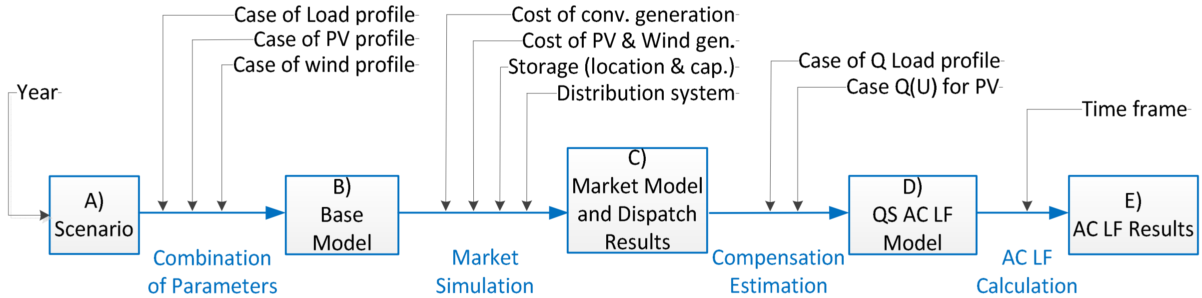


Fig. 3 Overview of Module 1

D) QS AC LF Model

To proceed with a more realistic level of system representation, the assumption of equality of voltage magnitudes throughout the system should be eliminated and reactive power flows should be taken into account. Therefore, within this step reactive power profile cases for loads and PV are appended to the market model.

To accomplish a transition to AC LF representation without access to actual installed compensation data (due to commercial restrictions), a method to estimate reactive power compensation was developed as described in [5]. It is based on calculation of optimal amount of compensation such that the following system constraints are satisfied:

- voltage magnitude limits at buses,
- generator reactive power capability requirements,
- line flow limits,
- line angle deviation.

The determined reactive power ranges serve as capacity limits for compensators to cover the system's needs for all loading situations within the selected *Profile Case*. Along with compensation estimation, generator dispatch is corrected on this step due to consideration of network code requirements and application of non-linearized power flow equations. Thus, a QS AC LF model of the ETS is generated by the framework.

E) AC LF Calculation

An AC LF calculation is facilitated if a QS AC LF model is generated. Any time frame of interest can be selected from the yearly profiles for the AC LF calculation. To initialize the AC LF calculation, firstly complex voltages at compensator buses and generator dispatch are derived in AC OPF. Then a simple AC LF simulation can be conducted to obtain the final operating points of system elements.

3.2.2 Module 2

For any known state of the system, a more detailed analysis can be conducted. In other words, the results of an AC LF calculation can serve as starting points to evaluate the system response to events happening on millisecond time resolution level. Therefore, Module 2 is a continuation of the Module 1 and facilitates short circuit calculation, transient stability analysis, eigenvalue analysis and other dynamic simulations. These calculations are well programmed in different commercial software. Therefore, a correct input should be provided for a desired simulation. Figure 4 shows the formulation of the input for a dynamic simulation. Parameters are specified for dynamic generator models and governor, exciter and stabilizer characteristics. This process and the used data sets are based on information provided in [6].

Therefore, all necessary parameters and characteristics of the ETS are provided within the framework to perform simulations under both normal and various abnormal conditions. Several examples of the framework execution are provided in the results section.

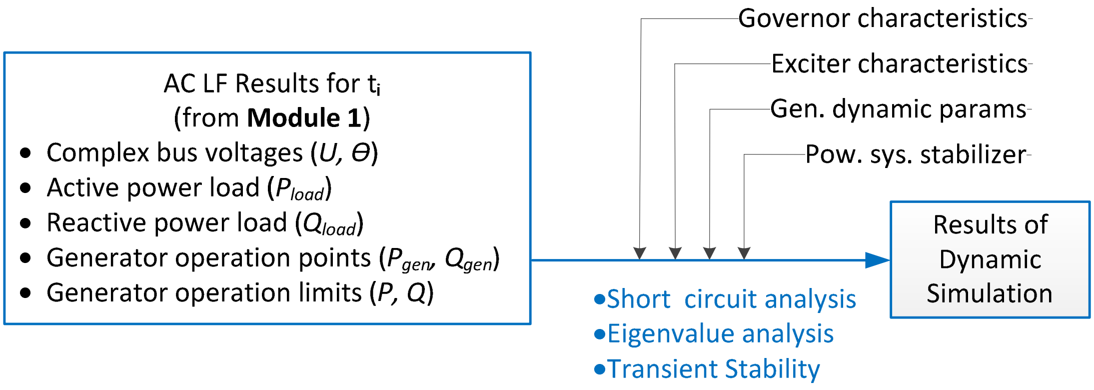


Fig. 4 Overview of Module 2

3.3 Organization of the Framework

The organization of the framework is displayed in Figure 5 and includes four main blocks. GUI ensures the data input for both Modules, communication with a user and shows an output information (calculation status, results location). The Control Block is responsible for the framework logic: it searches necessary data in the Data Storage, ensures data processing, makes calls of necessary simulation scripts and monitors their execution. Data Storage is a collection of all simulation parameters and results.

A prototype of the presented framework is currently implemented, where Matlab serves as the main environment for the user interface and for connections between steps of the method. Calculations of the Module 1 are facilitated using Matpower package [9], whereas Module 2 is currently implemented in the Netomac [10] software with a corresponding call from Matlab. A set of tables in the form of .csv files is prepared to structure the necessary input data. To facilitate more efficient data traffic, further modernization of the data structure to a database is planned. It should be mentioned that each model and corresponding simulation results are saved. It implies that execution of the framework should not always start from the very beginning with the base DC model preparation. Any previously generated model with a satisfying parameter set can be chosen as a starting point for further data addition. It reduces the amount of repetitive computations and allows the obtained results to be exported after every step.

4 Framework Results and Applications

This section demonstrates capabilities of the presented framework by showing possible outcomes, obtained for different types of simulations.

4.1 Results of the Core Simulations

Three core calculations are selected to describe the results of the direct framework application: market simulation, AC LF and short circuit calculation. These calculations show the capabilities of both Modules.

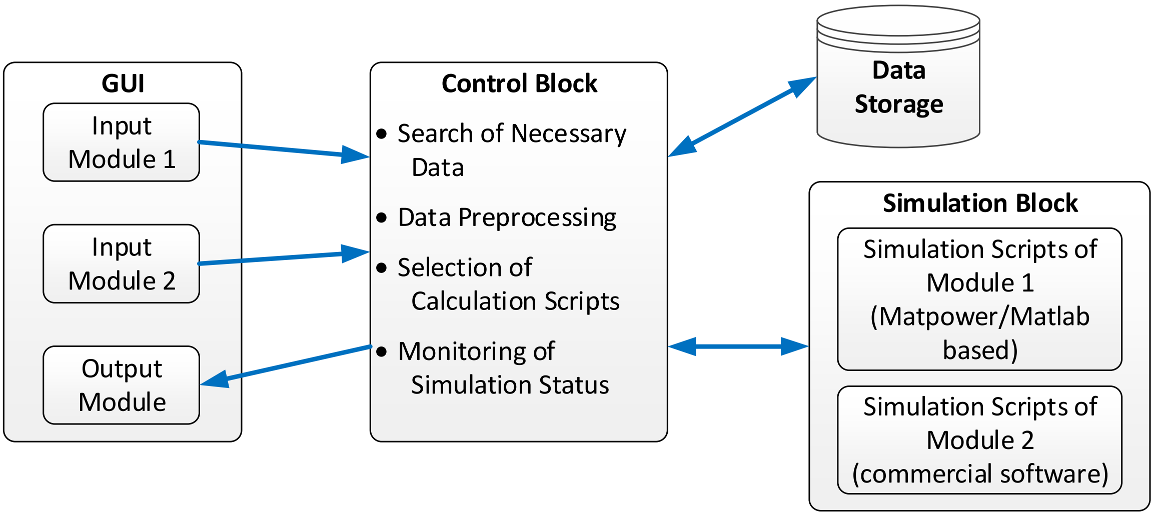


Fig. 5 Framework structure: main blocks and their interconnections

For analysis using AC LF results the *Scenario* and historical demand and weather *Profile Cases* 2012 are selected. Figure 7a provides an impression on the voltage distribution over the entire territory of the continental Europe, whereas Figure 7b provides assessment of critical line loadings at a particular time instant (23 March 2012, 8:00).

To represent functionality of the Module 2 an example of a short circuit simulation in Germany is taken [12]. The fault has caused a voltage droop over a large area (Figure 8a). The voltage recovery process is presented on Figure 8b.

4.2 Potential Applications

The developed flexible framework allows to execute a wide range of system simulations derived from its main functionalities. Here we provide an overview of possible framework applications.

1. Market and AC LF simulations:
   - Network expansion: This functionality is planned to be a part of the framework to facilitate creation of a new *Scenario*.
   - Curtailment of RES output with a dispatch corrected in AC OPF: The advantage of a more realistic dispatch schedule can be used to assess different cases of the trade-off between RES and conventional generation.
   - Net Transfer Capacity (NTC) calculation: Conservative values of the NTC flow limits can be improved and calculated for every desired time instant.
2. Dynamic simulations:
   - Virtual inertia: The concept of synthetic rotating inertia and its application within the power system can be examined on the European level in terms of required volumes and most effective regulation concepts for frequency support.
   - Dynamic system support requirements of RES: A study of RES capabilities to provide reactive current infeed to the system under different fault conditions can be performed.

- HVDC connection: HVDC facilities can be located in the presented ETS model with a high accuracy to study their influence on stationary and dynamic behavior of the system.

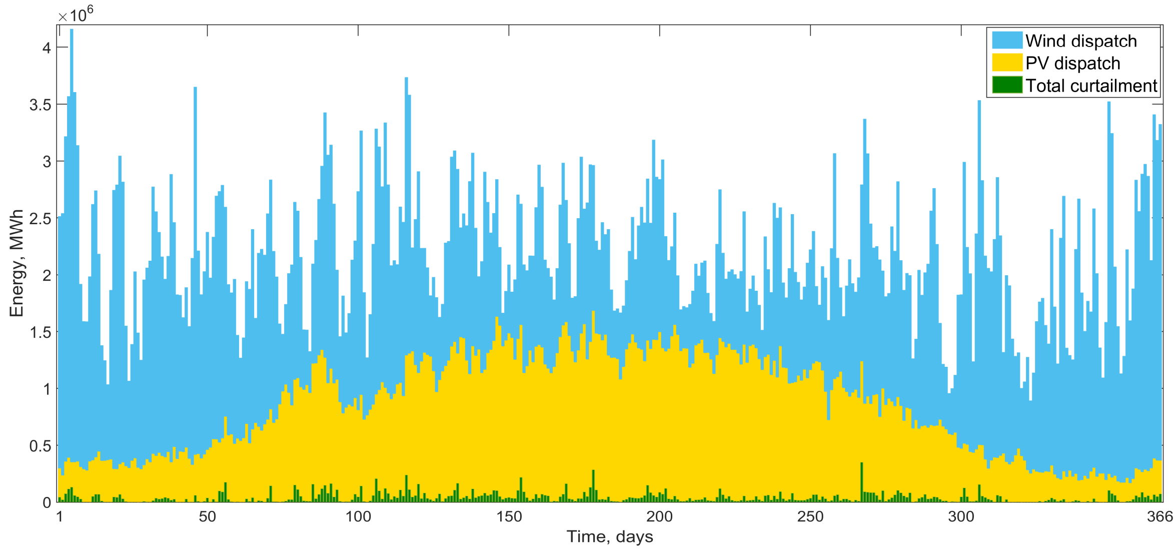


Fig. 6 Time-series market simulation results: daily dispatch and curtailment of PV and Wind generation (scenario 2030 [15])

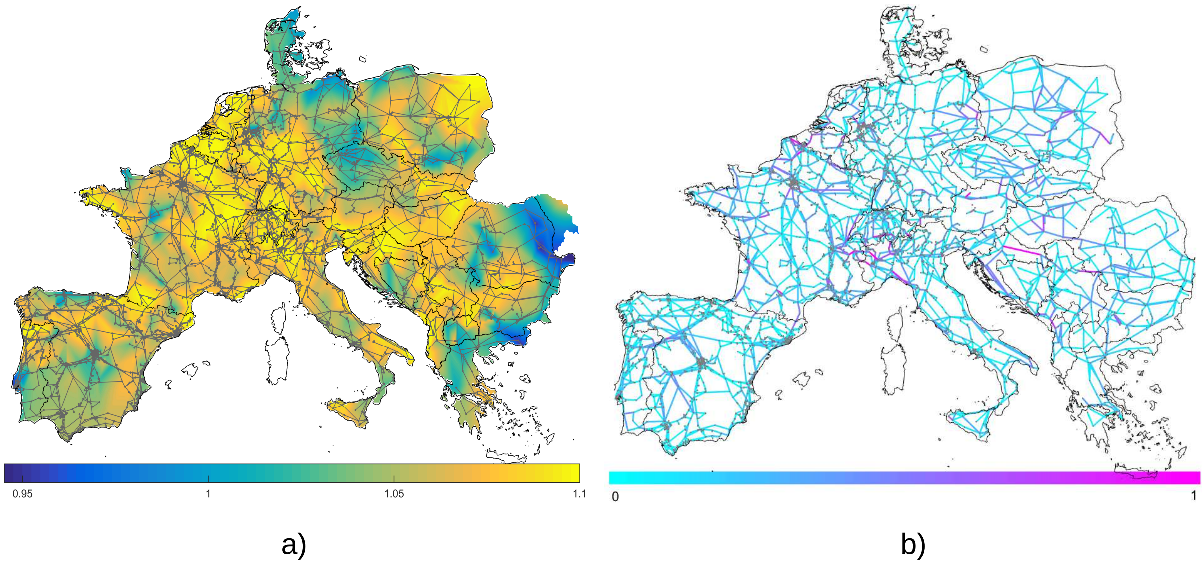
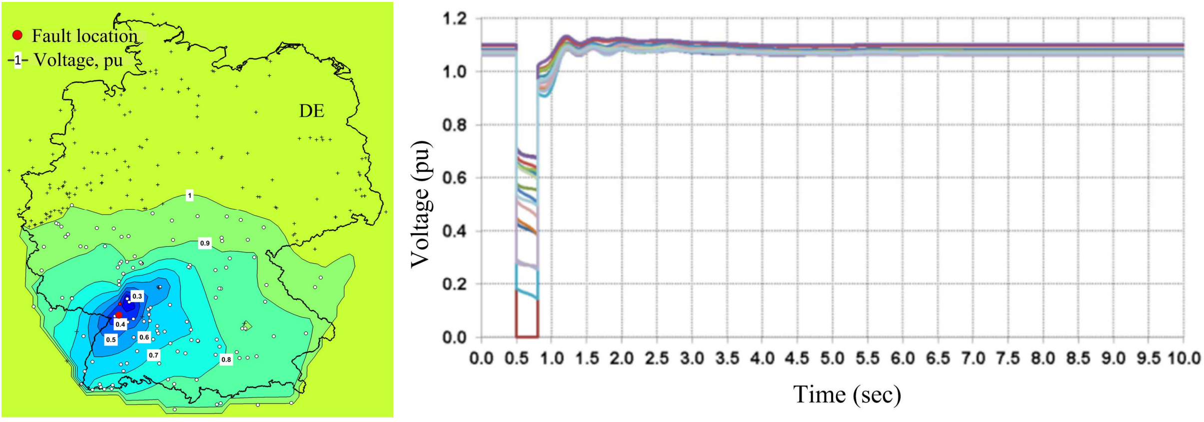


Fig. 7 AC LF simulation results: a) voltage profile in p.u. (23.03.2012, 8:00), b) line loading (23.03.2012, 8:00)



a) b)

Fig. 8 Short circuit in Germany [12]: a) voltage profile, b) voltage transient at all nodes

5 Conclusions

The presented simulation framework is a generic tool with potential application for ETS development studies. The developed method of consequent addition of necessary parameters to the model allows all possible system representations to be obtained: from DC to AC and dynamic. Another advantage of the modelling process in the framework is that the initial 2012 network topology has a high level of details giving a possibility of considering strategies of the Ten-Year Network Development Plan (TYNDP) [14] more precisely for the topology update.

A great variety of demand (active and reactive power), weather and economic cases can be simulated using the framework. The section 4 has shown that generated models are suitable for testing of both normal and abnormal operation conditions of the system. It demonstrates that the framework provides flexible modelling and simulation capabilities. It is also significant that the influence of changes in static system parameters or economic factors can be investigated and assessed in dynamic simulations.

Finally, the framework provides independence from TSO data for performance of system analysis.

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