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EXECUTIVE SUMMARY

This report is a second public deliverable from work package 4 of the GARPUR project: system development. Particular objectives of this report are as follows:

1. to propose a methodology for building a credible set of operating conditions for future operation of a power system;
2. to define a methodology for the assessment of a large set of credible operating conditions;
3. using the above two points, propose a system development process that gives a better appraisal mechanism for future investments in an electricity transmission network;
4. illustration of the proposed method on a 10 bus network.

The planning horizon for a system development planner is long and a system planner must take into account potential changes to generation capacity and demand during that horizon. The uncertainties that affect system development are greater than those that apply, for example, in system operations. Thus, it is important to build up a credible set of operating states that is informed by various uncertainties and adequately represents the range of conditions that might reasonably be expected to arise. The next step in the system development process is to assess these operating states for system operability. If a power system is *not* operable on some (probable) operating states, then it identifies a potential need for investment in the system. However, given the number and range of uncertainties relevant to system development, pragmatic approaches must also be developed allowing their assessment.

In first chapter of this report, we give a high level view of objectives of WP4 of the project and give details about the on-going and planned work in various subtasks. This chapter also includes a discussion on relevant uncertainties that affect the future operation of a power system, and ways to capture such uncertainties from the perspective of a system development planner.

Work packages 2 and 3 of the GARPUR project concern the development of reliability management approaches and criteria and a socio-economic impact evaluation framework respectively, and give vital information for work packages 4, 5 and 6. In the second chapter of this report, we give a brief summary of how methodologies proposed by work packages 2 and 3 could be used in the context of system development in WP4.

In chapter 3 of this report, we propose a methodology for a system development process that takes account of a number of key uncertainties. This methodology encapsulates the reliability criteria and socio-economic measures and aims to assess the operability of system for a given set of credible operating conditions.

The first step in our proposed methodology is to build a set of credible future operating conditions, i.e. combinations of states of demand, generation and network components that might reasonably be expected to arise. This set must consider all the relevant dependencies of exogenous factors e.g. effect of temperature on demand, impact of weather on outages etc. In order to capture the uncertainties in demand at nodal level, we generate large number of nodal demands for a single aggregated zonal demand. This process is based on the historic correlations of nodal demands and is explained further in chapter 3. The set of credible operating states is used as an input to a model of the behaviour of the electricity wholesale market. Given the demand for power and what can be produced by weather-dependent renewable energy sources (RES), this model outputs the commitment and set points of all the generating units.

The set of credible operating states that capture the future operation of a power system is inevitably very large. We propose to use clustering to reduce the size of this set. After clustering is performed, we use an assessment model to characterise each operating state as operable or critical. The critical operating

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states arise due to non-operability or operability at a very high cost; both reasons identify a possible need for investment. Moreover, each assessment identifies the locations where investment in new facilities might be most useful. To summarise, our step-by-step approach to system development consists of following 9 steps:

1. Select a target year for system development studies.
2. Using existing macro-scenarios, identify peaks of various parameters like demand, RES penetration, and fuel prices.
3. Construct micro-scenarios that specify hourly profiles of demand, RES and maintenance of assets for the specific year.
4. Using micro-scenarios as an input for the market tool identify the commitment of thermal generators in accordance with prevailing market rules but otherwise unconstrained by the network's capacity.
5. Perform zonal to nodal conversion for demand on the operating states determined by the market tool, and build a very large set of representative operating states for the target year.
6. Reduce the size of the large set of credible operating states using an appropriate clustering method.
7. Optionally, perform an initial screening of centroids of each cluster thereby allowing (a) the number of cases to be studied in detail to be further reduced and, depending on the screening method used, (b) to identify system problems that are common to more than one cluster.
8. Through detailed assessment on the centroids of clusters, provide insights to the system planner of system weaknesses and possible mitigations.
9. Allow the analysis of different system development options proposed by the system development planner and the quantification of metrics that can contribute to investment decision-making.

The proposed methodology is illustrated using a 10-bus network described in chapter 4. We use realistic demand and wind data to build a set of credible operating states. A market model is used to determine the set points of thermal generation units whilst considering temporal constraints like ramp rates and minimum up and down times. We describe the use of zonal to nodal conversion and clustering concepts that were introduced in chapter 3 of this report and show how the process can reveal key system limitations and the conditions under which they arise. We show how a traditional approach to system development planning based solely on a peak demand condition would have missed these critical limits. Moreover, the assessment model takes account of both continuous and short-term ratings of lines and post-contingency corrective actions by a system operator and a discussion is presented on options for how a system development planner might take account of the need for planned outages to be accommodated on the system. These are:

1. to model, albeit in some approximate way, the way in which outages would typically be planned, and then to assess the operability of the system given such outage plans;
2. to assess the maintainability of the network while still being secure against contingencies (unplanned outages), i.e. to determine if there is margin for planned outages to be taken.

Some conclusions and recommendations for further work are presented in chapter 5. This includes: the sharing of learning between GARPUR work packages that have been undertaken simultaneously; highlighting of the significance of weather in affecting a number of states of the system, the likelihood of fault outages and the impacts of interruptions to supply; and further steps towards a system development methodology that might be practically applied by TSO personnel.

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1 INTRODUCTION

1.1 The GARPUR project and the goals of system development

This deliverable is a summary of the work done in the framework of the GARPUR[1] project in Task 4.2 and Task 4.3 ("Task" will henceforth will be denoted by letter "T") of Work Package 4 ("Work Package" will henceforth be denoted by letters "WP") as defined in the Description of Work ("Description of Work" will henceforth be denoted by "DoW") of the GARPUR project.

WP4 focuses on system development, including paths for the development of new network facilities in the long-term timeframe and optimisation of the network investment project portfolio in the mid-term timeframe. These decisions influence how the transmission system is maintained (asset management) and operated (real-time operation) as shown in the Figure 1-1. Therefore, a system planner has to accommodate foreseeable challenges that can arise in mid-term and short-term time horizons, as planning decisions largely effect the management and operation of the system.

In this report, we will focus on the functional analysis of system development and propose possible improvements in the current practice of system development. However, in-depth analysis of asset management, operational planning and real-time operation are out of the scope of WP4.

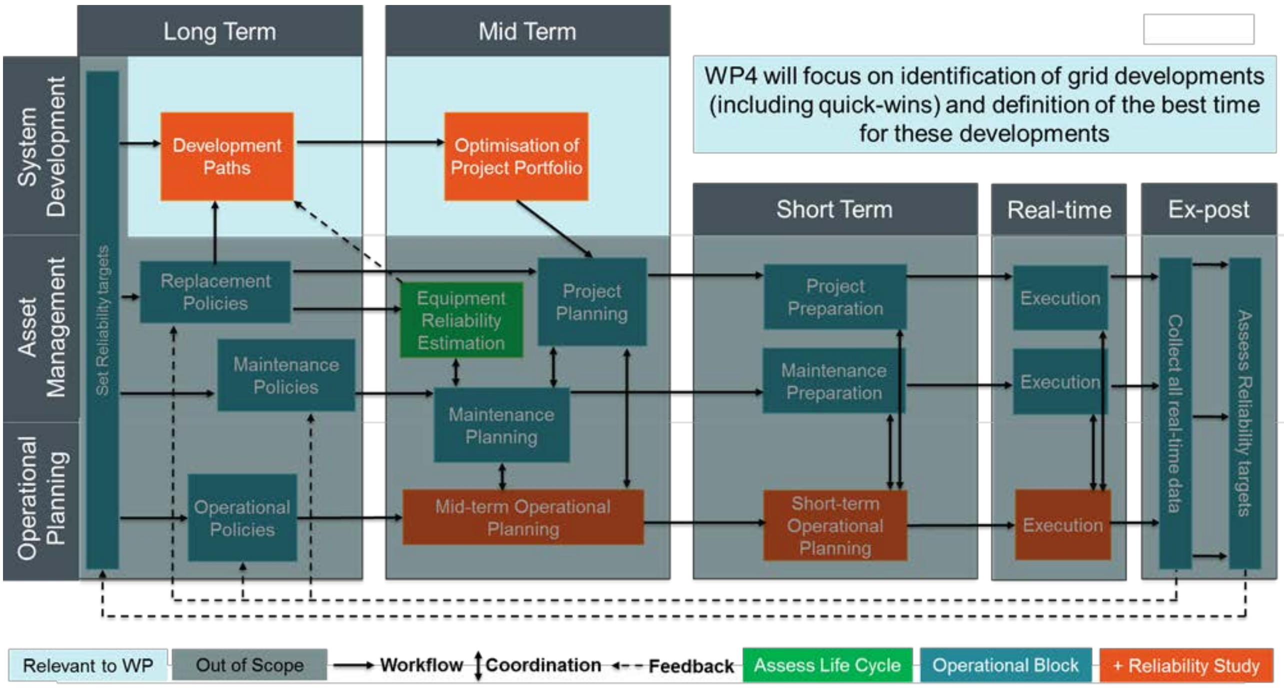

Figure 1-1: Activities of a TSO across three time scales and their relationship

1.1.1 Context: a paradigm shift

The electricity industry is in the midst of a comprehensive change: a paradigm shift of the ways we consume and generate electricity. Our increasing awareness about the environmental impact of electricity generation has contributed significantly to this paradigm shift. Consequently, in today's world, policies

[1] http://www.garpur-project.eu/

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and investments in the electricity industry should be consistent with societal commitments towards de-carbonisation and sustainability.

Renewable energy sources (RES) are location constrained. That is, renewable energy generation can only economically be sited in areas with strong natural resources. These resources are not distributed evenly across regions and are not correlated with areas of high load or areas where the existing grid is adequate. Accessing these resources may require significant transmission investment.

On one hand, we need to invest in the transmission resources to capitalize on RES, and on the other hand the existing transmission asset base may be expected to become increasingly redundant due to smarter grids, in particular the increasing use of corrective, i.e. post-fault actions, including modification of demand. The trade-off between potentially cheaper power from RES, lumpy investment costs to reach them and the cost of managing existing assets is at the heart of transmission expansion problem (TEP), and this is a problem that is extremely difficult to quantify. TEP is further exacerbated by some particular risks and uncertainties imposed by the liberalised market structure of present electricity industry, not least the division of responsibilities between different parties, e.g. generation development and network development, by increasing public opposition to development of overhead transmission lines and by growing political concerns about possible unreliability of electricity supply due at least in part to retirement of older generating plants. Finally, there is growing concern in public discourse that the global climate may already have led to changed weather patterns that involve greater extremes or more frequent storms.

In Europe, there is increasing recognition of the interconnectedness of different regions and a desire on the part of policy makers to minimize total costs of electricity to consumers. This leads to greater market integration and a desire to make best use of the most economically efficient locations for development of different RES. However, success in achieving these goals depends on there being an appropriate amount of transmission network capacity. As a consequence, planners today must design network architectures for areas the size of continental Europe. The design of these new networks will determine the efficacy of expanding electricity markets and the ability to integrate high penetrations of renewable and other location-constrained generators.

1.1.2 Goal and drivers of system development

The main role of the system development planner is to ensure that sufficient facilities are installed on the system to enable it to be operated in accordance with relevant operating standards. In particular, the system development planner should ensure that the future system's capability to transfer power from producer to consumer would be sufficient. Moreover, it should be done in such a way that the sum of network costs and the negative impact on social welfare is minimised. Because any insufficiency may require investment in the network's facilities and such investment takes time – relevant equipment and its location should be identified, the functional requirements specified, and the equipment procured, installed and commissioned – the system development process is commonly identified with timescales of a year or more ahead of real-time operation. Thus, the process of system development is often described as 'long-term planning'. However, it may be possible for some equipment, e.g. new control facilities such as special protection schemes or reactive compensation, identified by the system development planner to be specified, approved and installed in less than a year[2]. In addition, as noted by CIGRE Working Group C1.17, "The [system development] planner [is] responsible not only for providing network capacity but

[2] Even if, in a particular company, the system development planner does not directly specify and procure protection or control equipment, the system development planner is involved in the process since they must confirm that such 'secondary' equipment, beyond the usual fault detection, location and clearance function, is a viable and cost-effective alternative to investment in primary network assets.

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also for providing a system operator with the means of managing the consequences of N-1 violations or combinations of outage events."

In respect of facilitating system operation in accordance with operating standards, two main drivers may be noted:

- Provision of power transfer capability such that the demand for electricity in a given area can be met with a given, minimum level of reliability, i.e. 'reliability driven' capability;
- Provision of power transfer capability such that demand for electricity on the system can be met, over the medium to long term, in an economically efficient manner, i.e. 'economics driven' capability.

The second driver involves an assessment of relative costs and benefits of investment in enhancement of power transfer capability compared with network congestion and running of 'out of merit' generation. Viewed another way, because a lack of power transfer capability can lead to the opportunity for the exercise of market power by particular generators in liberalized markets, it can be seen as being concerned with facilitation of competition. To the extent that a price can be put on an inability to utilize low carbon generation due to power transfer limitations, it can also be seen as concerned with carbon reduction.

From what is explained above, we can state that the core of system development is about making the right trade-off between investment *i.e.* capital expenditure (CAPEX), socio-economic welfare (that can be measured by the total generation cost obtained by the market dispatch[3]) and reliability (that can be measured by the OPEX cost for preventive and curative measures and the total cost of unsupplied energy when it happens nonetheless). This is illustrated in Figure 1-2. For example, one could decide not to invest in cross-border grid capacities, but to nevertheless make more capacity available to the market. If the border in question was a limiting factor, this will result in an increase of the total socio-economic welfare (in general, a cheaper market dispatch), but depending on how reliability of supply is valued, the consequence may also be a degradation of the reliability of supply and an increase in the TSO's operating costs.

The goal of system development is to assess as properly as possible each of the above-mentioned costs over a long time-period, and under a very large set of future credible operating conditions that model the relevant uncertainties, as explained in the next subsection.

[3] As explained in D.4.1 and in the ENTSO-e Guideline for Cost Benefit Analysis of Grid Development projects, there 7are two different approaches for calculating the increased benefit from socio-economic welfare: the generation cost approach and the total surplus approach. As long as the demand is inelastic, both methods will yield the same result.

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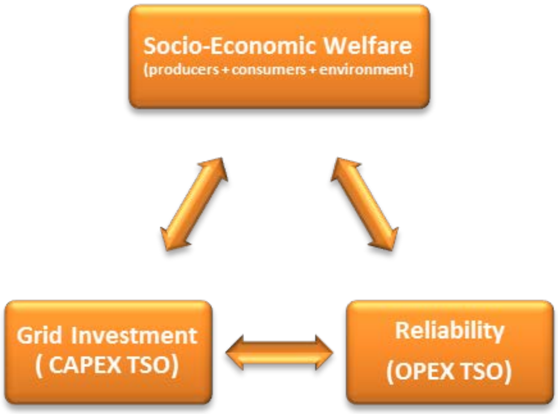

Figure 1-2: The triangular relation between grid investment, socio-economic welfare and reliability

1.2 Relevant uncertainties in system development context

In system development studies, one must take proper consideration of various uncertainties. We can divide these uncertainties in two major categories; macro-scenarios and micro-scenarios, and these are defined as follows:

- Macro-scenarios group all the uncertainties about how the "electricity system landscape will evolve between now and the studied time horizon". Examples of such uncertainties are the evolution of fuel costs, CO_2 prices, demand, installed capacities per production type in each country or region, the level of local storage and demand response, the evolution of the regulatory framework, etc.
- Micro-scenarios group the uncertainties around the actual operating states that we might expect. For example, at macro-scenario level, we define how much wind generation capacity will be installed in each country or region for example by 2030 and how growth of demand will happen. In order to define a micro-scenario, we have to generate credible time-series of wind power output and demand for each country or region in hourly or sub-hourly resolution.

1.3 Overview of WP4: System development

In this section, we give a brief overview of the organization of WP4, and description of each task in WP4. WP4 of the GARPUR project is divided into four tasks. Figure 1-3 shows the organization of the tasks within the work package 4.

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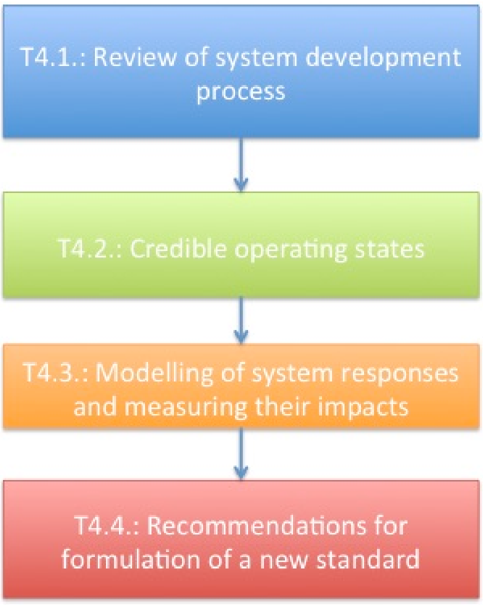

Figure 1-3: Organization of the tasks within the work package 4 of the GARPUR project

1.3.1 Task 4.1: Functional workflow of the system development decision making process

The first task of the WP4 was about reviewing current practice of system development process at a TSO's level. The first deliverable from WP4 (D4.1 Functional analysis of System Development process [GARPUR, 2015c]) documents the current practice of system development at TSOs based on feedback from workshops in the GARPUR project and a questionnaire to 10 TSOs that are either part of GARPUR consortium or a member of GARPUR reference group. It is a detailed step-by-step analysis of the system development process that, among other things, includes discussion on macro-scenario building, data sets, assessment of technical candidates and project portfolio management. It concludes with a discussion of the potential benefits of probabilistic methods in system development planning. A flowchart of the long-term development process is presented in D4.1 (see Figure 1-4) that describes current step-by-step approach to system development.

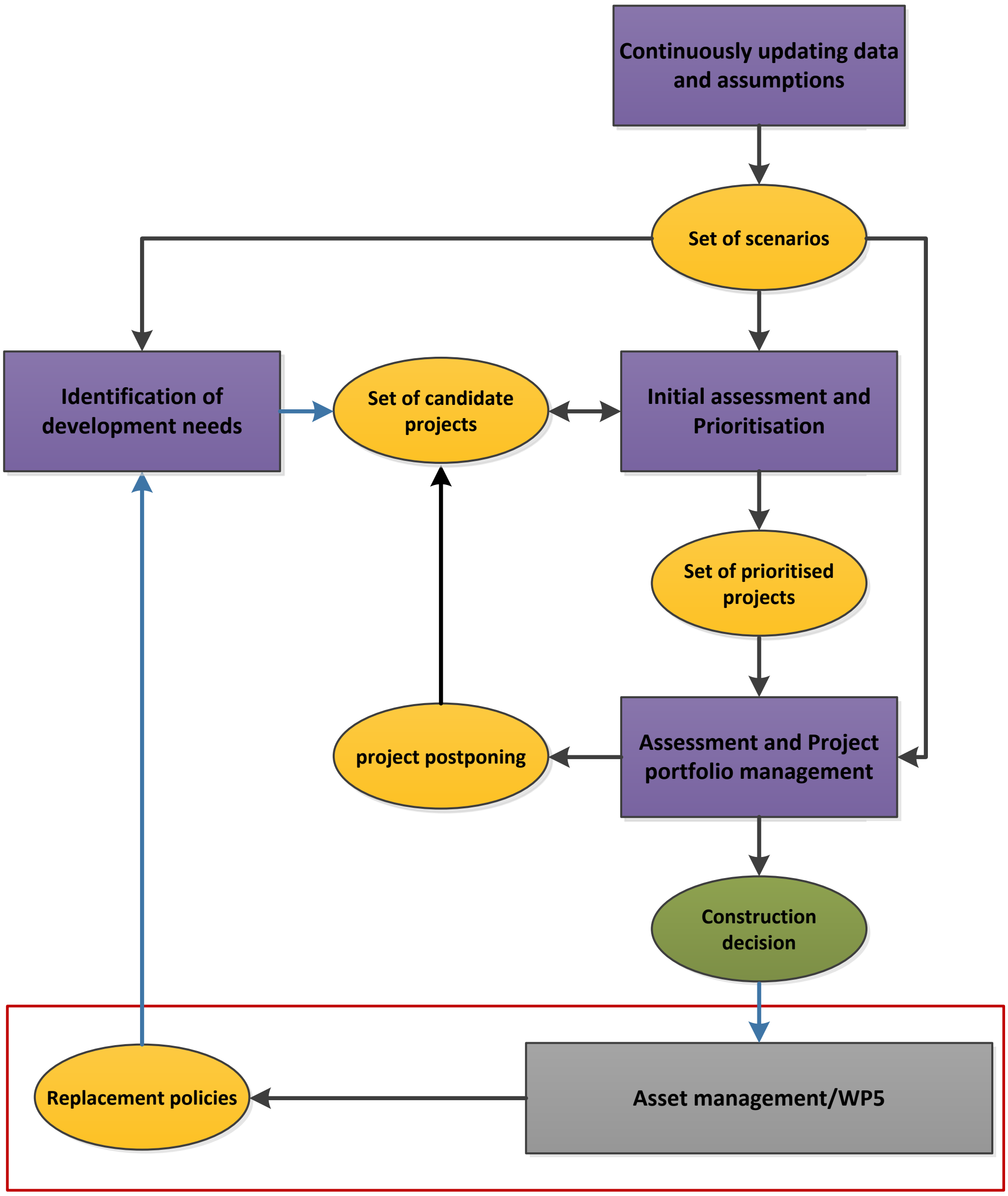

Figure 1-4: Top-level diagram of the long-term decision making process (Figure 3-2 in D4.1 [GARPUR 2015c])

An important point that is raised in D4.1. is as follows:

> *These results indicate that the TSOs are and have already been developing their tools and methods, so that many different scenarios are considered instead of worst-case analyses. This can be interpreted as a small step towards using more probabilistic approaches, or* ***at least acknowledging the potential excess cost of analysing worst-case scenarios only****.*

The above clearly states that what are assumed to represent the worst-case (e.g. snapshots of maximum demand) are not representative of the overall system behaviour and do not necessarily robustly indicate need for investment. For this reason, T4.2 of WP4 looks into finding representative credible operating states. D4.1 also insists on the importance of the use of high-level macro-scenarios in system development, as well as the role of market analysis. Both of these aspects have already been mentioned here and will be further discussed in chapter 3 of this report.

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1.3.2 Task 4.2: Bridging gaps in terms of data, models, and tools for dealing with uncertainties for further upgrading reliability management in system development

The main goal of the second task in WP4 (T4.2) is to define how to manage the different uncertainties that occur during future operational activities, notably how to synthesise them while maintaining the credibility of the assumptions and physical meaning including relevant temporal and spatial correlations between them. T4.2, jointly with T4.3, should also analyse how the concepts proposed by WP2 and WP3 could be put in practice in the context of system development.

1.3.3 Task 4.3: Upgrading reliability management of the system development decision making process

The third task in WP4 (T4.3) is about assessment of credible operating states that are proposed by the T4.2. The assessment methodology will identify possible need for investment in the infrastructure. This task also aims to find an acceptable balance between the reliability indicators defined in WP2, the socio-economic measures defined in WP3 and the tools, data and human resources that are likely to be available for the practical assessment and interpretation of a possibly very large number of credible future operating conditions. For the assessment part, T4.3 depends on the provision of credible operating states coming out of T4.2. This is why a close cooperation and coordination between T4.2 and T4.3 was necessary.

It must be pointed out that reliability and socio-economic indicators are fundamental measures in a system development process in which investment decisions are made and, as such, a worst-case scenario approach is not appropriate for their calculation. Moreover, in spite of what might conventionally be assumed, the worst-case scenario might not be that associated with the maximum possible realisation of an uncertain parameter. That is, for example, a maximum demand condition is not necessarily most expensive and/or most un-reliable operating state. In addition, as shown later in this report, it has been identified that snapshots cannot always be relied upon to be sufficient to represent realistically enough possible future generation dispatches. Instead, time-series are necessary to simulate (approximate) market dispatch and account for generator ramp rates and so on.

1.3.4 Task 4.4 Recommendation for the formulation of new system development approaches and for validation and migration towards new reliability management

The last task of WP4, T4.4, ties everything together and makes recommendations towards a new system development standard. This task also proposes a migration pathway to enhance and incorporate the probabilistic reliability management methodology approaches in the TSO practices of System Development proposed in GARPUR.

1.4 Report Structure

The layout of this report is as follows. In chapter 2, we briefly discuss the outputs from WP2 and WP3 of the GARPUR project. In the chapter 3, we propose a framework for the system development process. The proposed framework is illustrated on a 10-bus example in chapter 4, and we conclude in chapter 5.

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2 RELIABILITY CRITERION AND ASSOCIATED SOCIO-ECONOMIC COSTS

The aim of WP4 of the GARPUR project is to study and improve the system development process in the context of the new reliability management approach and criterion (RMAC) that has been proposed by WP2, and the socio-economic impact assessment framework that has been proposed by WP3.

Figure 2-1 gives an overview of the relationships of WP4 and other work packages of the GARPUR project. The definition of a new reliability criterion is an input from the WP2. Socio-economic metrics are also an inputs from WP3. The first aim of WP4 is to exploit these inputs in the context of system development.

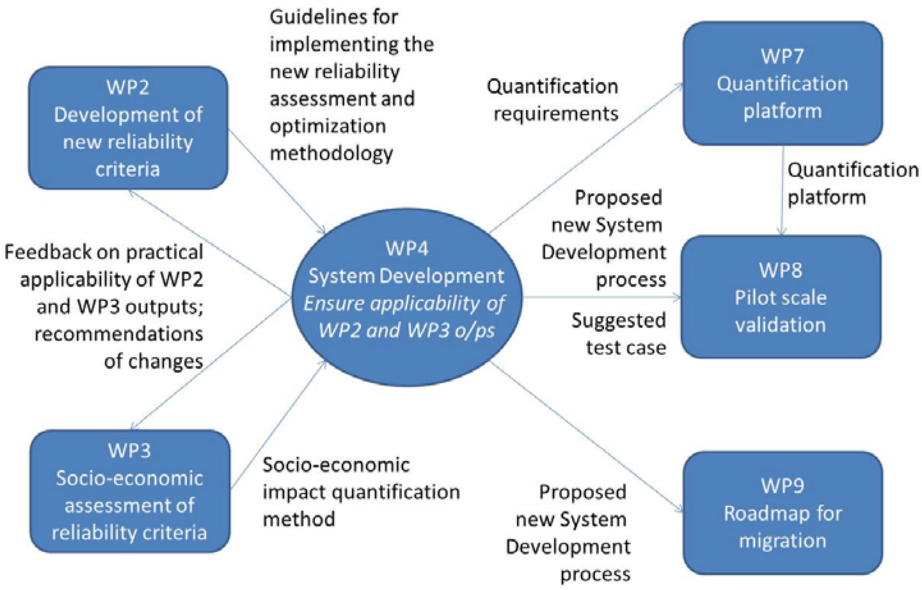

Figure 2-1: WP4's relationship with other WPs in GARPUR

The blocks on the right hand side of the Figure 2-1 show the expected outputs from the WP4. WP7 deals with setting up a quantification platform for simulation purposes and requires inputs for the system development process. These requirements have been formed and there is an on-going work in WP7 specific for long-term studies. WP8 is about validating models on real transmission networks. Work on this has been started and an agreement among the partners about the pilot test has been reached (see [GARPUR, 2016b]) . Finally, WP9 of the GARPUR project proposes a roadmap for migration towards a new probabilistic reliability criteria and this work package will rely on the output from WP4 for a new system development process.

In the following two subsections, we have tried to provide a brief summary of the work proposed by WP2 and WP3. For complete formulation and details about ideas from WP2 and WP3, please refer to the public deliverables available from these work packages [GARPUR, 2016a][GARPUR, 2016d][GARPUR, 2016e].

2.1 Development of new reliability criteria for the pan-European electric power system

Work package 2 of GARPUR has proposed formulations for reliability management approaches and criteria (RMACs) for long-term planning, mid-term asset management, short-term operation planning and real-time operations [GARPUR, 2016d]. The proposed probabilistic RMAC seeks to ensure that the system follows an acceptable trajectory, with a very high probability, for a subset of all possible scenarios for the

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considered uncertain exogenous parameters, while ensuring that the residual risk of the discarded scenarios, i.e. those not assessed explicitly or secured against, is below a pre-defined threshold. The objective function is to minimize the total system cost throughout the considered time horizon. The proposed ingredients of an RMAC are as follows:

1. A metric of the total system cost, to be minimized. In WP3 terms, we could also say that the aggregated surplus has to be maximized, which, under certain assumptions, is similar.
2. A discarding principle that sets a threshold on the residual risk of discarded scenarios.
3. A reliability target that ensures that the system fulfils acceptability constraints with a high probability, expressed through the application of chance-constrained optimisation.

The discarding principle aims at reducing the size of set of operating states and disturbances to analyse. It suggests that for a certain value of residual risk ΔE, we could identify a subset of scenarios for which the total residual risk is smaller than this value ΔE. The reduction of the size of the set of scenarios to be considered will help in decreasing the computation time of the relevant objective function and facilitate the computational tractability of the optimization problem.

2.2 Socio-economic assessment of reliability criteria

The objective of WP3 is to develop a sound and general methodology for assessment of the socio-economic impact of different reliability management strategies. The socio-economic impact assessment developed in WP3 aims at studying the difference of surplus between different reliability-related TSO decisions in multiple decision-making contexts, both aggregated and for different stakeholder groups separately [GARPUR, 2016e]. The socio-economic impact assessment is carried out for a system defined by:

2. The assessed market, i.e. the electricity market.
3. The included stakeholder groups, i.e. electricity consumers, electricity producers, the TSO, the government surplus from taxes on electricity and environmental surplus from electricity related externalities.
4. The geographical scope, i.e. the TSO area and neighbouring areas affected by the TSO decisions to the extent that the impact is significant. This geographical scope also needs to be defined in the pilot test.

Surplus is defined as the difference between the benefits and the costs to a stakeholder or the system under study. As the difference in surplus will be studied, only costs and benefits that significantly change between different decisions need to be included.

2.3 Assumptions used for shorter-term reliability management and socio-economic assessment

At the start of the work being reported here, WP2 of GARPUR had presented a conceptual framework within which decisions on assessment of reliability and residual risk could be undertaken. However, the socio-economic criteria used to inform decisions – the subject of WP3 – and some of the practical considerations for asset management (WP5) and system operation (WP6) arising from the concepts described in WP2 were still in progress when the work reported here was being done. Particular questions not resolved at the start of the work reported here included how specific values for residual risk and chance constraints are chosen and how these, in turn, inform the formation of a contingency list and the utilisa-

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tion of corrective actions. For this reason, in WP4 we made following assumptions for socio-economic assessment and for the modelling of the mid-term and short-term reliability management contexts.

- A market tool is used to measure and maximise the socio-economic welfare. This market tool is an extension of a traditional unit commitment problem and its objective function is to minimise the sum of the overall cost of generation and the cost of interruption of supply while satisfying demand and generation balance in each control zone and taking into account cross-border transfer capacities between control zones. It must be noted that the economic assessment process that uses the market tool is iterative and that the cross-border transfer capacities used between different market zones within the model and at the spatial outer limits of the model are normally those that comply with a specific reliability criterion (e.g. N-1).
- We use a deterministic (N-1) reliability criterion for the assessment of credible operating conditions. Notice that the real-time reliability management methods proposed by WP2 and further adapted in WP6 result in a dynamic contingency list, i.e. one in which the contingency list changes in a way dependent upon real-time conditions. In other words, the probabilistic RMAC developed in GARPUR can be thought of as an extension of the conventional (N-1) security criterion [GARPUR, 2016d] and, if we can perform our analysis with the (N-1) criterion, we will be capable of integrating this probabilistic RMAC in the proposed methodology at a later stage.
- The classic (N-1) criterion in system operation stipulates that the system should be capable of surviving a new, unplanned outage. The prevailing conditions faced by the system operator in real-time may include some prior outages such as planned outages for maintenance or construction or previous unplanned outages that have not yet been restored to service[4]. Broadly speaking, the challenge for asset managers and operational planners is to schedule the planned outages such that the reliability of individual assets can be managed in the medium to long term and the system can be operated in accordance with the relevant system operation criterion such as, at present, (N-1) unplanned outages [GARPUR, 2015a]. The challenge for the system development planner is to provide sufficient network capacity such that maintenance and construction outages can be facilitated and the system operated in accordance with the operating criterion.
- WP5 is concerned, among other things, with the development of a process for the scheduling of maintenance and construction outages [GARPUR, 2016c]. Ideally, in checking that such outages can be facilitated, the system development planner would use a proxy for this process. Until an appropriate proxy has been developed, WP4 uses a simple version of it for periods of the year in which planned outages would normally be scheduled, e.g. the so-called (N-1)-1 state where one outage is planned and the other is unplanned[5].
- WP6 is concerned with the implementation of the GARPUR RMAC in the short-term operation planning and real-time operation contexts [GARPUR, 2016f]. Ideally, checking how well the system can be operated along a future horizon would imply the modelling of these shorter-term reliability management contexts in the form of a suitable combination of proxies (e.g. Day-ahead and real-time ones). Until an appropriate proxy for these processes has been developed, WP4 uses the N-1 criterion to check whether the system reliability in operation is ensured to a sufficient level.

[4] In Britain, this requirement for the prevailing conditions to be secure against a further, unplanned outage is sometimes referred to as N’-1 where N’ denotes that there may be one or more prior outages on the system.

[5] The significance of the distinction between the planned and unplanned outages is that the system operator generally has the opportunity to (a) control the timing of the planned outage and (b) configure the system such it would survive the unplanned outage were it to occur.

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3 PROPOSED WORKFLOW FOR SYSTEM DEVELOPMENT ANALYSIS IN THE GARPUR FRAMEWORK

In this chapter, we will present and describe the system development workflow that is proposed by WP4 in the GARPUR framework. The work carried out in WP2 of the project has proposed a probabilistic RMAC, which seeks to ensure that the system follows an acceptable trajectory, with a very high probability, for a subset of all possible scenarios. To select this subset we would need to perform a risk / cost assessment of all scenarios throughout the whole time-horizon in order to identify the subset to discard. Solving all the subsequent asset management, operational planning and real time operations problems in order to assess system development candidate decisions are beyond the scope of WP4, especially on a large system like the European electricity grid. What is proposed here is nonetheless intended to take some pragmatic account of these considerations.

3.1 General overview

In this section, we give a general overview of the proposed approach for system development. Each step in our proposal is explained in detail in the subsequent sections of this chapter.

Our step-by-step approach to system development consists of following 9 steps:

1. Select a target year for system development studies.
2. Using existing macro-scenarios, identify peaks of various parameters like demand, RES penetration, and fuel prices.
3. Construct micro-scenarios that specify hourly profiles of demand, RES and maintenance of assets for the specific year.
4. Using micro-scenarios as an input for the market tool, identify the commitment of thermal generators in accordance with prevailing market rules but otherwise unconstrained by the network's capacity.
5. Perform zonal to nodal conversion for demand on the operating states determined by the market tool, and build a very large set of representative operating states for the target year.
6. Reduce the size of the large set of credible operating states using an appropriate clustering method.
7. Optionally, perform an initial screening of centroids of each cluster thereby allowing (a) the number of cases to be studied in detail to be further reduced and, depending on the screening method used, (b) to identify system problems that are common to more than one cluster.
8. Through detailed assessment on the centroids of clusters, provide insights to the system planner of system weaknesses and possible mitigations.
9. Allow the analysis of different system development options proposed by the system development planner and the quantification of metrics that can contribute to investment decision-making.

The step-by-step approach means that not all subsequent asset management, operational planning and real time operations are explored. Instead, the system development planner can use the results in Steps 8 and 9 to consider repetition of any part of the process.

The first task in our methodology is to select a target year for system development planning. The target year is the last year of the considered time horizon. For example, we can select 2030 as a target year for the system development study. In order to reduce the complexity of the system development problem, in the process as proposed at present, we have decided to limit our attention only to the target year whilst building a set of investment decisions and not to look at the years leading up to or extending beyond the target year. However, in due course we propose to assess the impact of our investment decisions for all years leading up to the target year. The main motivation behind selecting a target year at the end of the considered time horizon is that the macro scenarios will show the most diversity and the investment choices made by reference to such point are more likely to be robust to various realisations of uncertainties. However, an optimal decision for a target year is likely to be suboptimal when transition from *now* to the target year is considered. For this reason, we propose to build a set of feasible solutions for the target year, and test each feasible solution for the transition in respect of its socio-economic performance and robustness[6]. In addition, the latest year in which any solution should be committed to in order to achieve a robust target year outcome is identified. Although each solution may have been designed having in mind conditions in particular years of one or more macro-scenarios, an important feature of each possible solution is the way it can adapted to system conditions that are different to those for which it was designed. The main outcome is the set of investments that should be taken forward and further developed in the next year from now with other solutions that are part of the most robust set being retained as options until further information is gained on the key uncertainties influencing decisions.

The system development process is started by using existing macro-scenarios for demand and RES penetration in the target year[7]. Next we use this information, along with historical data to build a credible set of micro-scenarios that might arise for that macro-scenario in that year. By default, these scenarios are in hourly resolution and give information about aggregated load (in each zone). The micro-scenarios are used as an input for the market tool. The market tool is a proxy for modelling the behaviour of the wholesale electricity market. The output from the market tool is the commitment and initial dispatch of the thermal generators and also the cross-TSO transfers. We perform zonal to nodal conversion on the output from the market model. This zonal to nodal conversion results in an increase in the number of operating states because of the fact that an aggregate sum can be obtained by various combinations. We cluster the large set of credible operating states into representative clusters. A screening process can be run on the centroid of the clusters to find clusters that lead to line over loadings. We deduce that these clusters need further analysis to determine the type and reason for the overloads. We further analyse the problematic clusters in detail in the subsequent assessment step. This assessment step determines the critical operating states of the system for which future investment might be required. Such critical operating states are then passed on to the system planner who can propose investment candidates.

Figure 3-1 gives a general overview of the proposed system development workflow. At the end, for each investment candidate, we will have an investment cost, total reliability cost and a given impact on socio-economic performance during the target year. These three inputs will allow us to choose the best grid reinforcement option for a target year.

We note that the best grid reinforcement option for a target year might not be a best option when integrated over the years leading up to the target year. To address this issue, as outlined above, we propose that a set of investment options are constructed for the target year and these options are assessed using the same methodology proposed year for the years leading up to the target year.

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[6] Robustness can be quantified in a number of different ways. For example, given a number of discrete macro-scenarios, the most robust solution could be regarded as that for which the difference between socio-economic impact in the worst scenario for that solution and the best scenario for that solution is smallest, i.e. the most robust solution is that with the smallest maximum regret. Consideration of such criteria is the subject of future work.

[7] The formation of macro-scenarios is a major subject in itself. Because any existing process for forming them is essentially unaffected by any new RMAC, it was decided at the outset of GARPUR to rule processes for forming macro-scenarios as being out of scope. For the purposes of the remaining discussion, it suffices to note that many TSOs already have their own procedures but, also, that some macro-scenarios are formed and, at a high level, published by ENTSO-E. Macro-scenarios are discussed further in section 3.2.

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In order to define the best transition from a given reference topology, e.g. the present day system, towards the target topology, the timing, i.e. date of commissioning, of each member of the set of infrastructure projects should be identified. For this, the step-by-step approach presented here can be re-used on the whole time horizon (from now to target years). For each year and for each macro-scenario, the 'best' trade-off between operating costs and generation dispatch improvement must be considered in order to decide when to implement steps towards the target topology. The global overview is shown in Figure 3-2 and Figure 3-3. However, the process by which this 'best' trade-off and the timings of individual investments are decided such that risks of under- or late investment, excessive cost to meet a given need and stranded assets (investment to meet an anticipated need that did not materialise) are adequately balanced is the subject of a future work.

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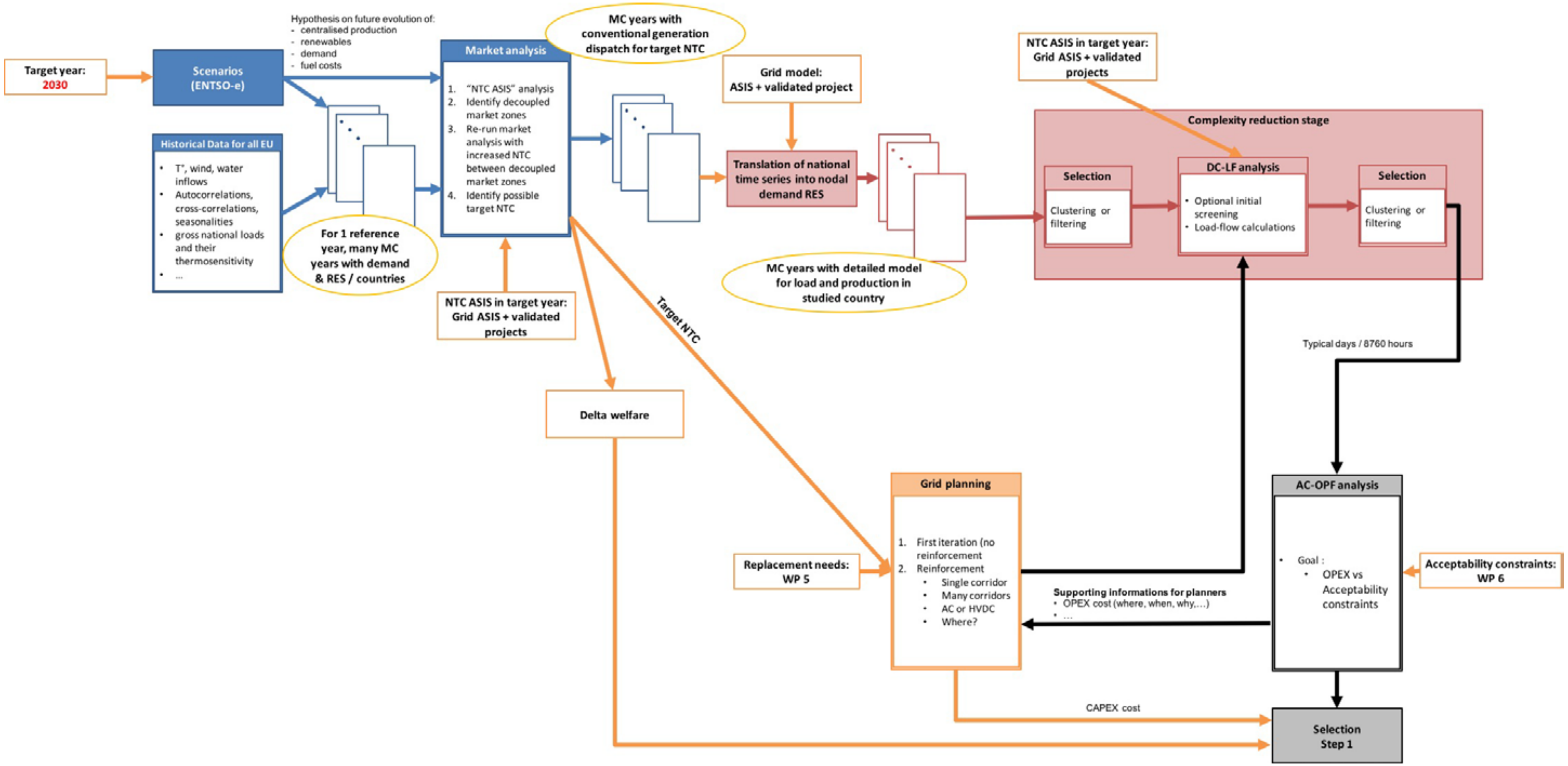

Figure 3-1: Overview of the proposed workflow for system development analysis (MC:Monte-Carlo years and NTC:Net-Transfer Capacity)

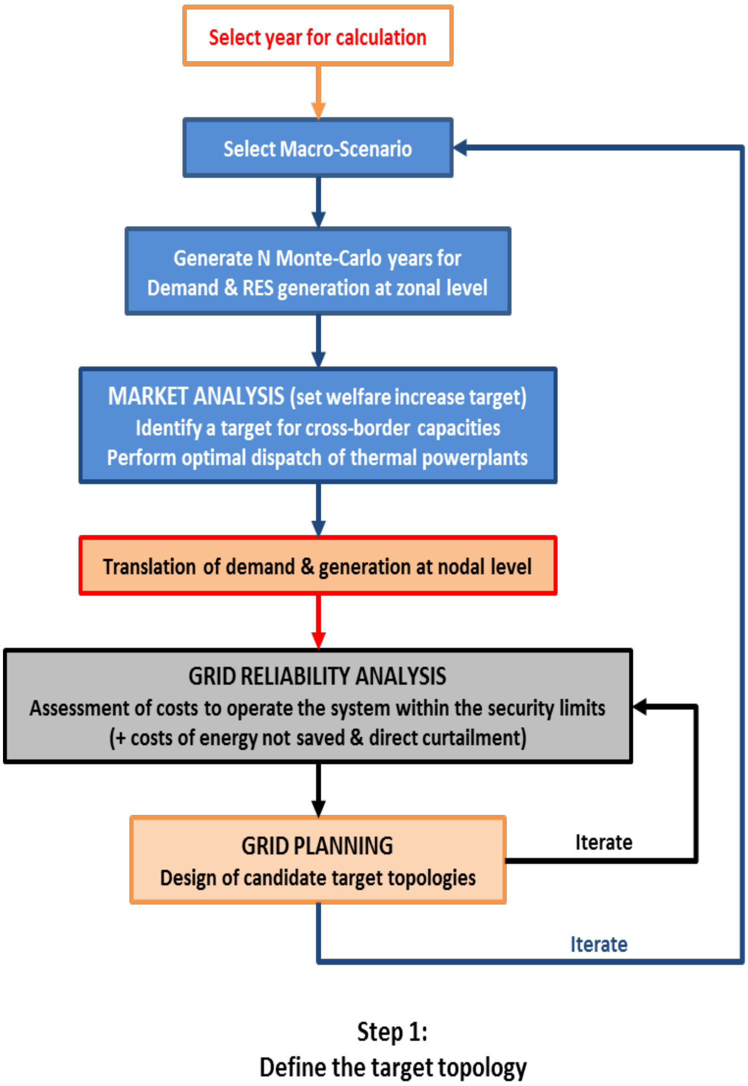

Figure 3-2: A step-by-step approach to system development process

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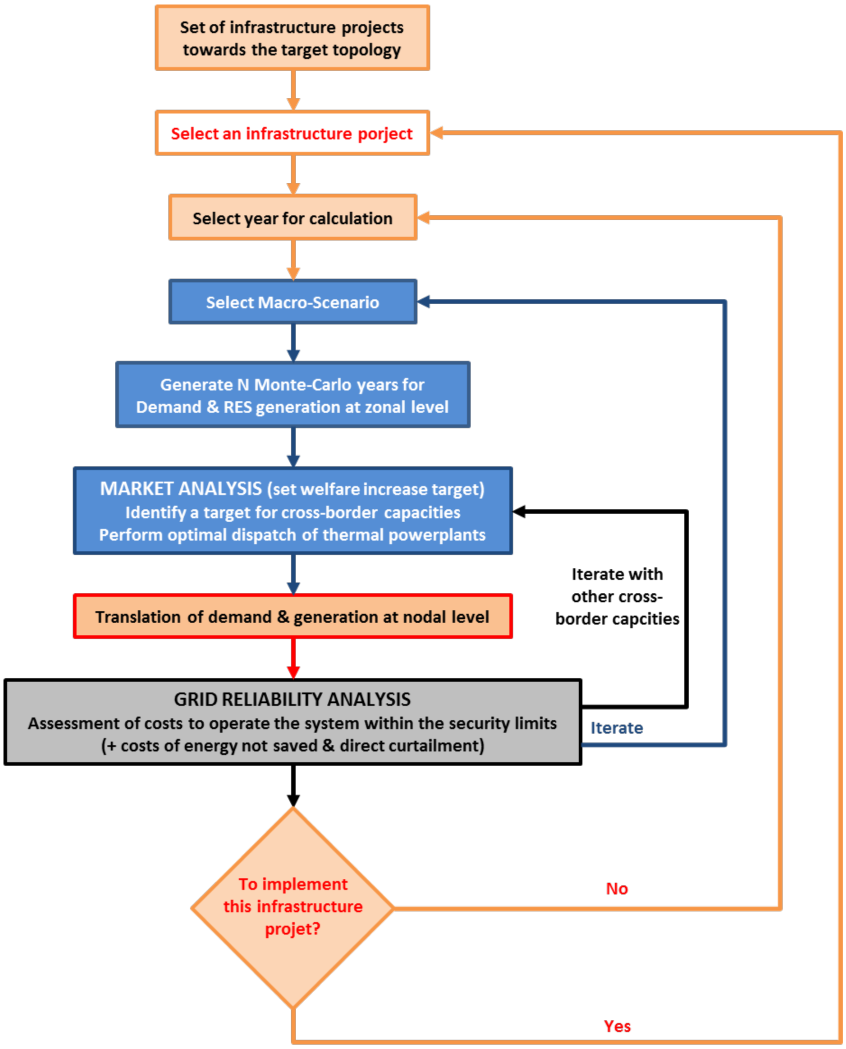

Step 2:
Define the most optimal grid development path

Figure 3-3: Global overview of decision-making process for system development

3.2 Macro-scenarios

Macro-scenarios are used to capture uncertainty in a distant future. As explained earlier in this report, the more we look towards the future, the more uncertain we are about the operating state of a power system. In the context of grid development, it is impossible to make reliable forecasts or even quantify the probability of the forecasts. Macro-scenarios are used to model the uncertainty in long-term evolution of the parameters that affect the future operation of a power system. For example, the ENTSO-e studies (TYNDP 2014 & 2016) are based on extensive exploration of the 2030 horizon. The basis of these studies is four 2030 visions, shown in Figure 3-4. These visions are very distinct from each other and they try to cover as much as possible the space of possible realisations. It is expected that the real trajectory towards 2030 (blue arrow on Figure 3-4) will land somewhere within the space described by the four macro-scenarios.

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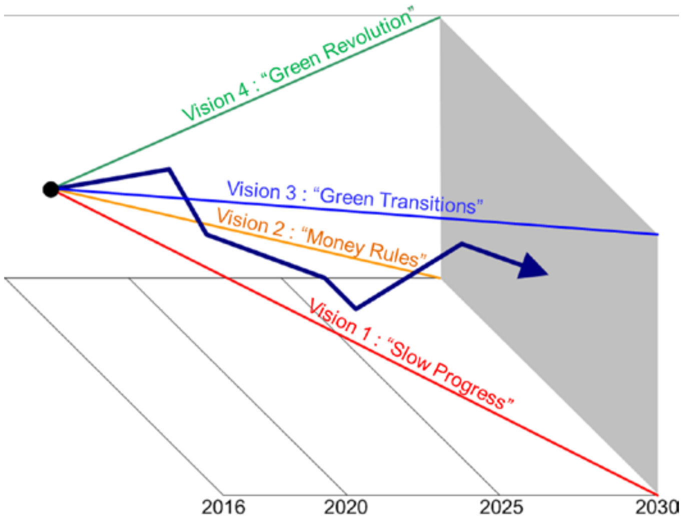

Figure 3-4: Illustration of the ENSTO-e macro-scenario approach to cover uncertainties towards 2030

The scenarios used as an input of the methodology are based on a set of exploratory macro-hypotheses. Thus, by definition, a scenario will not be either more probable or more preferred than another. Each scenario provides a possible picture of the future based on a macro-hypothesis. A macro-hypothesis results from the choice about possible energy policies of countries, for example, support for energy efficiency, deployment of electric vehicles and even the use of demand side management, etc., and postulations of economic growth and use of electrical energy. Thus, each scenario includes for each country the expected overall demand, installed capacity and the costs of different generation sources and the CO_2 price in accordance with to the macro-hypothesis considered. The macro-hypothesis projections and the scenario creation are out of scope for the GARPUR project.

3.3 Generation of micro-scenarios

In the second step of our approach, we try to capture the operational uncertainties around the actual operating states that we might expect. These are constrained by the maximum demand and the location and capacities of generation defined by a given macro-scenario, but there can be many combinations of operating states within those constraints. Historically, grid development is based on the extreme values of the demand of a country; however, due to the development of RES and interconnections between countries, there is no longer any certainty that this state is really the worst state the system will face. Moreover, a worst-case scenario is not an acceptable approach if we want to quantify the expected costs related to reliability management or the likely year-round economic impact of different macro-scenarios and grid developments. For these purposes, it is necessary to generate more credible time-series that capture the full range of variability of load and RES generation patterns and their correlations.

Based on the available historical data, e.g. demand, generator availability and availability of power from renewable energy sources, we generate time-series that are used to describe the real-time operation of the power system. These time series are generated with an hourly time step over a period of one year and for each area of the modelled power system. The number of time-series is increased by applying planned outages for generation and transmission system assets.

Similar idea of generation of so called Monte Carlo years is used in system development work package of another European project called e-Highways (see [e-Highway, 2012] for more details).

3.4 Market tool

Once all the micro-scenarios are defined, we need to determine which generators will be brought online to meet the expected demand. This depends on the behaviour of the wholesale electricity market and its preference for the type of generation. We use a market tool as a proxy for modelling the electricity market's preference for generation. A time-series of one year can be used as an input for this market tool. Using a time-series for a whole year is intended to give more realistic results especially considering the seasonal changes which are important for certain generation types e.g. hydro, pumped storage etc. The objective function of this model is to minimize the overall cost of electricity generation whilst meeting demand in each zone, respecting, if they are specified, cross border transmission constraints, constraints on generation e.g. ramp rates, min-up and down times etc., and maintenance of a given level of reserve in each zone.

The market tool receives as an input the techno-economic characteristics of the production units (start-up cost, installed power, ramp-up and ramp-down time, minimum power, etc.) and the fuel costs. These data are specified in each studied macro-scenario. Besides generation dispatch, the market tool provides as output the cost for producing and consuming electricity in each bidding area, either per generating unit or in terms of zonal marginal prices.

The market tool is solved for each time-series constructed in the previous step. The output of the model is the set-point of all the available generators and cross border flows. However, at this stage – which represents the market's behaviour before any intervention by a system operator – the transmission limits within a region do not constrain the dispatch of generation. In cases where a market solution violates transmission constraints and/or reliability constraints, an intervention from a system operator is required to make a market proposed solution a secure operating solution.

3.5 Translation from zonal to nodal data

The precise within-zone network impacts of a given market dispatch can only be analysed by going down to a nodal level. We use a top-down approach for translation from zonal to nodal level to determine how aggregated quantities are distributed at a nodal level.

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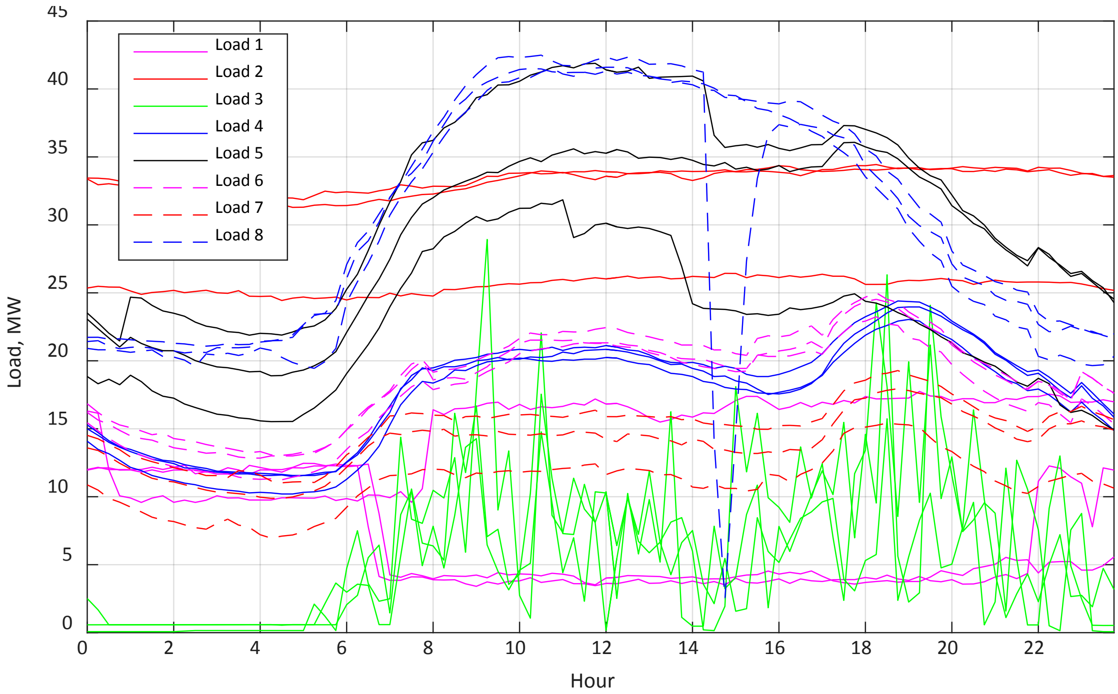

Figure 3-5: 24 hour recorded demand profiles (15-minute resolution) of 8 different loads (representing different types of customers) for the third Wednesday of January, in three subsequent years

Up to this stage of the methodology for synthesis of credible operating states, time-series were crucial in order to get credible generation dispatch. The generation set points have been obtained from the market model which used, as inputs, time-series of demand and power available from RES based on historic observations, and the relevant unit commitment constraints for other generators. However, if time-series have to be sampled for each year for each load and for each RES generation, e.g. for use in a Monte Carlo assessment of system operation risks and costs of system operator interventions, the possible number trajectories grows exponentially and become unmanageable. However, for zonal to nodal conversion of demand and RES and the further analysis, we propose to use snapshots, instead of time-series.

For the top-down approach, a few options for translating from zonal to nodal snapshots are available. Current practices used in system planning most often use operating states from benchmark recorded days (or snapshots) of the total system load, which are scaled proportionally to the forecasted total system load growth. Then, the first option is to use constant shift keys (representing proportions of each load from the total system load) to distribute the total load proportionally for all the benchmark snapshots. The second option is to use a set of limited number of shift keys. These two options are very simple and are often used as of today. However, as can be seen in Figure 3-5, this might not be enough to capture either the variability of the system at all time, or the uncertainties in the long term horizon. Task 4.2 aimed at improving the process by introducing a third option – sampling snapshots of demand and RES generation. Actually sampling a big enough number of snapshots is the main strategy to cope with the big uncertainties (in terms of load and RES generation snapshots) in the long-term context of work package 4.

Figure 3-6 summarizes the whole algorithm. At a zonal analysis level, different patterns of availability of schedulable generation, i.e. not weather-dependent, highly variable RES, can be modelled in a Monte-Carlo simulation of different years giving a number of “Monte-Carlo years” (a concept described in [e-Highway, 2012]) . The corresponding credible generation dispatch time-series are treated as an input to the algorithm, as well as available demand, RES generation records and load growth forecast. There are well-developed tools like the Weather Research and Forecasting (WRF) model (described in Section 6.2)

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which can be used to sample weather parameters at specified locations and account for the spatial-temporal correlations. It is well understood that demand is also correlated with weather but it is also influenced by other factors such as time of day, day of the week, whether the day is a public holiday and time of the year. In the longer term, demand is also influenced by changes to the kinds of electrical equipment used by energy users and patterns of use within the wider economy.

It is important to note that the approach used in the e-Highways project [e-Highways, 2012] for zonal to nodal conversion make use of constant shift-keys for zonal to nodal conversion. Therefore, what we propose here for zonal to nodal conversion is an extension of the e-Highways approach.

The algorithm starts with a pre-processing stage comprising of the standard statistical procedures for data cleaning and data validation. It should be noted, though, that because a lot of RES generation is being installed in the distribution grid, its output needs to be subtracted from the demand records for each node in order to capture the different trends between load and RES generation. Then, before the actual sampling, we propose that in order to capture better the correlations, nodal demand records should be grouped by season, weekend/weekday, and time of day (morning/noon/afternoon/evening/night). For consistency, the rest of the data (the conventional and RES generation) should also be grouped in the same way.

There are various sampling techniques that have been applied with success in power system analysis and reference [Rios, 1999] gives a good overview of a number of them. However, for the purposes of Work Package 4, one main characteristic of the sampling strategy is to provide not purely random combinations of load and RES generation, but realistic ones that respect spatial-temporal correlations between elements. One such algorithm is the NORTA sampling that is presented in the appendix of this report. It must be noted, though, that if the number of samples is not enough, then extremes can be missed (Figure 6-9 from the Appendix “6.4.10 Difference between clustering and sampling” demonstrates this). However, the main paradigm of Task 4.2 is that capturing the correlated variability of load and RES generation is far more important than limiting the number of samples. Thus, in order to ensure that extremes are not skipped, a large enough number of samples have to be generated. Also, in the framework of the Task 4.2 methodology for synthesis of credible operating states, a further research topic might be improving the correlated sampling procedure. A number of options are available with different trade-offs between computational load and relative ease of implementation. (One advantage of NORTA is that, although it is fairly approximate, it is relatively straightforward to apply which can be a significant advantage as the number of nodes to be modelled increases).

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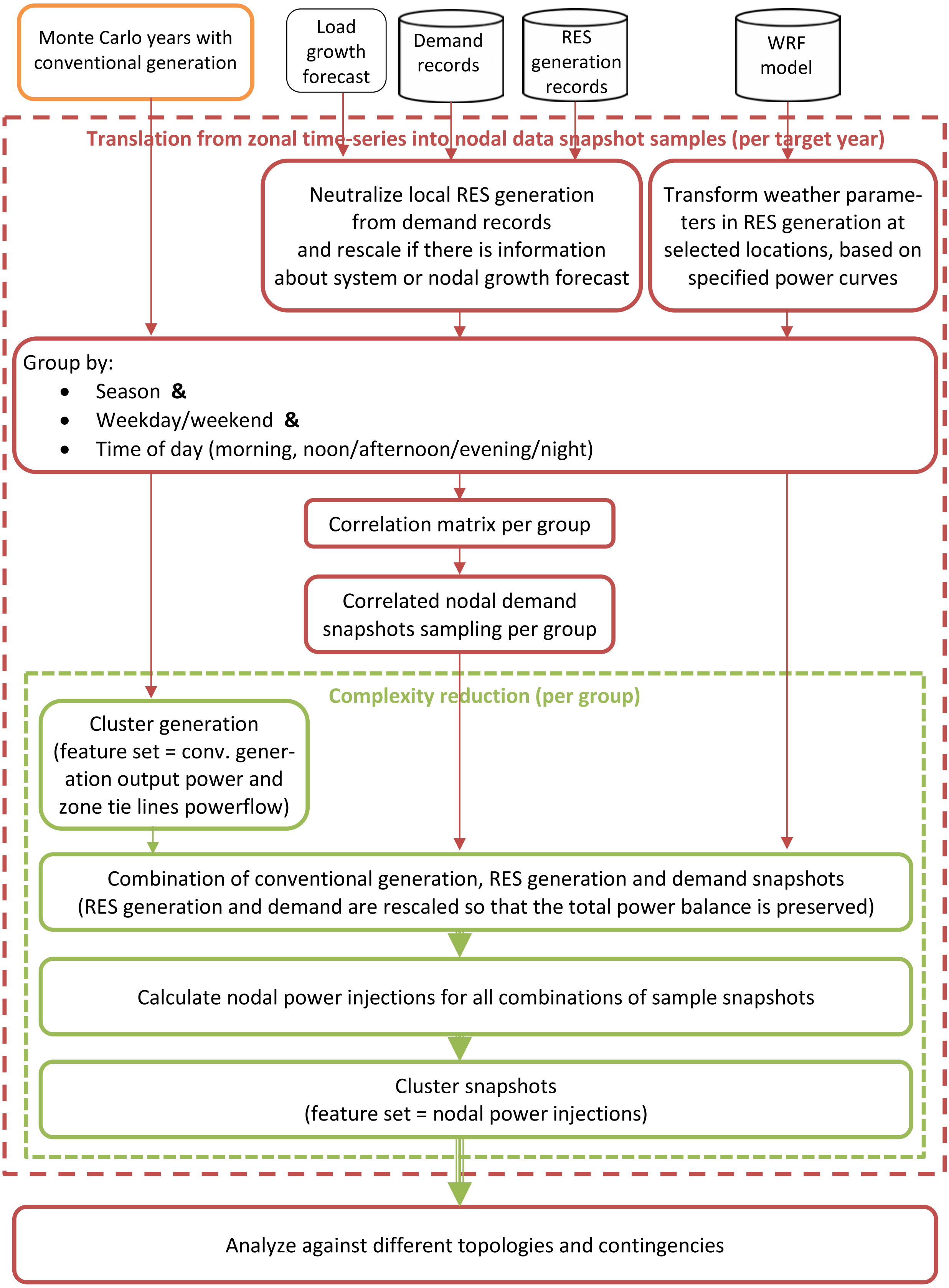

Figure 3-6: Algorithm for translation of zonal to nodal data

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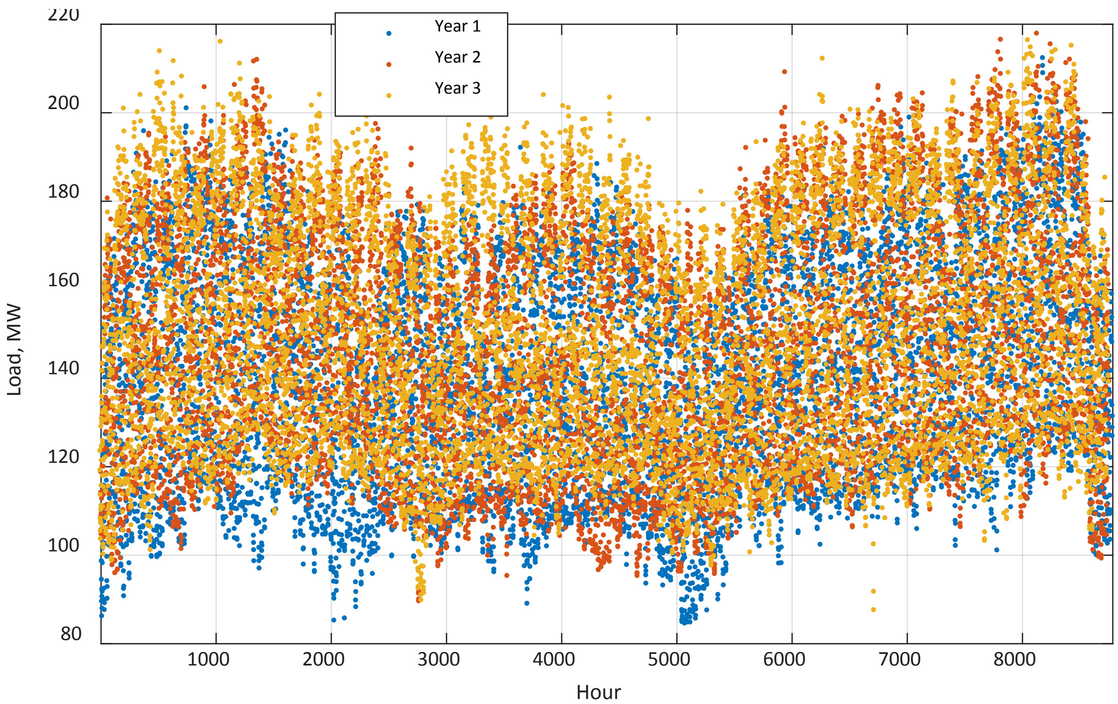

Figure 3-7: The total load of three subsequent years of records (1 hour resolution) of an example zone, comprising of the 8 different loads from Figure 3-4

3.6 Clustering

The previous section explained that the translation from zonal to nodal loads can be performed by generating a large enough number of correlated samples of loads (each representing snapshots and not time-series but, by virtue of zonal totals being correct, still consistent with unit commitment time series). Figure 3-7 shows the total load of three subsequent years of records (1-hour resolution) of an example zone, comprising of the 8 different loads from Figure 3-5. The similar demand values in the similar seasons and times of the day, in the process of translation from zonal to nodal loads, will result in similar sets of correlated samples. In line with the concepts developed in WP2 of GARPUR, a large number of operating states can be discarded (in order to avoid having to analyse them in detail) without any significant impact on the risk assessment.

Reference [Kile, 2014] has demonstrated that clustering can be applied to group similar operating states and calculate reliability indices with good precision by analysing only the cluster centroids instead of all samples (i.e. sampled snapshots). Thus, clustering can be regarded as a complexity reduction technique. In other words, similar operating states will not be analysed in detail twice.

The required minimum number of samples is determined by the variance of the sampled values and needs to be high enough to capture extremes (as already discussed). Because the sampling (in the context of this report) is correlated, if the number of samples is increased, most of the new samples are expected to fall into the regions of already defined clusters (i.e. of the most probable operating states). Thus, although the number of samples may, for example, be doubled, the number of clusters will be somewhat less than doubled. Only the centroids of clusters are subject to the computationally demanding task of analysis of the operating states. The sampling itself is not computationally demanding. As a consequence, this approach makes it feasible to increase the number of samples without unduly increasing the total computational burden.

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For more details on clustering itself and discussion on its application in work package 4 please refer to section 6.4 . Here will be briefly presented its general place in the algorithm from Figure 3-6.

The clustering can be performed in two stages. They both aim at reducing the number of snapshots that needs to be further analysed. The first one, however, is optional. It is aimed at identifying similar generation patterns because intrinsically generation dispatch is a function of the total system load (and of course subject to technical constraints of the grid, but this is usually not considered in the market tools). However, the same total system load can be realized with different combination of nodal demand and because of that the clustering of the conventional generation dispatch can be treated separately from the nodal demand samples. It is most appropriate to use conventional generation output power and inter-zone power transfers as a feature set for such clustering.

The next step is to create combinations of the sampled load and RES generation and the conventional generation (either clustered in the previous step or the whole set). Then, for each combination the nodal power injections are calculated and they are used as a feature set for the second stage – clustering of the operating states (snapshots) with nodal "resolution". The result is a reduced set of credible operating states that are realistic and representative of the future power system (of course, under the initial scenario suggestions).

Any changes in the network topology (for example due to maintenance) can be treated as events imposed on the combined generation and demand states afterwards. It should be noted, though, that the clustering is done for each group of season, weekday/weekend and time of the day. In this way partial temporal information is preserved for the snapshots, which in turn can be used, for example, in a maintenance proxy.

3.7 Assessment of the credible operating states

In this section, we propose a modelling framework for assessment of a large set of credible operating states. The assessment procedure forms the basis of the analysis that is performed in a system development activity. The assessment process will provide a system planner with necessary evidence for the *need* of investment and will also give insights into *what* to invest in.

In the following subsections, we discuss the inputs that are required for the assessment procedure, modelling framework and also the outputs from the proposed process.

3.7.1 Inputs required for assessment methodology

In the following, we list required inputs for our proposed assessment procedure.

3.7.1.1 A set of credible operating states

As discussed in earlier sections, a credible operating state is a particular realisation of generation and demand levels, as well as flows between the interconnected control areas and also network configuration. Figure 3-8 shows different components of an operating state and also show how each component is related to the other. For example, we note from Figure 3-8 that the demand depends on the weather and time of the day i.e. demand has diurnal and seasonal dependencies. Similarly, generation from wind turbines and solar panels depend largely on the weather. From the system development perspective, it is very important that we take proper consideration of such temporal and spatial correlations.

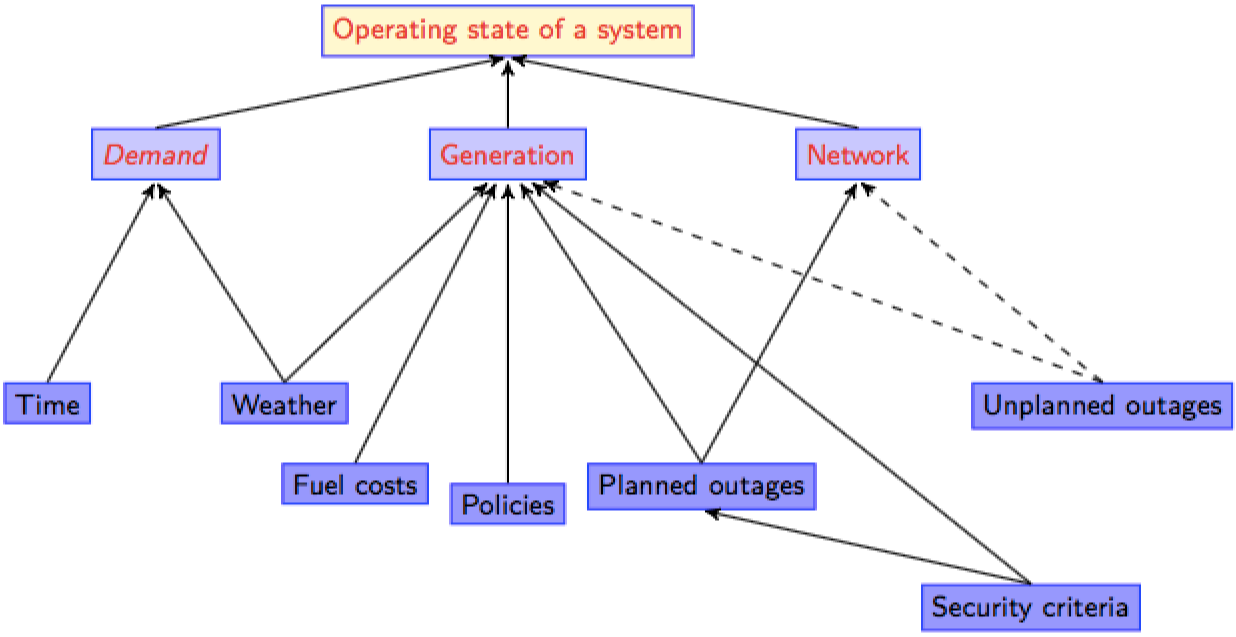

Figure 3-8: Components of an operating state

A set of credible operating states is required for our assessment process. The assessment can be carried out on snapshots or on time series of daily profiles. The proposed methodology is a proxy for short-term operational planning and therefore the time-series analysis need not look across more than a 24-hour time horizon. However, although a 24-hour cycle is common for scheduling of generation, it starts from some knowledge or suppositions of generators' states at the end of a previous 24-hour period and acknowledges that units can continue beyond the end of the new one. Thus, in order to avoid 'end effects' in unit commitment, a few additional hours at the beginning and end of a period might be modelled. In the market tool in the illustrative test case described below, we used time-series of one year and the generation set-points are obtained such that they respect temporal constraints such as ramp-rates and min up and down time constraints. Moreover, the clustering is carried out on each interval within the time series, i.e. on snapshots, with the network adequacy assessment process carried out once for each similar snapshot.

3.7.1.2 A proxy for asset management

As was discussed in section 2.1, to assess a credible operating state we need to take account of the maintenance of assets. Note that here we are only concerned with the planned outages (e.g. time-based maintenance, condition-based maintenance, …) of transmission components. Planned outages of generation have already been taken into account while building the set of credible operating states. Unplanned outages will be managed through a contingency list.

Two broad approaches are possible in respect of the treatment of planned outages of transmission assets:

1. to model, albeit in some approximate way, the way in which outages would typically be planned (time-based maintenance and/or maintenance triggered by inspections or component monitoring devices), and then to assess the operability of the system given such modelled maintenance activities;

2. to assess the maintainability of the network while still being secure against contingencies (unplanned outages), i.e. to determine if there is margin for planned or inspection triggered outages to be taken on top of the envisaged 'maintenance-less' scenarios.

In approach 1, planned outages of assets may be sampled randomly for a given target year subject to some high level constraints. Past records and information about the evolution of maintenance practices are inputs to create assumptions about the timing and duration of planned outages. For example, the expected time and frequency of tower painting can be extracted from past records to form a base set of assumptions. However, it is also possible that particular maintenance tasks can be carried out more quickly in future or are needed less frequently. If judged to be credible, such changes would be represented in the set of input assumptions.

Relative to an aim to assess the feasibility of days of operation, it may be noted that planned outages typically last longer than a day. Thus, for a given day being assessed, a particular planned outage is either present or absent. It seems justified that not all sampled maintenance plans, i.e. sampled combinations of planned outages, will be acceptable as the grid should not be designed to accept maintenance even in the worst context. For example, outages are typically scheduled to take place when power flows are relatively low. This may be correlated with low demand or, for exporting areas, the anticipated unavailability or low merit of generators in that area. As a proxy of the outage planning process with which WP5 is concerned, the system development planner might do one of the following:

- ensure a certain level of maintainability of the network, expressed through the requirement that a given, minimum proportion of sampled maintenance patterns must be 'operable' in respect of the system being able to meet all demand under those conditions; or
- define a set of conditions of context (e.g. low load, no output from renewables, …) in which all sampled maintenance should fit while still meeting all demand.

Finally, normally, only a certain, maximum number of outages can be accommodated simultaneously in a particular area. This limit arises for one of two reasons: the maintenance crew, i.e. the human resource carrying out the work, only has a certain capacity; or the network capacity is such that the system cannot be operated in accordance with the reliability criteria relevant to system operation if there are too many planned outages. If asset management issues require a higher number of outages to be taken in the same area at the same time, grid reinforcement and/or enhancement of maintenance crew staffing levels may be triggered (provided it is economically justified).

No search for an optimal maintenance plan will be conducted in the framework of system development. In fact, except as an example of the kind of outage plan that might 'typically' be encountered, it does not make much sense to define the exact maintenance plan decades in advance largely because of the uncertainties that would normally be resolved within year or, at best, year-ahead. These include altered priorities because of equipment faults or because of system developments and the uncertain behaviour of generators that are owned and operated in liberalized electricity markets independently of transmission owners and operators. It is, however, a fact that in real-time operation, it is relatively rare for all grid components to be fully available at the same time, while at the same time each component individually is available most of the time. Outage planning is thus mostly about finding the right moment and the right combination of outages, which is not simple. An approach has been proposed in work package 5 for the maintenance policy budgeting problem and can be found in [GARPUR, 2016d]. This approach could be considered for long term planning context even though its complexity seems challenging for this context.

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In light of the complexity of the maintenance scheduling problem, the participants in WP4 suggest approach 2. This proposed to address the maintainability of each asset, which is the feasibility of the maintenance action. An estimate can be made of which combinations of outages – whether planned or unplanned – can be taken together. This 'envelope of maintainability' could be assessed by means of simple 'single state' optimal power flow in which the 'single state' is an initial N-2 condition where one of the outages is planned and the other is unplanned – something that might be referred to as (N-1)-1 – with results classified as (i) those that require no constraint of a market-driven generation dispatch, (ii) those that can be accommodated but with some re-dispatch cost; and (iii) those that cannot be accommodated even with re-dispatch of generation.

One challenge in this approach for a large network is the very large number of combinations of (a) planned outage and (b) unplanned outage that may need to be assessed for each credible combination of demand and generation. Other issues are:

1. The way a system operator treats a planned outage is different from how it would treat an unplanned outage. The timing of the former can be controlled but, once the outage is taken and because it lasts, in general, at least a day, continuous thermal ratings must be respected. On the other hand, the timing of unplanned outages is random but, when an outage occurs, a breach of continuous ratings can be tolerated provided the post-fault loading is within short-term ratings and a post-fault corrective action can be carried out sufficiently quickly to reduce loadings to within continuous ratings.
2. It might be difficult to determine whether results indicate a *sufficient* level of maintainability. This is because, in practice, combinations of planned outages will often be taken, as far as possible, in electrically remote parts of the system. Careful interpretation of N-2 or (N-1)-1 modelling would be required in the context of best advice on the number of planned outages that should normally be taken in the course of a year and how long each outage wold normally last. Furthermore, consolidation of individual asset maintainability needs to be made to consider the fact that the maintenance of several assets is likely to be required within the same timeframe. Asset maintenance frequency is therefore an important input to consider.

Further work will be required to address the above issues[8].

3.7.1.3 A contingency list

A contingency list is required for the assessment procedure. This list includes the set of all unplanned events to secure against in the base case. We propose to start with (N-1) contingency list in respect of unplanned outages. The reason behind this choice is two-fold: first, the probabilistic reliability criterion (which is likely to involve changes to the contingency list depending on prevailing conditions) is still under development in WP2 and in WP4 we are not yet sure how to fully utilise it; and, second, we believe that if we can solve the assessment process with (N-1) contingency list then we would be able to solve it with a dynamic contingency list that would result from the work of WP2.

[8] There is a relative dearth of literature on power network outage planning, However, it is noted that a few papers on modelling of the outage-planning problem have recently been published, not least at the 19th Power Systems Computation Conference.

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3.7.2 The assessment process

3.7.2.1 Conceptual framework of the assessment process

The conceptual framework of our assessment model is as follows: a system planner is faced with a possibility that a credible future operating state will be insecure (under a given reliability target), or worse, the network's capacity will be inadequate, i.e. not capable of meeting all the demand. When the time comes, the system operator should intervene to change the operating state to make it secure (with the action very likely to incur a cost) or, if they do not, it is because insufficient means are available to them to do so. In either case, the transmission expansion planner should consider whether investment in additional network facilities is required to render the system securable under those circumstances or reduce the cost of the operator's intervention. As explored within WP3 of GARPUR, one particular difficulty is to determine the indirect costs that could be incurred after an unplanned event. In a system development timeframe and given a large set of operating states, it is not possible to estimate all the indirect costs related to unplanned outages and make a judgement about preventive and corrective control and the need for investment in new facilities. Therefore, we propose to simplify the process.

The proposed model is a proxy to an operational planning problem, and checks the operability of a power system given a set of initial conditions. By operability we mean the following two things:

- Ability to meet the total demand while respecting network constraints, facilitating planned outages and maintaining a level of reliability that is described by the given reliability criteria (in this case we use 'N-1' in respect of unplanned outages).
- If an operating condition is not operable, then through the model we answer two questions:
    - could it be made operable through system operator actions i.e. using control actions such as generation rescheduling and contracted load shedding/demand reduction.
    - If it could be made operable via means of control actions, then how much does that cost[9].

If a given situation is not operable, it implies a risk to reliability of supply to energy users; if the risk, summed over all such situations, is regarded as excessive, investment in new network facilities – 'reliability-driven' investment – should be carried out such that the risk is reduced.

3.7.2.2 If investment in new facilities reduces the total costs – taking into account the investment costs – then 'economy-driven' investment should be carried out. Mathematical framework of the model

Mathematically, our assessment model assumes the form of a security constrained optimal power flow (SCOPF). The proposed model is centred at a market-defined solution and calculates the cost of deviating from it when network and security constraints are applied to it. The market-defined solution is an input in the form of a snapshot that gives the wholesale electricity market's preference for the commitment and generation of conventional generators for a given pattern of demand, the available power from renewable sources and the availability of generation plants. The initial condition for the operability assessment also includes any 'prior' outages for network maintenance or construction work.

[9] Given enough notice, one possible action would be the re-scheduling of any 'prior' planned outages. If an appropriate outage window exists and the necessary human resources are available, the planned outage can be brought forward. However, in shorter operational planning timescales, e.g. less than a year ahead, often the only option is to postpone the outage. This runs the risk of an increased probability of failure of the asset and/or longer repair time, or outage congestion and associated risk of higher cost of system operation or non-operability.

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For a given contingency list of unplanned events, we secure against all events in the base case. We use continuous line ratings for the base case (pre-contingency, bit including any ‘prior’ outages) and short-term (e.g. 20 min) line ratings for the post-contingency cases before any post-contingency corrective actions are carried out.

Table 3-1 lists the main ingredients of the optimisation model. The objective of the problem is to minimise the cost of deviations (mainly pre-contingency (preventive) actions) from market solution and cost of load shedding (mainly post-contingency (corrective) actions).

In general, there is the option to use either a simple “DC” model of the line flow equations to keep the formulation simple or an AC model with the addition of voltage constraints and limits on the production and consumption of reactive power on generators and controllable reactive compensation.

Although a DC load flow does not give totally accurate results, it has significant computational benefits compared with an AC load flow. Moreover, it may be argued that, in a long-term system development context that is subject to many uncertainties, it is better to analyse, quickly even if somewhat approximately, many micro-scenarios than to be very precise about just a few. However, resolution of the trade-off between computation time and precision is usually a matter of judgment for those responsible for the overall process and how much resource – human and hardware – they are prepared to commit to it. On the other hand, it will be clear that system limits associated with reactive power and voltage cannot be identified by only DC load flow. The identification of need for additional voltage control capability and reactive power resources and the development of the case for any associated investment are very much part of the process of “system development”. However, because these needs can, to a large extent, be met by reactive compensation that can be specified, procured and commissioned relatively quickly, e.g. in between 12 and 18 months, there is arguably less need to address voltage and reactive power issues over time horizons of, say, 5 or more years than there is for thermal issues for which the solutions may require entirely new lines that are likely to have very long routing and consenting processes. On the other hand, in future scenarios that have both thermal and voltage issues, the best solution may only become apparent when both are considered. This may lead to, for example, re-construction of a given overhead line route at a higher voltage or development of a voltage-source converter-based embedded HVDC solution that also gives the possibility of using underground or undersea cables.

A practical recommendation made here is for DC power flow to be a first step but not necessarily a last step in system operability assessment. In a second step, more detailed assessment may include AC steady state analysis followed by, for micro-scenarios judged to be near to stability limits, stability analysis.

Table 3-1: Ingredients of our optimisation model

Objective function	Minimise - cost of pre-contingency deviation of generation from the market solution and optionally post-contingency deviation - cost of load shedding (mainly post-contingency deviations)

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Constraints	• power balance equations • power flow equations • Generation bounds • Regulation bounds, e.g. for phase-shifting transformers • (optionally) Ramp rate/rate of change constraints • Continuous line ratings for pre-contingency (unplanned outage) case and post-contingency, post-corrective action case • Short-term ratings for post-contingency (i.e. post-fault outage) case • (optionally) pre-contingency voltage limits • (optionally) post-contingency voltage limits[10]

3.7.3 Outputs from the network reliability assessment process

The assessment process is used to identify the critical credible operating states. A critical operating condition could arise because of any or some of the following reasons:

- The cost of re-dispatches of generation is very high;
- The cost of load shedding (necessary to ensure feasibility of the OPF solution) is very high.

It is important to note that a judgement is required when characterizing operating states as critical operating states. This judgement could be based on how often the problem occurs and/or what are the consequences.

From the output of the optimisation model, we can find the locational marginal price (LMP) or 'shadow cost' across buses. If the price differences are very high then it identifies a possible need for investment and gives an insight to the system planner that reinforcing the corridor between the corresponding buses would help to reduce the price differences and may be justified from an economic point of view (through the reduction of constraint costs) even if the particular market being modelled does not trade on a basis of LMP. As discussed earlier in this report, these types of investment candidates are economy driven investments.

If the cost of load shedding is very high (i.e. above a certain threshold, which might be set at zero) then it identifies a problem in respect of reliability. An insight can be gained from the solution that could identify the location and amount of load shedding and possible constrained generation that cannot be ramped to meet the demand.

The objective function of our assessment model is a sum of costs of regulation and load shedding. Note that in post-contingency operation, we allow the flows on the lines to exceed continuous line-ratings and go up-to short-term line ratings. Such violations can be penalized in the objective function if the planner chooses not to make full use of post-contingency corrections of line loadings. However, where ramp rate or rate of change limits are specified for generators or other controllable facilities such as phase-shifting transformers, the solution of the OPF is also constrained to ensure that post-contingency loadings can be reduced to the continuous rating within the given time period of the short-term rating, e.g. 20 minutes. If

[10] Practical solution of a full AC security-constrained OPF is likely to be able to deal with only a very short list of contingencies which, in turn, may require pre-filtering of the contingencies to be studied.

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this cannot be achieved, the optimisation finds the least cost pre-contingency adjustment of the operating state, i.e. preventive actions. (See Figure 3-9).

Table 3-2: Critical operating states and the insights for a system planner

Reason of critical operating state	***Type of criticality***	***Insights from the model for a system planner***	***Possible system development options***
High cost of operating a system	Economy related	Difference of locational marginal prices across nodes	Reinforcing the corridors between high price difference zones/buses
High cost of load shedding	Reliability related	• Location of load shedding • Active line limits on transmission lines	Increase transmission capacity where the generation is constrained Increase transmission capacity where load is being shed
Post contingency, pre-corrective action line flows above continuous ratings	Reliability or economy related	Identification of the lines with high post-contingency flows and of dependency on corrective actions	More transmission capacity in the zone will help to ease off the congestion; steps could be taken to enhance confidence in the success of corrective actions

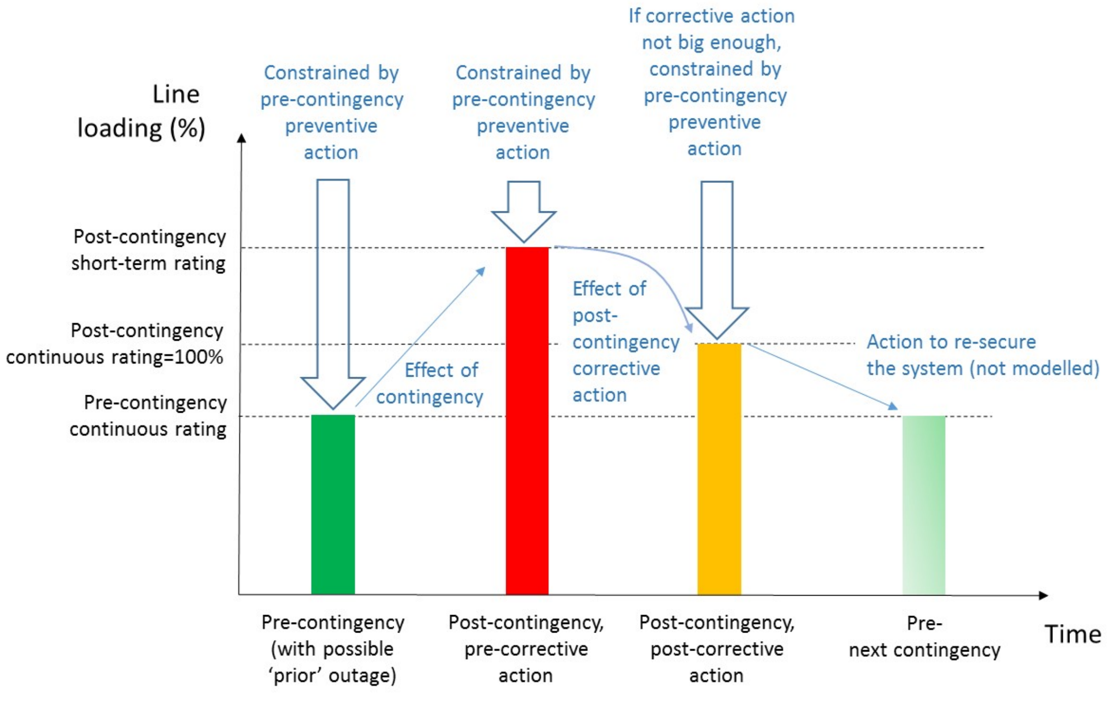

Figure 3-9: Preventive (pre-contingency) and corrective (post-contingency) actions and line limits

Note: in GARPUR WP4 to date, the pre-contingency continuous rating has been taken to be equal to the post-contingency continuous line rating; in general, they may be different in order to ensure a certain, minimum thermal 'headroom' for the short-term rating to be valid.

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4 AN ILLUSTRATIVE EXAMPLE

In this chapter, we illustrate the proposed methodology on a small 10-bus network. The 10-bus test case is proposed by the WP7 of the GARPUR project for reliability studies. The details of the test case and numerical results are presented in the subsequent sections of this chapter.

4.1 The 10-bus test case

The topology of the 10-bus network is presented in Figure 4-1. This network is constructed by combining two modified versions of the Roy Billinton test case [RBTS, 1989].

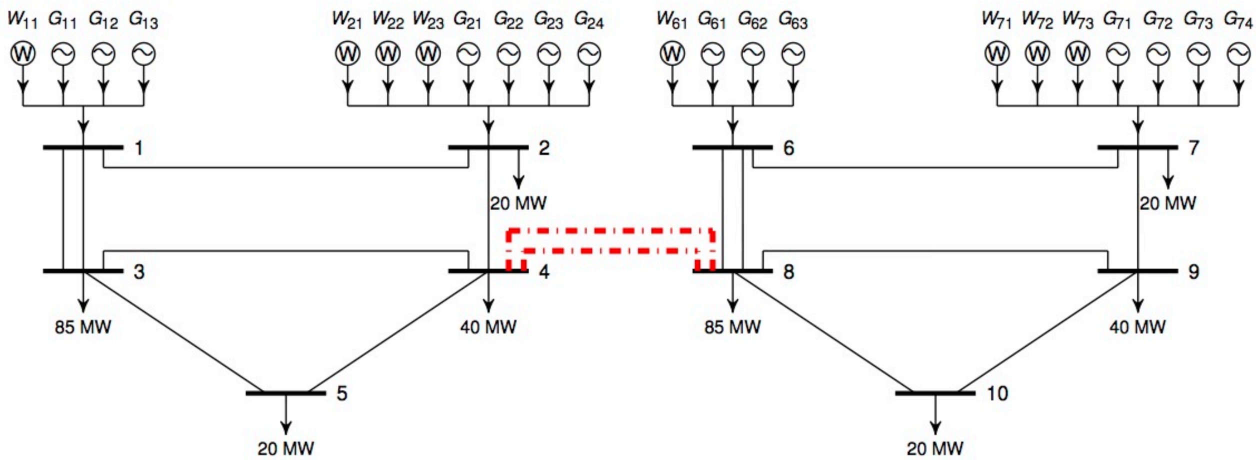

Figure 4-1: A 10-bus network consisting of two zones. Each zone is symmetric and contains 7 thermal generators and 4 wind generators

The 10-bus test case consists of two zones. We consider just one 'macro-scenario' in which each zone has 7 thermal generators and 4 wind generators. In each zone, the overall thermal generation capacity is 190 MW and peak demand is 165 MW, giving total system thermal generation capacity of 380MW and total demand of 330MW. The total wind generation capacity is 190 MW with 150 MW in zone 1 and 40 MW in zone 2.The two zones are connected with two tie lines of total capacity 150 MW i.e. each line with 75MW pre-fault continuous rating. Each zone has 7 transmission lines. Detailed data of this test case are given in the appendix of this report.

4.2 Assumptions

In this section, we list a number of assumptions that we have made in order for the numerical results presented in this chapter.

4.2.1 Reserve requirement

The market tool enables us to specify a reserve requirement in each zone. We use 40 MW as a reserve requirement in each zone. This is because the largest single thermal generator in each zone has a capacity of 40MW. This reserve requirement means that each market simulation will commit thermal generation such that at least 40 MW of spinning reserve will be available in each zone.

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4.2.2 Contingency selection

We consider all single line and generator contingencies, double circuit contingencies, and the contingencies of singe tie-lines that connect the two zones giving a total of 38 contingencies, i.e. unplanned outages, for this case. The details of each contingency are given in Table 4-1.

Table 4-1: A list of contingencies that are considered for analysis

Contingency #	1	2	3	4	5	6
Contingency	Line 1-3	Line 2-4	Line 1-2	Line 3-4	Line 3-5	Line 1-3
Contingency #	7	8	9	10	11	12
	Line 4-5	Line 6-8	Line 7-9	Line 6-7	Line 8-9	Line 8-10
Contingency #	13	14	15	16	17	18
	Line 6-8	Line 9-10	Gen @ Bus1	Gen @ Bus1	Gen @ Bus1	Gen @ Bus2
Contingency #	19	20	21	22	23	24
	Gen @ Bus2	Gen @ Bus2	Gen @ Bus2	Gen @ Bus6	Gen @ Bus6	Gen @ Bus6
Contingency #	25	26	27	28	29	30
	Gen @ Bus7	Gen @ Bus7	Gen @ Bus7	Gen @ Bus7	Wind @ Bus1	Wind @ Bus2
Contingency #	31	32	33	34	35	36
	Wind @ Bus2	Wind @ Bus2	Wind @ Bus6	Wind @ Bus7	Wind @ Bus7	Wind @ Bus7
Contingency #	37	38				
	Lines: 1-3, 1-3	Lines: 6-8, 6-8				

4.2.3 Reliability criterion

We use (N-1) as a reliability criterion (relating to unplanned outages) for our analysis. As discussed earlier in chapter 3, we impose continuous line ratings for the pre-contingency operating point, short-term ratings for the pre-corrective action, post-contingency operating point and again continuous line ratings for the post-contingency corrected operating point. Generation rescheduling is allowed as a corrective action following a contingency and it is constrained by the ramp rate constraints and by the 'headroom' (scope to increase output) and 'footroom' (scope to decrease output) determined at the pre-contingency stage.

4.2.4 Time horizon and target year

For this illustrative test case, we consider one target year and a time horizon of one season (90 days) with a temporal resolution of 1 hour. This results in approximately 2160 time steps. We assume 10 different micro-scenarios for this study to allow some study of the variability of available generation and de-

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mand[11]. This implies that the market model is solved 10 times and a total of 21,600 snap shots of operation are analysed to start with. This number of snap shots is increased in the zonal to nodal conversion (because each zonal demand can be composed of different demand combinations).

4.2.5 Maintenance policy

We have not considered any planned outages (e.g. maintenance) of thermal generators or transmission assets in this illustrative case study

4.3 Generation of micro-scenarios

In this section, we discuss the generation of micro-scenarios for the test case. The micro-scenarios are in principle hour-by-hour evolution of the demand, renewable generation, grid topology and fuel prices. For this illustrative test case, we only build micro-scenarios for demand and wind generation. These micro-scenarios will be used as an input for the market model that determines the commitment of the thermal generation units.

We use the historic demand data supplied by the Belgian TSO Elia for three subsequent years, for eight different types of consumers, and constructed 10 different micro-scenarios. Each micro-scenario is a realisation of particular demand in a 90-day period and has temporal resolution of one hour. Figure 4-2 shows a single micro-scenario, where 90 24-hour periods are plotted. We can observe a typical daily demand pattern in Figure 4-2, and the spread around the mean is a product of the variations between days within the 90-day period.

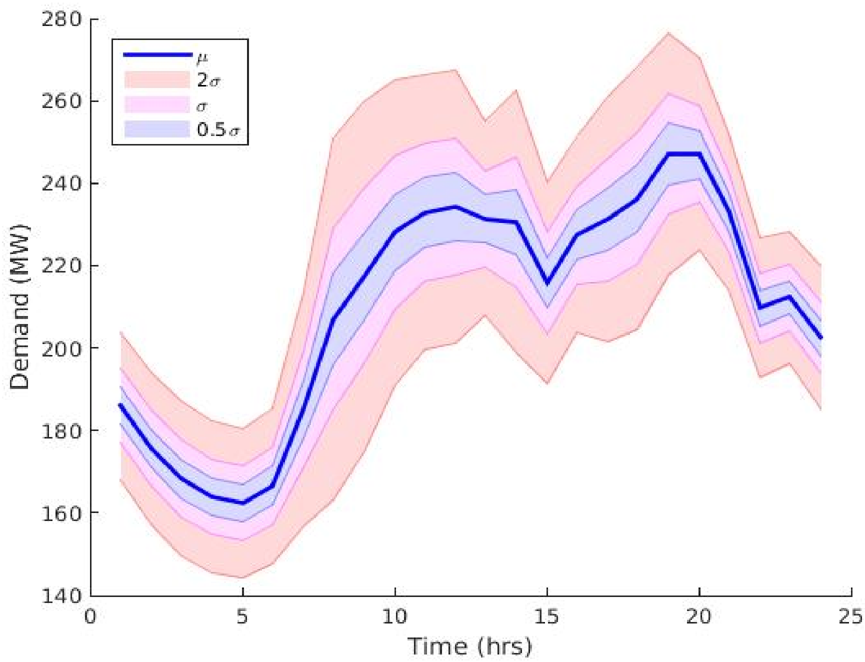

Figure 4-2: Daily demand spread of micro-scenarios for one particular scenario. Horizontal axis represents one day (24 hours) and vertical axis is total demand in MW

[11] At the level of study of international transfers of power and their variation, micro-scenarios may be referred to as 'Monte-Carlo years'.

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Figure 4-3 shows one micro-scenario for the total wind output in a single micro-scenario. Again the data is plotted for against 24 hours. We use 10 micro-scenarios for our analysis. This means that 2160×10=21,600 operating conditions are used as a starting point for our analysis. The operating states would increase when we perform the zonal to nodal conversion.

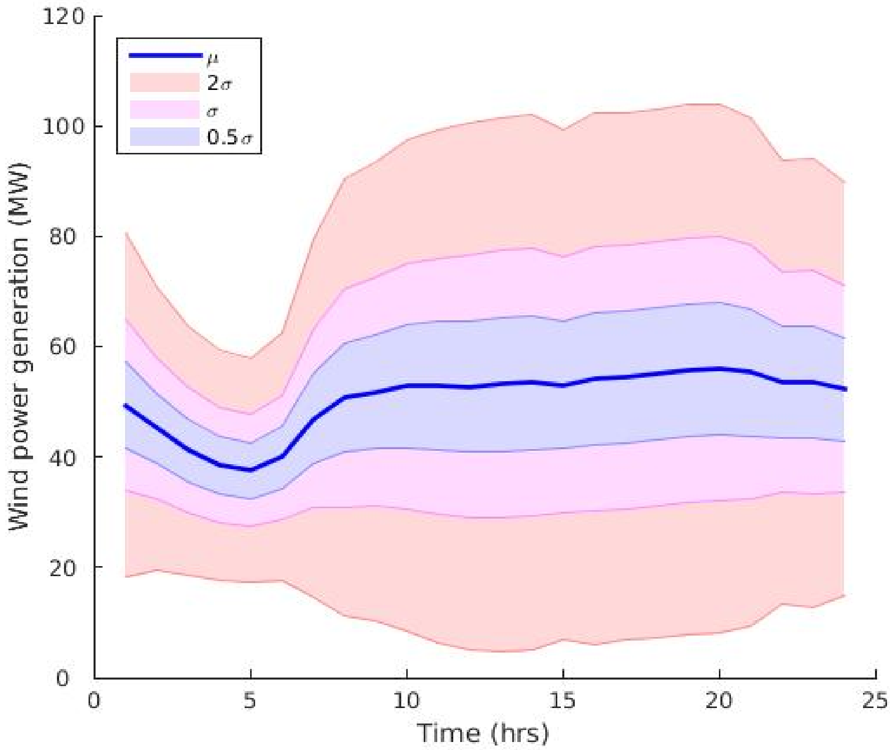

Figure 4-3: Spread of total generation from wind for one scenario

4.4 The market solution

The 10 micro-scenarios that we constructed are used as an input to the market model. The market model is used as a proxy for the behaviour of the wholesale electricity market and decides on the optimal commitment of the thermal generators. The objective of the market model is to minimise the total cost of generation whilst respecting the following constraints:

- Overall demand is satisfied;
- Reserve of 40MW is met in each zone through thermal generators;
- Capacity constraint on the interconnector between the two areas is satisfied;
- Constraints on the ramp rate of thermal generators;
- Minimum up and down time of thermal generators;
- Minimum stable output of dispatched generators.

Note that it is assumed that the market is indifferent to within zone network constraints. The inter-area constraint is taken to be equal to 75MW. Figure 4-4 shows the average total generation from the thermal units only and the minimum and maximum spread of the generation in each time period during a day for 10 micro-scenarios. We note that the minimum generation in all scenarios in each hour is 120MW. This is

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because that minimum number of generators that were switched on was 6 (see Figure 4-5) and each thermal unit has a non-zero minimum stable operating point. Note that this graph only show thermal generation and wind generation is shown in Figure 4-3. Demand is always greater than 140 MW and when thermal generation is 120MW the difference is covered by wind generation. It is also important to note that in all cases a minimum number of thermal generators need to be switched on because of the constraint on the reserve requirement, to meet the demand whilst respecting the minimum up and down times. In our market model, the reserve requirement can only be met by thermal generation and not by wind generation.

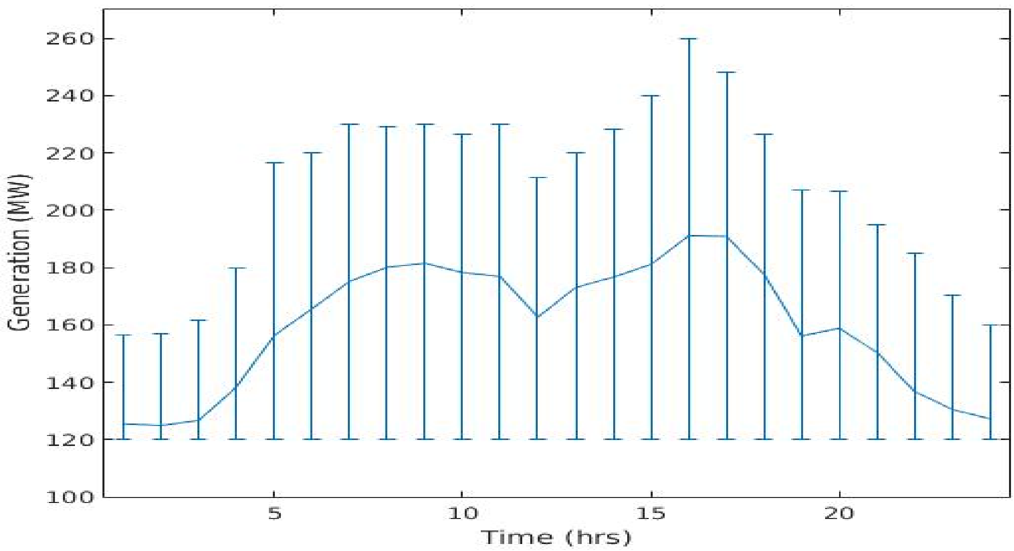

Figure 4-4: Average, minimum and maximum *thermal* generation across 24 hours for one micro-scenario. The horizontal axis shows hours and vertical axis shows the power in p.u. (100 base)

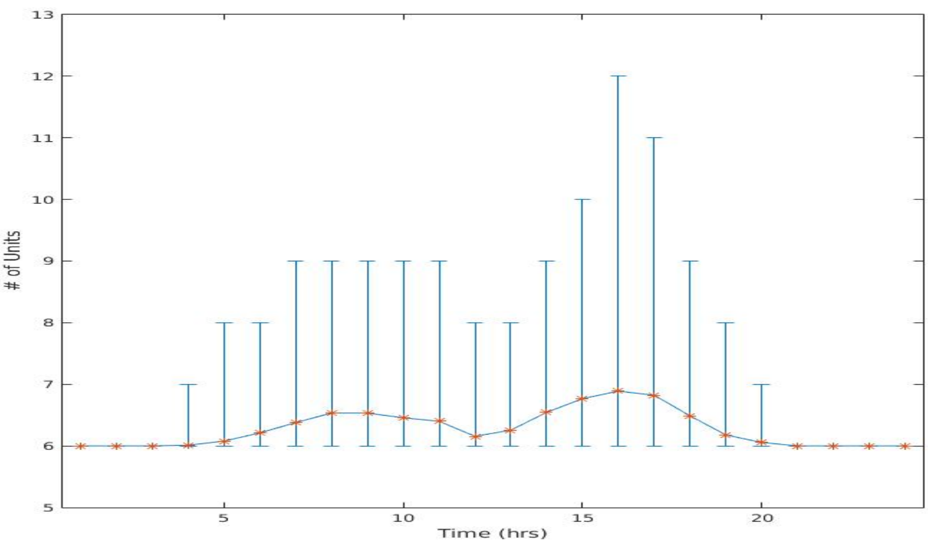

Figure 4-5: Average number of units committed

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Figure 4-6 shows average, minimum and maximum power flowing over the interconnector from zone 2 into zone 1. We note that the average flow of power is always from zone 1 to zone 2. This is because there is more renewable generation capacity in zone 1 as compared to zone 2 (see appendix for renewable generation capacity). In a market solution, wind generation has a zero cost and is high in the merit order. We note that the average flow transfer decreases as the average demand is increased. We also note that in some cases (max power transfer in Figure 4-6), the flow of power is from zone 2 to zone 1.

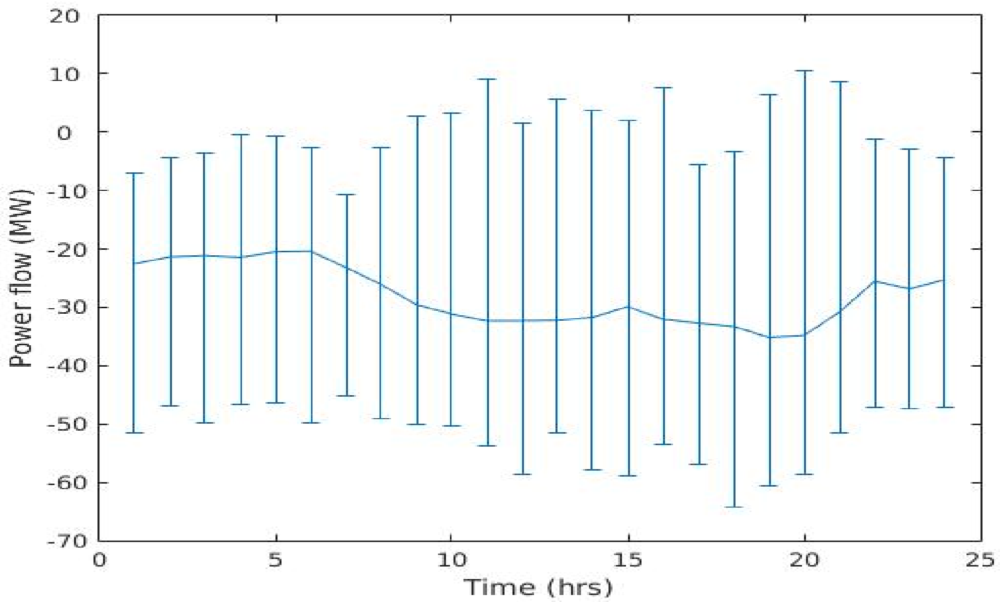

Figure 4-6: Flow over the interconnector from zone 2 to zone 1. This figure shows that on average the flow was always in one direction. However, there were some cases where the flow reversed.

In our market model, we have a constraint over the transfer capability of the tie lines that connect zone 1 and zone 2. In this small illustrative example, there are only two tie-lines between the two zones. However, in real networks it is possible to have many different zones with multiple tie-lines. The market model can be used to predict an optimal net transfer capability (NTC) of such tie lines. For example, we parameterized the maximum capacity of the interconnector in the range [0, 70] MW, and ran the simulations for all the micro-scenarios. Figure 4-7 shows the effect of transfer capacity on the cost of generation. We observe that the cost of generation decreases by approximately 9% if the transfer capacity of the link is increased from 0MW to 40MW. For transfer capacity greater than 40MW, we observe no significant decrease in the cost of generation.

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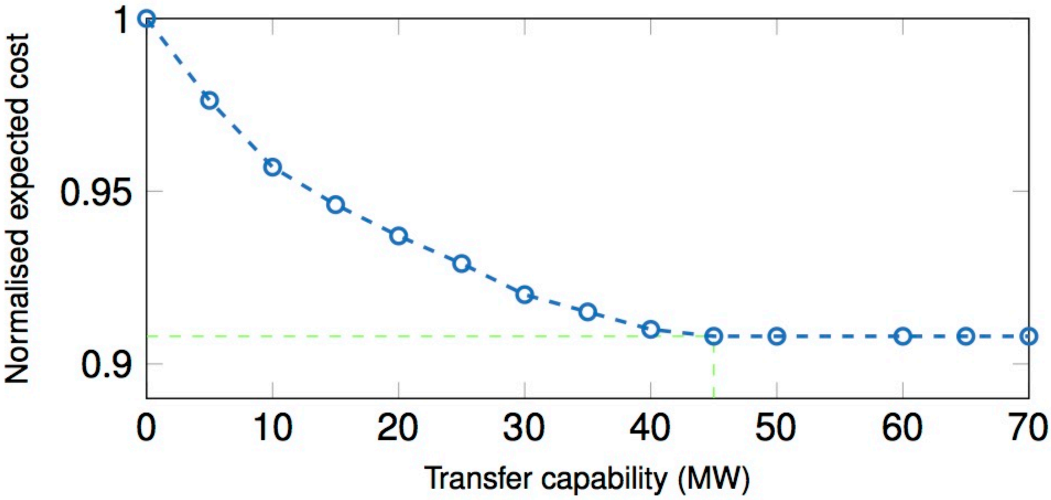

Figure 4-7: Effect of transfer capability on the overall costs of the solution. The vertical axis shows the normalised expected cost. The average is obtained by solving the market model for 10 micro-scenarios and taking the average across 21,600 snap shots.

4.5 Zonal-to-nodal conversion and clustering

We note that a long-term planning study on a realistic power system network should make use of the specificity of the studied system and apply various heuristics in the generation of plausible future micro-scenarios, learned from the experience in operating the system. It also should make a more comprehensive sensitivity analysis on the appropriate number of clusters and samples, the results of which will be again specific for the analyzed grid. In this context, the presented numbers of clusters and samples should be regarded as simply exemplary because the considered test case is artificially created for the purpose of showing the reader the possible stages of the proposed methodology for long-term planning analysis and putting context into the discussion of the necessary data, tools and considerations.

The market model used here is a dispatch model that, in addition to generator constraints, only considers capacity constraints between zones. We note that an aggregated zonal demand can be formed of many different combinations of nodal demand and, without network constraints in a zone, the market model is not able to differentiate between different combinations of nodal demands that sum up to a constant value. In this step, we take a zonal demand and generate many different nodal combinations. The details of this process were described in section 3.5.

As presented in Figure 3-6, the analysis starts with grouping of both the calculated generation dispatch and the available records for individual loads and wind speed. The used time of the day grouping was as follows: morning – from 06 to 10 h; noon – from 10 to 14 h; afternoon – from 14 to 18 h; evening – from 18 to 22 h; and night – from 22 to 06 h. The seasonal grouping is based on the astronomical dates, i.e. winter from 21st December 00:00 to 20th March 23:59; spring – from 21st March to 00:00 to 20th June 23:59; summer – from 21st June 00:00 to 22nd September 23:59; autumn – from 23rd September 00:00 to 20th December 23:59. Since the generation dispatch was calculated only for the first 90 days of the year, most of the records were from the winter, and only 10 days from the spring.

The generation dispatch for each season and time of day was clustered in 30 clusters. Also, for each season and time of day 100 samples for individual loads (per bus) were sampled. Thus, the combination of clustered generation snapshots and sampled loads for a full year will result in 60 000 snapshots. However, because generation dispatch was calculated only for two seasons, the number of snapshots generated in this test case is 30 000.

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Then, the injected power per bus is calculated for each snapshot, and they are used for the final clustering which groups the snapshots in 600 clusters (the 600th represents the zero records and this is why from here on their number is treated as 599 in total). Figure 4-8 presents the number of clusters per cluster ID. The number of snapshots per cluster varies from 7 to 133.

All clustering was performed with the K-medoids algorithms, with Chebychev similarity measure (see Appendix 6.4.3). All sampling was done with the NORTA sampling algorithm (see Appendix 6.3).

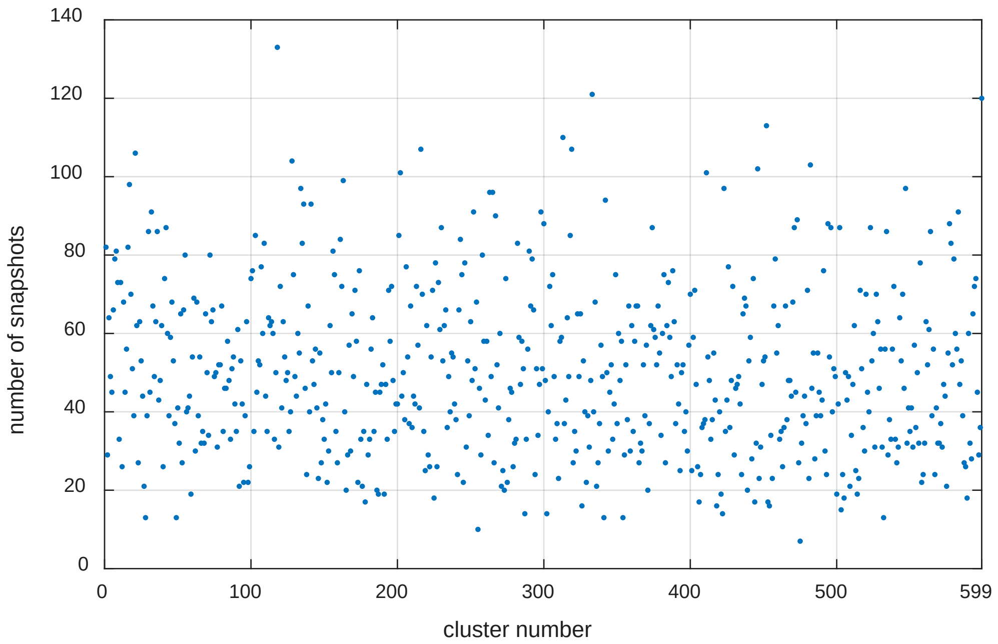

Figure 4-8: Number of snapshots per cluster ID

It should be noted, though, that the necessary numbers of clusters and samples depends mainly on the variability of the parameters (e.g. generation, demand, power injected per bus). In this sense, as the size of the analysed system grows, the number of clusters and samples will also grow (because of the increased variability of the parameters), but not exponentially.

4.6 Assessment

The details of our assessment methodology are given in chapter 3 of this report. We assess the centroids of the clusters, and, starting from the wholesale market solution, the objective function of our assessment model is to minimise the total cost of balancing actions while respecting the security and network constraints. As discussed in chapter 3, we use the continuous line rating for pre-contingency cases and short-term line rating for post-contingency, pre-corrective action cases. The objective function only minimises the pre-contingency cost and, because the probability of a fault outage is normally low (meaning that the expected cost of post-fault corrective actions is small), does not consider the cost of balancing in post-contingency cases but only seeks to establish that viable corrective actions are available.

We assessed 599 cluster centroids and found only 54 centroids that lead to non-zero cost of balancing. This means that most of the cluster centroids (approximately 90 %) satisfy network and security constraints and do not require pre-fault actions from a system operator to secure them. Moreover, for the given macro-scenario and the 90-day period used for this illustration, we did not find a single case where load shedding was required (pre or post-contingency) to operate the system.

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Figure 4-9 shows the normalised cost of balancing the system for the 54 centroids. We have sorted the cluster number by the cost of the balancing and that is why we see a monotonic increasing trend in the cost of balancing. We observe that approximately 81 % of these 54 centroids are below 50 % of the worst-case situation.

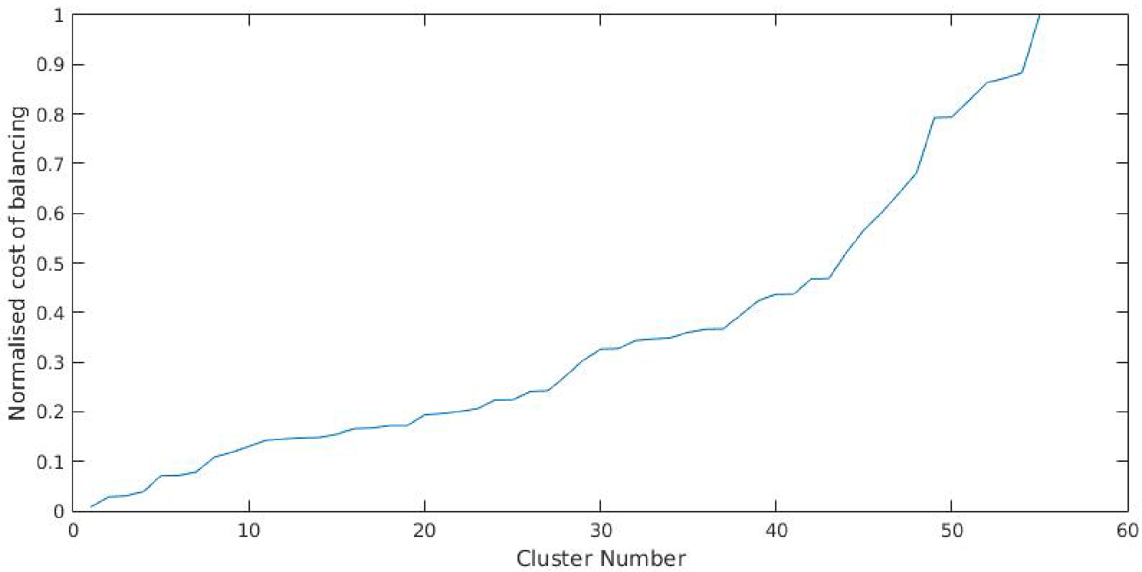

Figure 4-9: Normalised cost of balancing the system in the test case. We analysed 599 cluster centroids, and only 54 centroids have non-zero cost of balancing

Next we analyse the four most expensive centroids. The details of these centroids are given in Table 4-2. We remind ourselves that the assessment model tries to accommodate the wholesale electricity market's preference at least cost. The costs are incurred for generation regulation (re-dispatch) that is done in order to respect the power balance and (N-1) security constraints. It is interesting to note that the centroid with maximum demand – on which conventional system development methods are likely to have focused – is cluster number 401 (with 7 members) but it does not appear in Table 4-2. The cost of balancing cluster 401 is 1610.88, which is 20 % less than the most expensive cluster 314. The demand of cluster 401 is approximately 10 % more than cluster 314.

Table 4-2: Four most expensive clusters and assessment costs for their centroids.

Cluster #	Number of elements	Pre-fault cost (£/MWh)	Post-fault corrective action cost (£/MWh)
314	37	2029.28	23234.17
356	52	1791.95	54665.83
173	22	1770.20	50171.14
62	3	1751.99	54224.99

Note that in the proposed model, the post-fault flows are allowed to exceed continuous line ratings and go up to the short-term ratings such that these flows can be corrected to continuous ratings by post-fault corrective actions. This is an extra layer of flexibility for the system operator. Table 4-3 shows the difference in pre-fault costs with and without using corrective control to relieve the overloading on certain

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lines[12]. We note that without using corrective controls, the cost of pre-fault operation is about 40-60 % more expensive for the four clusters. One would expect that such increase in pre-fault operational cost comes with a decrease in the expected post-fault costs. However, we observe that the expected post-fault cost of operation in each case only decreases by less than 1%, when corrective actions for corrective overloaded lines were not allowed. This is because the main cost of post-fault operation is due to generator outages and corrective actions for line flows have little effect in this case.

Table 4-3: Comparison of pre-fault operating costs with and without corrective actions to relieve overloading of a line

Cluster #	Pre-fault cost (£/MWh) with corrective actions	Pre-fault cost (£/MWh) without corrective actions	% Increase in cost
314	2029.28	3229.28	59
356	1791.95	2541.95	42
173	1770.20	2520.20	42
62	1751.99	2501.99	43

Figure 4-10 shows the assessment results on the centroid of cluster number 314 that has a total demand of 227.19 MW. This is the cluster that has the most expensive cost of balancing. We note that the market solution proposed 49.12 MW of wind and 60 MW of thermal generation at node 2 giving a total at node 2 of 109.12MW. The market solution proposed that the power would flow from zone 1 to zone 2. Our assessment model showed that this situation is not feasible for the single circuit line outages at 1-2 or 2-4 or for the double circuit outage of line 1-3. The model regulated the generation by curtailing wind by 0.18 MW and reducing thermal generation by 20 MW at node 2, and increasing generation by 19.78 MW at node 6 in zone 2.

Figure 4-11 shows the assessment result for the centroid of cluster number 356. This centroid is the second most expensive centroid in our assessment. Cluster number 356 consists of 52 members. Total demand in this centroid is 246.3. We note that in comparison to centroid 314, extra generation at node 7 is committed by the market solution. The market solution proposed 68.30 MW of thermal generation at node 2. Again, the total real power injection at node 2 is not feasible for line outages connecting nodes 2-4, 1-2 and 1-3.

Figure 4-12 and Figure 4-13 show the results for assessment of centroids 173 and 62. We note that 17.70 MW is regulated in the centroid of cluster-173 and 18.02 is regulated in the centroid of cluster-62. However, the cost of regulation of 17.70 MW is higher than the cost of regulation of 18.02 MW. This is because the market solution in centroid of cluster 173 does not commit the generator at node 7 that can be regulated cheaply.

[12] Generator post-contingency actions include those to replace lost generation in the event of a generator outage, i.e. the utilisation of spinning reserve to maintain total system balance of generation and demand. On a real system, a major part of that action will the automatic actuation of frequency containment reserve via governor response, something that is location specific only to the extent that, in general, only a certain of generators are in 'free-governor' mode and have both 'headroom' and 'footroom'. For the results shown in this table, because no generator post-contingency actions are allowed in the second case, only line outage contingencies are applied and not generator outages. (If there is a generator outage and no generator corrective action were allowed, the only to maintain an overall system balance would be by shedding load.)

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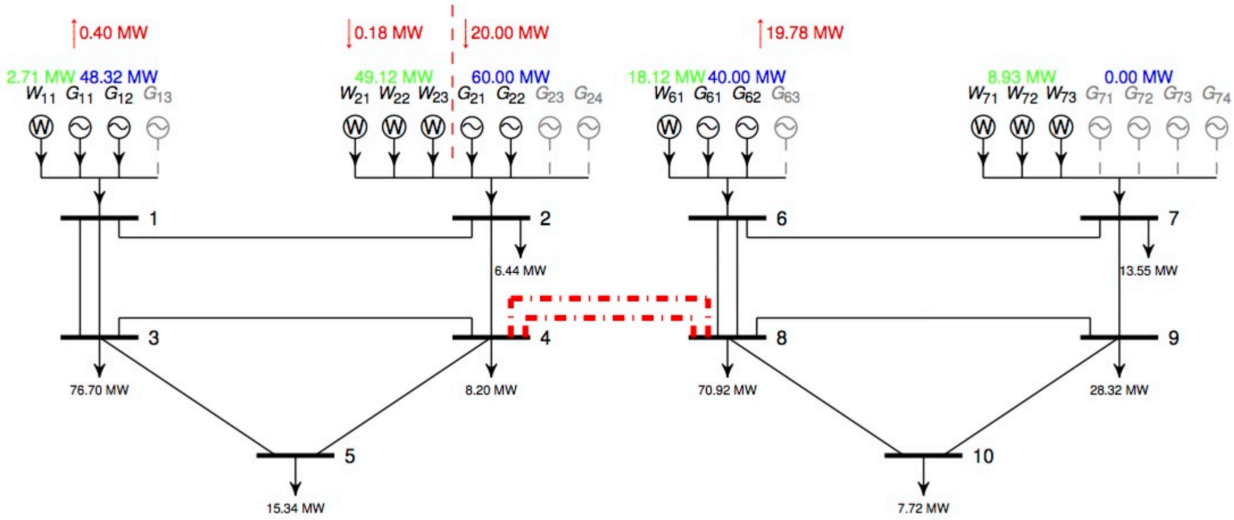

Figure 4-10: Centroid of cluster number 314 that has 37 members. The market solution proposed 49.12 MW and 60 MW at node 2. However, using the assessment model, optimal regulation is to curtail wind at node 2 by 18.28 MW and regulate down the generation at node 2 by 20 MW.

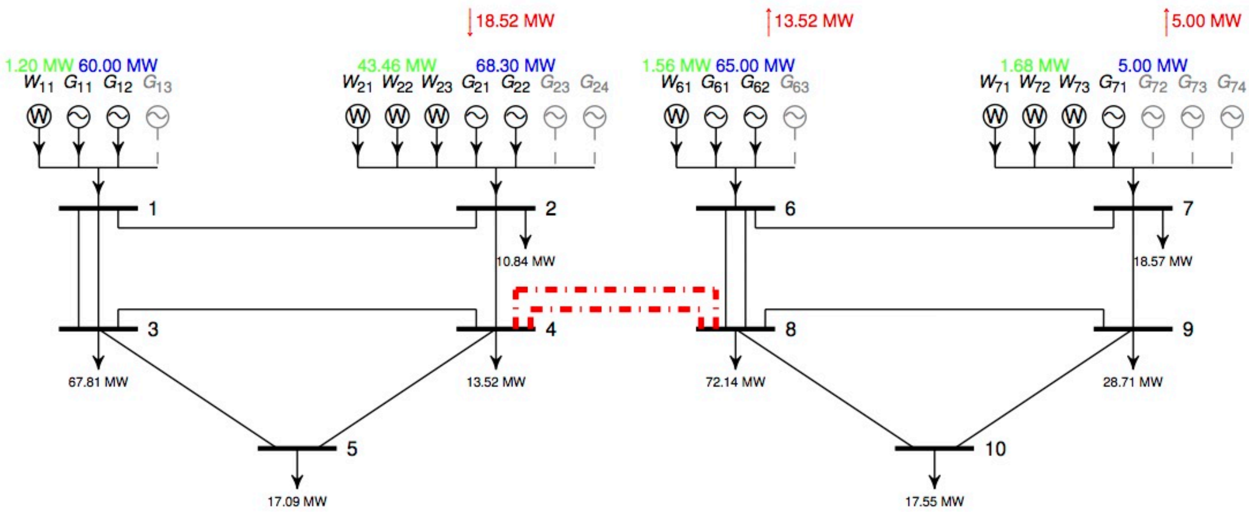

Figure 4-11: Centroid of cluster number 356 that has 52 members. Generation at node 2 is regulated downwards and the down regulation is compensated by the up regulation of thermal generation at node 6 and node 7.

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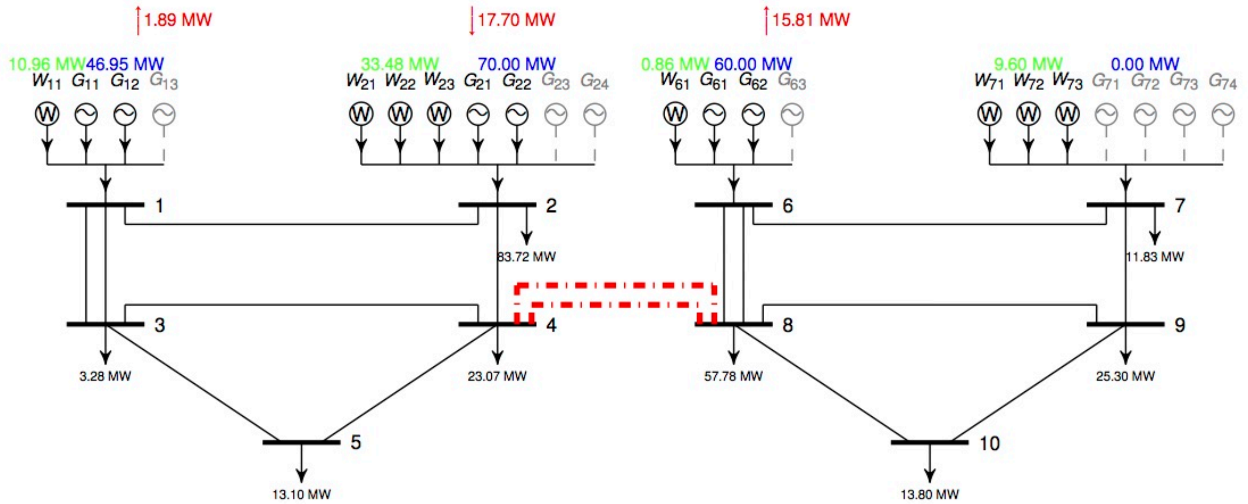

Figure 4-12: Centroid of cluster number 173 with 22 members. Thermal generation at node 2 is regulated downwards by 17.70 and the generation is compensated by up regulation of generation at bus 6 in zone 2.

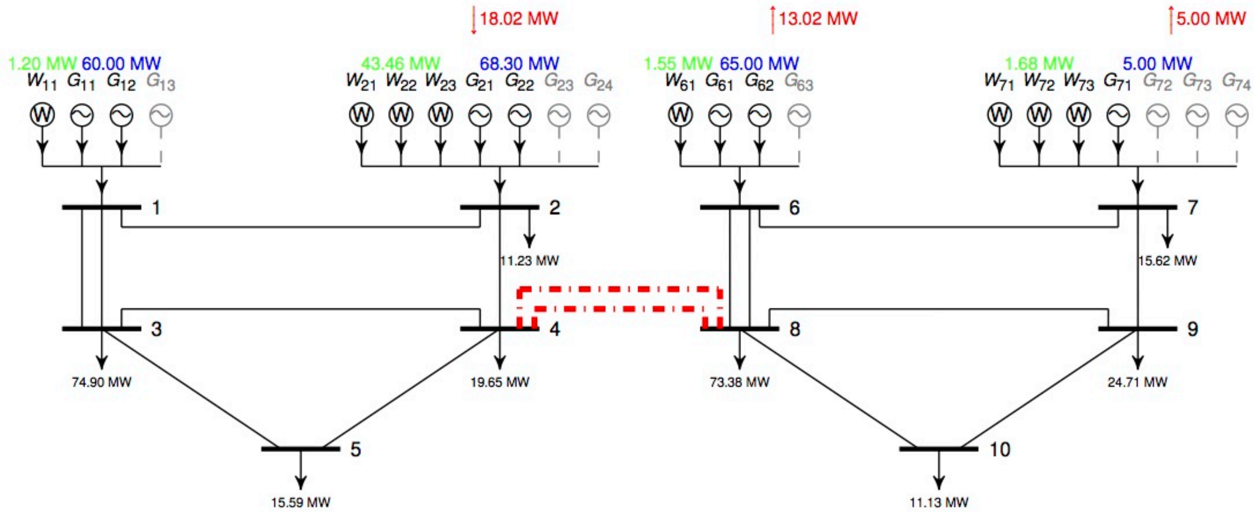

Figure 4-13: Centroid of cluster number 62 with 3 members. Thermal generation is regulated downwards in zone 1 at node 2 by 18.02 MW. The decrease in generation in zone 1 is compensated by increase in zone 2 at node 6 and 7.

Figure 4-14 shows the number of overloaded lines for each contingency. Here overloading means post-contingency flows that exceed continuous ratings, but are correctable by post-fault actions. The total number of overloaded lines is calculated for the 599 centroids that were assessed by summing, over all of the centroids, the number of lines in each centroid case in which the post contingency flow exceeded the normal continuous ratings. We observe that, as may be expected, the double line contingencies 37 and 38 lead to most line overloads. The other contingencies that cause overloads are the line contingencies 1-3 (contingency 1 and 6), 2-4 (contingency 2), 4-5 (contingency 7), 6-8 (contingency 8 and 13), 7-9 (contingency 9), 6-7 (contingency 10).

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The lines that are overloaded are listed in Table 4-3.

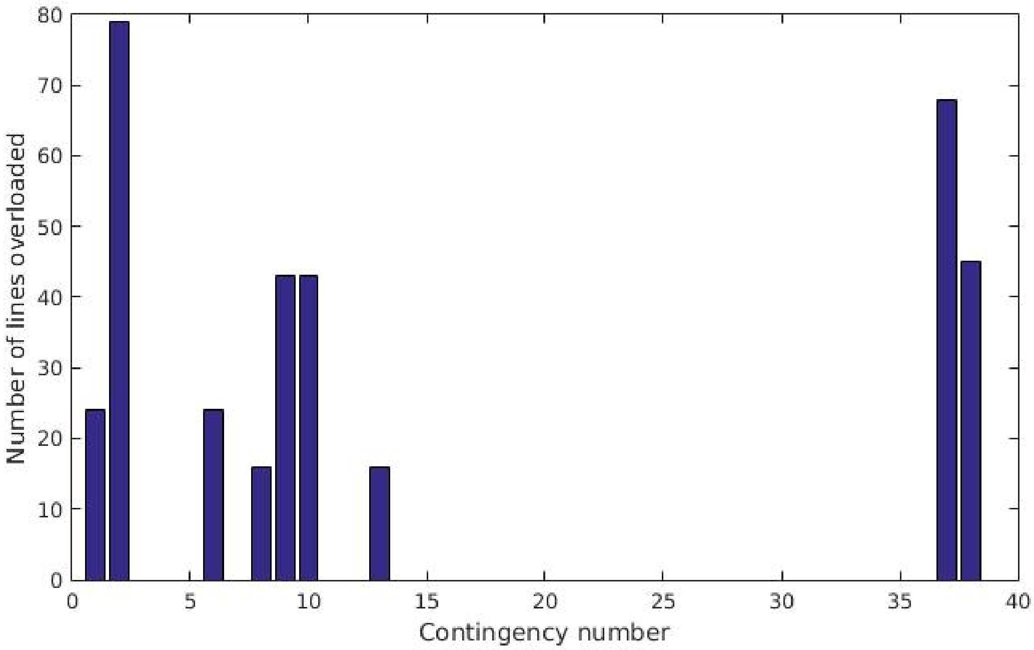

Figure 4-14: Number of overloaded lines in post-contingency steady state. The horizontal axis is the contingency number, and vertical axis is the number of overloaded lines. Note that we allow the line to overload in post-contingency up to their short-term rating.

Table 4-4: Overloaded lines and contingencies that led to overloads

Line	Line contingency that led to an over-load of continuous rating	No. of operating states in which the overload occurred
1-2	2-4	79
1-2	1-3, 1-3	68
1-3	1-3	24
6-7	6-8, 6-8	45
6-8	6-8	16
7-9	6-7	43
6-7	7-9	43

4.7 Insights for a system planner

From the assessment results, we observed the following:

1. For the given macro-scenario and the particular 90-day period of operation studied, the network is capable of accommodating market proposed solutions without any case leading to loss of load;
2. In most of the cases (~88 %), power flows from zone 1 to zone 2;
3. Double circuit outages between nodes 1-3 and 6-7 lead to overloads. However, double circuit outage 1-3, and single circuit outages connecting nodes 1-2 and 2-4 lead to most pre-fault regulation of power, i.e. the largest deviations of power output compared with the initial market solution;

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4. The maximum loading condition does not necessarily lead to the most expensive cost of regulation case. This is because maximum loading tends to commit more generation in the market simulation and, as a consequence of the commitment of additional units, is more likely to carry more than the minimum reserve. The most expensive cluster centroid in terms of pre-fault balancing cost is not the one with maximum demand;
5. An increase in cost of regulation is not necessarily a result of more power being regulated. In some cases less power is regulated but at a higher cost.

From the above observations, we note that the bottleneck for this system is at node 2 where majority of the generation is being regulated. For this reason the following two investment options have been assessed:

Option 1: A single transmission line between nodes 2 and 6 of capacity 75 MW[13].

Option 2: Reinforcing the corridor between node 2 and 4 with a line of capacity 85 MW.

We use the capacities of 75MW and 85MW because lines with similar characteristics are present in the test system. It is possible to find a least capacity figure that is required to reduce the amount of regulation at node 2. This capacity will be the sum of injections at node 2 and node 1 (because outage of double circuit 1-3 will direct the power towards node 2). In a 'real-world' test case, it may be possible to achieve the minimum capacity uprating through operation of key existing lines at higher temperatures (provided the towers can support the extra mechanical loading and minimum clearances can still be respected) or re-conductoring with higher rated conductors (again, provided the towers can support it). Furthermore, just some increase in capacity may have a positive net present value through reduction of constraint costs even if those costs are not reduced to zero in every case.

We re-run our analysis by changing the topology of the network. Table 4-5 lists the improvement in pre- and post-contingency costs of operation. We observe that the number of cluster centroids with non-zero balancing costs is significantly reduced by the investment decisions from 54 to 14 in respect of option 1 and 54 to 27 in respect of option 2.

Table 4-5: Effect of investments on operating costs

		Improvement in costs (%)	
Investment Option	Number of cluster centroids with non-zero balancing costs	Pre-contingency costs	Post-contingency costs
Option 1	14	78.36	95.01
Option 2	27	59.83	44.86

We note that the investment option 1 reduced the pre-contingency costs by approximately 78 % and post-contingency costs by 95 %. However, there were still cases where generation regulation was required to achieve post-fault feasibility. Figure 4-15 shows one case where generation regulation was required on node 7, and the investment did not have any impact on the cost of regulation. This case corresponds to the minority of the operating conditions where power is flowing from zone 2 to zone 1.

[13] This option represents additional capacity between the two market areas. In practice, such a reinforcement often presents significant regulatory challenges.

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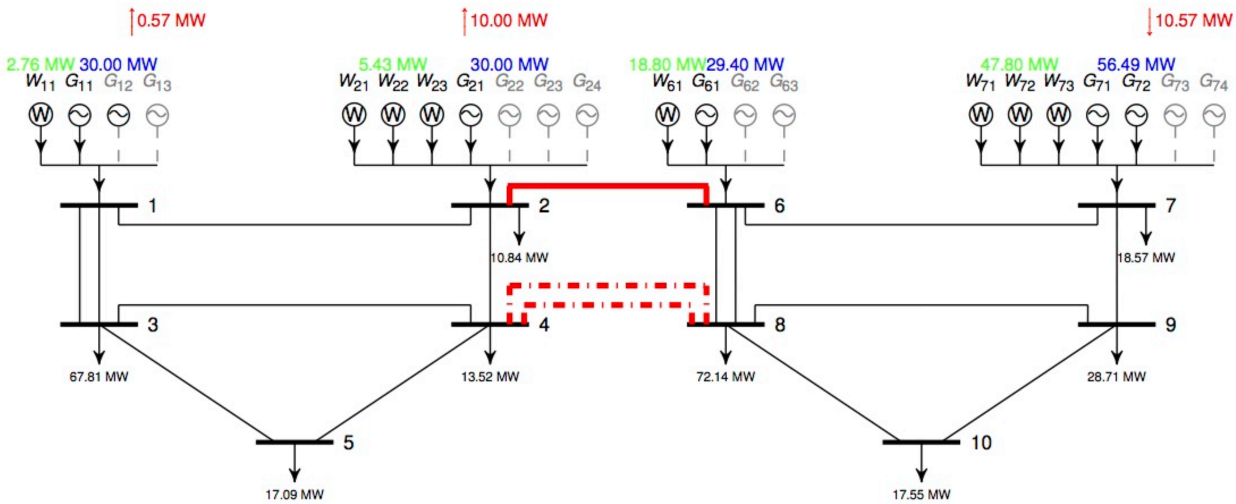

Figure 4-15: Cluster number 150 with 33 members. The two investment options do not have any significant impact on the costs of balancing this cluster.

5 DISCUSSION AND CONCLUSIONS

5.1 The proposed methodology and achievements to date

In this report, we have presented the practical framework and discussed methods developed within WP4 of the GARPUR project aimed at improving the system development process.

In common with the rest of GARPUR, the main motivation behind the proposed methods is to enable a better understanding of risk. In WP4, that has meant, for a given 'macro-scenario', giving some confidence to a system planner that a network will be able to accommodate demand and the electricity wholesale market's likely dispatches of generation throughout a given target year. Such confidence is a result of detailed assessment on a quite large number of representative, credible, future operating states, and an ability to identify bottlenecks that might be missed whilst only planning against a few particular operating conditions, e.g. annual peak demand. In principle, such assessment gives a better appraisal mechanism for future investments in the transmission system.

The proposed system development methodology consists of 9 steps. These 9 steps can be characterized into two main categories: generation of credible operating scenarios, and assessment of these micro-scenarios. For generation of credible operating scenarios, we used a market model as a proxy for the behaviour of the wholesale electricity market. We also used historic data to learn about the correlations among nodal demands and applied a technique to convert zonal data into nodal data. For assessment of credible operating conditions, we proposed to use clustering to reduce the number of operating states. Borrowing from the concepts developed in WP2 of GARPUR, it can be thought of allowing a large number of operating states to be discarded (and to avoid having to analyse them in detail) without any significant impact on risk. We also proposed an optimisation model to model the behaviours of a system operator, establish the operability of future operating scenarios and to quantify the cost of operating a system.

The main contributions of the work done so far in WP4 of the GARPUR project are as follows:

1. A methodology to build a representative set of future operating states of a transmission system;
2. Use of clustering algorithms to reduce sample size;
3. A method for nodal to zonal conversion;
4. An assessment model for credible operating states that quantifies the cost of operation whilst considering security constraints.

Moreover, the assessment model takes account of both continuous and short-term ratings of lines and post-contingency corrective actions by a system operator and a discussion has been presented on options for how a system development planner might take account of the need for planned outages to be accommodated on the system. These are:

1. to model, albeit in some approximate way, the way in which outages would typically be planned, and then to assess the operability of the system given such outage plans;
2. to assess the maintainability of the network while still being secure against contingencies (unplanned outages), i.e. to determine if there is margin for planned outages to be taken.

Some initial testing and demonstration of the methodology have been undertaken for a simple, 10-bus test system. Starting from a 90-day period of potential operating conditions, more than 20,000 possible combinations of independent state variables were identified and, through clustering, reduced to 599 cases for analysis, each representing the centroid of a cluster. Of these, none yielded any operating conditions that led to load shedding; however, 54 centroids were found to lead to a non-zero cost of balanc-

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ing. Further analysis on these centroids identified a particular bottleneck on the network. Two investment options in the network were then identified and found to significantly bring down the cost of operation.

5.2 Future work

5.2.1 Sharing of learning between GARPUR work packages

The 10-bus system that we have used for our illustrative exercise is a self-constructed test case that was initially developed for software tests in WP7 of the project. This test system comes with its limitations and does not represent reality. However, we have demonstrated a proof of concept using this test case. As a contribution towards pilot testing (under the umbrella of GARPUR WP8) and in order to give more concrete evidence of the practicality and application of the methods outlined in this report, planned future work includes application of the methodology to a part of a real system.

For the illustrative case study we used (N-1) criteria in our assessment model for real-time reliability management. One of the key innovations emerging from GARPUR WP2, is a probabilistic reliability criterion in which risk is assessed in general terms in determining which contingencies and scenarios should be secured against and which can be 'discarded'. The impact of this not only on system operation but also on how the system is developed in order to enable future system operation needs to be considered and demonstrated. In the context of system development, the aim will be to find a practical way in which the principles can be used.

The current document – D4.2 – is produced as part of a suite of deliverables from the work packages led by Transmission System Operators. The others are D5.2 – "Pathways for mid-term and long-term asset management" – and D6.2 – "How to upgrade reliability management for short-term decision making". Work on these reports has been undertaken in parallel but the opportunity now arises for reflection across WP4, WP5 and WP6 alongside the conceptual foundations put in place by WP2 and WP3. This will address the following:

1. Are there any similar processes that have been proposed in the contexts of asset management, system operation and system development, what methods have been tested for them and what can be learned from the various studies that can be used in the other contexts?
2. How have the principles of a 'discarding threshold' been used in forming a contingency list and justifying the focus on a particular sample of scenarios, and how might chance constraints be used to take into account the reliability target?

5.2.2 The importance of weather

One key understanding that the research work in GARPUR has helped to disseminate from the research partners to the TSO partners in the project is the influence of weather. This has already been noted in section 3 above as affecting both the power available from renewables and the demand for power and reliability. In other words, there is at least some correlation between different weather-dependent renewables and between renewables and demand and, if system risks are to be adequately managed and stranded assets avoided, these correlations need to be correctly taken into account. Furthermore, it can be recognised that both demand and power from weather-dependent renewables have seasonal trends that are, in turn, linked to the scheduling of maintenance outages. Next, because, typically, around half of all transmission fault outages in Europe are weather-related, the principle of taking both the probability and impact of each possible contingency into account when forming a contingency list means that the current and forecast state of weather are likely to be key inputs to a contingency analysis. Finally, in view of the correlation between weather and demand, where there is a high dependency on electricity for key energy services such as cooling and heating, the impact of an interruption will also be heavily influenced

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by the weather. These relationships lead to formation of a more complex version of Figure 3-8, shown in Figure 5-1.

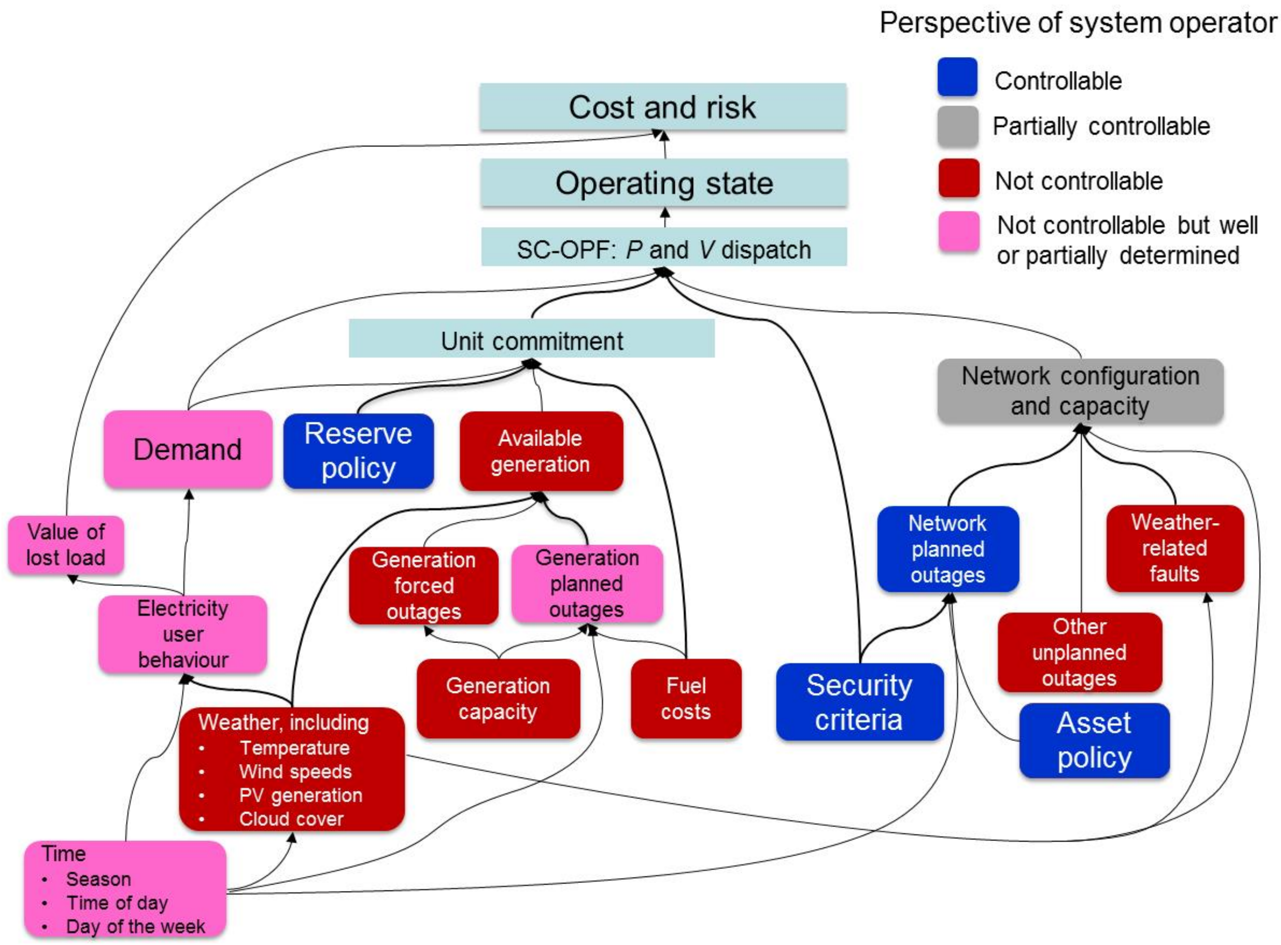

Figure 5-1: Key relationships in determining a power system's operating state, cost and risk

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6 APPENDIX

6.1 Data for the 10-bus test case

Table 6-1: Demand data for the 10-bus test case

Bus Number	Demand (MW)
2, 7	20
3, 8	85
4, 9	40
5, 10	20

Table 6-2: Generation data of the 10-bus test case

Bus Number	Generators	Generator type	PMin	PMax	Lin cost
1,6	G11, G12, G21, G22, G61, G62, G71, G72	COAL	20	40	13.9
2,7	G13, G23, G24, G63, G73, G74	GAS	5	10	26.7

Table 6-3: Network Data

Line	R	X	Continous Rating (MW)	Short Term rating (MW)
1-2, 6-7	0.091	0.48	75.0	82.5
1-3, 1-3, 6-8, 6-8	0.03	0.18	90.0	99.0
3-4, 8-9	0.023	0.12	75.0	82.5
2-4, 7-9	0.114	0.60	85.0	93.5
3-5, 8-10	0.023	0.12	75.0	82.5
4-5, 9-10	0.023	0.12	75.0	82.5
4-8, 4-8	0.023	0.12	75.0	82.5

Table 6-4: Wind generation data

Bus	Wind generator	Pmax (MW)
1	W11	100
2	W21	30
2,6,7	W22, W23, W61, W71, W72, W73	10

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6.2 Weather Research and Forecasting model (WRF) model

Translation from national to nodal data based on meteorological information

Over recent years, there has been a remarkable effort towards a higher degree of transparency following the liberalization of most of the European electricity markets. As a result, there is a comprehensive dataset of wind and solar generation per country. This information is currently provided by the (ENTSO-E) since 2015 [ENTSO-e, 2015a]. Previous years are also available from the different TSOs on an individual basis. Considering each country as a single node, these data can be used to characterize the total renewable generation in a country which might affect the power flows between areas i.e. high wind generation would drive the electricity price down in an area, hence pushing the excess of generation to neighbouring countries with higher prices. Nevertheless, the former simplification might become insufficient if more realistic studies were to be performed, where national data must be transformed into nodal data. This transition or disaggregation is one of the main challenges to be faced within GARPUR and therefore should be addressed.

Weather-driven renewable generation, namely wind and solar power depend on the local weather conditions and therefore require an alternative approach compared to conventional generation. The proposed methodology assumes that the weather variables in the future i.e. wind speeds, solar irradiation, etc., will behave relatively similar to the past. This implies for example considering the different cycles seen on a daily and seasonal basis, as well as at a longer time scale such as hydrological cycles. Therefore, by modelling the underlying resource driving renewable generation we would only need to address changes in the geographical distribution of the generators and their technology, in order to generate future scenarios. In the context of GARPUR, we propose to simulate the historical weather conditions using meteorological reanalysis. This technique aims at reconstructing plausible past states of the atmosphere by feeding real observations to a mesoscale meteorological model, which describes the evolution of the variables in time and space. This way, the existing gaps between real observations are filled, resulting in a complete dataset, consistent in both time and space. It represents a common practice in applied meteorology for wind energy applications [Hahmann, 2010] and has been previously applied to model regional wind and solar generation [Marinelli, 2015]. To this end, the well-known Weather Research and Forecasting (WRF) model is used in order to obtain hourly values of wind speed and solar irradiation on a regular 30 x 30 km grid between 2000 and 2015. This model essentially represents a set of differential equations describing the evolution of the atmosphere ensuring the spatiotemporal correlation of the data.

Following the characterization of the weather conditions, each grid point must be weighted according to the current or assumed future installed capacity in its vicinity. Each wind/PV generator is associated with a particular WRF grid point and it is assumed that all the generators linked to the same WRF grid point see the same “average” weather conditions. Points in the grid of the WRF with no allocated wind or solar installations would have a zero weight and hence will not be taken into account in further steps. All the WRF grid points are linked to relevant nodes of the power system. If there is more than one WRF point in the vicinity of a particular power system node, the weather conditions can be weighted based on the installed capacity associated with each WRF grid point. Figure 6-1 shows an example of an improved WRF domain for Spain and the distribution of the photovoltaic (PV) installations. Note that the presented domain in 10 by 10 kilometres.

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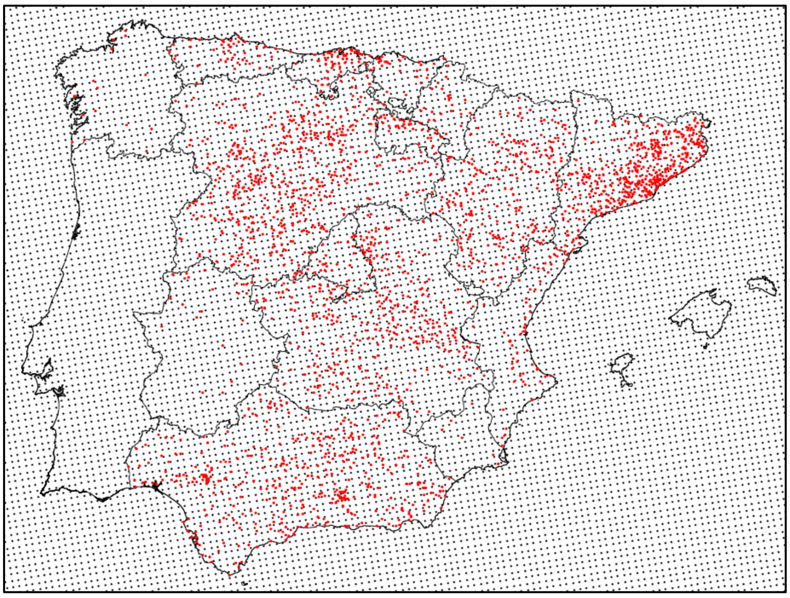

Figure 6-1: WRF grid points in (in black) and PV facilities in Spain (in red) in 2015

The last step in the process involves using an aggregated power curve for the selected areas that will transform the meteorological variable i.e. wind speed, solar radiation, into electrical power. This power curve can be derived empirically or based on expert judgment and can be modified in order to consider different future scenarios; for example, scaling the power curve would simply account for an increase of the installed capacity. However, modifying the shape would also capture plausible technological changes i.e. trends towards lower-speed wind turbines, and different geographical distributions. The overall methodology for a given scenario can be summarized as follows:

Step 1: Obtain the geographical distribution of the installed capacity for that scenario. It can be based on the actual information available of future predictions.

Step 2: Allocate weights to the WRF grid points and obtain the average weather conditions for the selected area.

Step 3: Apply an aggregated power curve in order to simulate the power generation inside that area for that specific scenario. Since all the calculations are based on the same synthetic weather database, the spatial and temporal correlation between the different areas would be inherently maintained.

The aggregated information available would allow selection of optimal weights for the different nodes in order to obtain the desired aggregated result. This methodology can be equally applicable to generate nodal load profiles by considering the temperature-dependent part of the electricity consumption. Consumers would respond to different levels of ambient conditions i.e. temperature, which could explain some of the variations on the load. In addition, by obtaining wind speed, irradiation and temperature from the same meteorological model we could guarantee that their inherent correlation is maintained and hence transferred to the nodal level.

6.3 NORTA sampling

Long-term weather modelling must be focused towards the definition of probability distribution functions matching some statistical properties of the real observations. Therefore, a robust method should be defined, flexible to generate different variables (not necessarily normally distributed) while conserving the distributional properties of the original data i.e. marginal distributions and correlation matrix. A non-

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sequential procedure is suggested [Cario, 1997]. It aims at specifying a vector of any meteorological variables X, $\boldsymbol{X} = (X_1, X_2, \dots, X_k)^T$ in which $X_i \sim F_{X_i}$ is an arbitrary cumulative distribution function and $Corr[X] = \Sigma_X$ where Σ_X is any feasible correlation matrix based on Pearson's correlation coefficient. The so-called NORTA (Normal-to-Anything) vector is defined as a component-wise transformation of a k-dimensional standard multivariate vector $\boldsymbol{Z} \sim N_k(1, \Sigma_Z)$:

$$X = \begin{pmatrix} F_{X_1}^{-1}[\phi(Z_1)] \\ F_{X_2}^{-1}[\phi(Z_2)] \\ \dots \\ F_{X_k}^{-1}[\phi(Z_k)] \end{pmatrix} \tag{6.1}$$

where ϕ is the cumulative distribution function of a standard normal distribution. This approach guarantees that every random variable X_i follows a desired marginal distribution through the inverse transformation $F_{X_i}^{-1}[\phi(\cdot)]$. In addition, the desired dependence structure for $\boldsymbol{X}$**,** i.e. obtained by expert judgment, is achieved by adjusting the correlation matrix of $\boldsymbol{Z}$, which has to be selected carefully**.** The previous transformation maps $\boldsymbol{Z}$ into $\boldsymbol{X}$, hence the pairwise correlation between two elements X_i and X_j can be expressed as a function of the correlation between the corresponding Z_i and Z_j:

$$Corr\,[X_i, X_j] = \frac{E[X_i, X_j] - E[X_i]E[X_j]}{\sqrt{Var[X_i]\,Var[X_j]}} = Corr\left\{ F_{X_i}^{-1}[\phi(Z_i)],\ F_{X_j}^{-1}[\phi(Z_j)] \right\} \quad \forall\, i \neq j \tag{6.2}$$

The values for $E[X_i]$, $E[X_j]$, $Var[X_i]$ and $Var[X_j]$ are constant, given by the marginal distributions F_{X_i},F_{X_j}. Besides, the expectation $E[X_i, X_j]$ can be expressed as:

$$E[X_i, X_j] = E\left\{ F_{X_i}^{-1}[\phi(Z_i)]\ F_{X_j}^{-1}[\phi(Z_j)]\right\} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F_{X_i}^{-1}[\phi(Z_i)]\ F_{X_j}^{-1}[\phi(Z_j)]\,\varphi_{\rho Z(i,j)}\,dz_i dz_j \tag{6.3}$$

where $\varphi_{\rho Z(i,j)}$ is the standard bivariate normal probability distribution function:

$$\varphi_{\rho Z(i,j)} = \frac{exp\{-(z_i^2 - 2\rho_Z(i,j)z_i z_j + z_j^2)/2(1-\rho_Z(i,j)^2)\}}{2\pi\sqrt{1-\rho_Z(i,j)^2}} \tag{6.4}$$

It is clear from the above that the pairwise correlation between X_i and X_j only depends on the correlation between Z_i and Z_j contained in $\varphi_{\rho Z(i,j)}$. Therefore, a nonlinear function mapping both measures can be defined:

$$Corr[X_i, X_j] = c_{ij}[\rho_Z(i,j)] \quad \forall\, i \neq j \tag{6.5}$$

The function c_{ij} presents a closed form in some special cases i.e. when X_i and X_j have continuous uniformly distributed marginal. In addition, if X_i and X_j are exponentially distributed, then $\rho_X(i,j)$ becomes invariant with respect to the chosen parameterization [Cario, 1997]. Nevertheless, a numerical search procedure is generally required to solve it such that $c_{ij}[\rho_Z(i,j)] \approx \rho_X(i,j)$. It can be proved that c_{ij} is a continuous non-decreasing function $-1 \leq \rho_Z(i,j) \leq 1$ under weak assumptions [Cario, 1997]. Moreover, the solution is unique under more restrictive conditions [Henderson, 2000]. It is worth noticing that not

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all the combinations of marginal distributions F_X and correlation matrix Σ_X are feasible. To be feasible, Σ_X must be nonnegative definite and each element must be contained between the minimum and maximum feasible bivariate correlations for random variables having marginal distributions F_{X_i} and F_{X_j} i.e. $\underline{\rho}_{i,j} < \rho_X(i,j) < \bar{\rho}_{i,j}$ for each $i \neq j$. This is perhaps the most challenging step of the method; however, there are different procedures to construct feasible correlation matrices [Rebonato, 1999]. Moreover, a nonnegative definite Σ_Z guarantees a nonnegative Σ_X. The general procedure can be summarized as follows:

NORTA Generation Procedure

Step 1: Calculate Σ_Z solving $c_{ij}[\rho_Z(i,j)] \approx \rho_X(i,j)$

Step 2: Determine a lower-triangular factorization L of the correlation matrix Σ_Z so that $LL^T = \Sigma_Z$ (Cholesky factorization).

Step 3: Generate a k-dimensional multivariate random vector $\boldsymbol{M}$ whose elements are independent and identically distributed (i.i.d.) standard normal random variables.

Step 4: Define the base vector $\boldsymbol{Z} = L \cdot \boldsymbol{M}$

Step 5: Return $\boldsymbol{X}$ where $X_i \leftarrow F_{X_i}^{-1}[\phi(Z_i)]$ $i = 1,2,\dots,k$.

Step 6: Go to step 3.

Having access to a comprehensive dataset allows for an additional simplification of the method. The correlation matrix Σ_Z obtained numerically after solving the previous nonlinear equation can also be approximated, as long as the marginal distributions of the weather variables are continuous on $[0,1]$. Then, they can be transformed into normal random variables through the transformation $Z_i' = \phi^{-1}[F_{X_i}(\cdot)]$ and the correlation matrix can be hence estimated empirically. This alternative represents a much simpler procedure compared to a numerical search algorithm, although it does not necessarily ensure that the resulting X variates will have the required covariance structure [Ghosh, 2002]. The joint normality of the transformed standard normal variables Z_i' cannot be guaranteed; hence the procedure may not fully capture the exact linear correlation matrix.

Empirical NORTA Generation Procedure

Step 1: Normalize the data

Step 2: Obtain the empirical correlation matrix Σ_Z'

Step 3: Determine a lower-triangular factorization L of the correlation matrix Σ_Z' so that $LL^T = \Sigma_Z'$ (Cholesky factorization).

Step 4: Generate a k-dimensional multivariate random vector $\boldsymbol{M}$ whose elements are independent and identically distributed (i.i.d.) standard normal random variables.

Step 5: Define the base vector $\boldsymbol{Z'} = L \cdot \boldsymbol{M}$.

Step 6: Return $\boldsymbol{X}$ where $X_i \leftarrow F_{X_i}^{-1}[\phi(Z_i)]$ $i = 1,2,\dots,k$.

Step 7: Go to step 3.

The proposed method provides a flexible procedure to generate synthetic data to be used in a non-sequential power system reliability simulation. It can be applied to any weather variable and even though it does not fully describe the underlying dependence structure between random variables, it can match any given marginal distribution and correlation matrix. The empirical NORTA procedure has been applied to a test case involving 15 power areas in the western Danish power system (DK1). The results are presented below:

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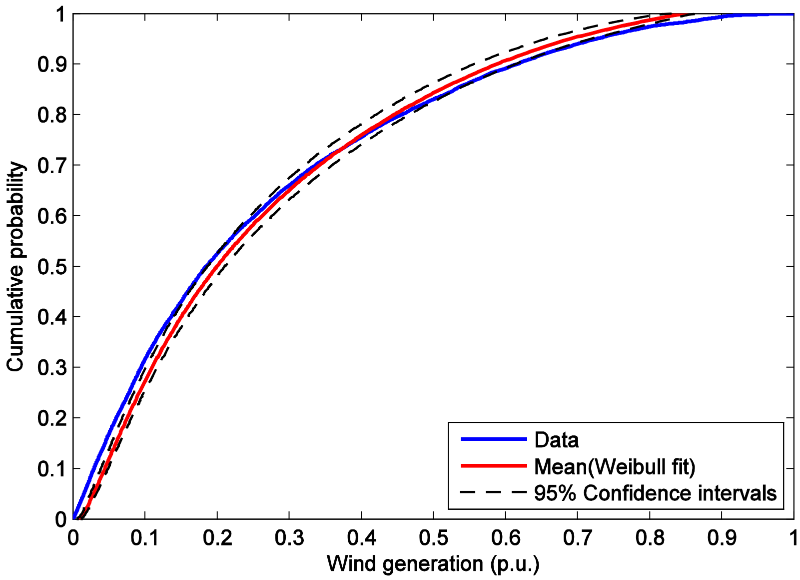

Figure 6-2: Cumulative distribution function for the aggregated wind generation in the Danish power system

6.4 Application of clustering in the synthesis of credible operating states

This section is based on the assumption that the credible synchronized time-series for load and generation per buses are available (sampled), as described in the previous sections. However, because of the possibly great number of operating states due to the increased uncertainty in the long-term horizon, clustering will be presented and considered as a reduction technique for coping with the higher complexity in terms of computational feasibility and interpretation of results.

6.4.1 Introduction

In the era of Big Data and fast advancements in computational power, Data Mining is a fast developing discipline which finds applications in various industries. The electric power system is no exception. With accumulation of huge amount of data and records from the SCADA system (and not only), with increasing time resolution, a main question is how to interpret and utilize all this data in a meaningful way. Even more, in many areas Data Mining leads to and is the main tool for knowledge discovery from data.

A major part of Data Mining is the so called Machine Learning algorithms which are basically about how to automate the process of finding complex patterns in the data and based on that to make intelligent decisions. It is divided into two main sub-classes: Supervised and Unsupervised. Supervised Learning can be viewed as a classification problem because it starts with a training set which is used to train the algorithm. From there on the algorithm has to classify the new data into the pre-defined by the training set categories. In other words, Supervised Machine Learning is “learning by example”.

On the other hand, Unsupervised Machine Learning operates on unlabelled data, i.e. it is “learning by observation”. Unsupervised Machine Learning is often referred to as clustering. Clustering partitions the data into groups (or also clusters) in such a way that objects (records) within a cluster are similar to one another and dissimilar to the other objects from the other clusters.

Both Supervised and Unsupervised Machine Learning can have their application in power system studies. However, in the context of long-term planning, the main focus in this report is put on the Unsupervised

Machine Learning (i.e. clustering) because of the big and various uncertainties in the long-term horizon it is suggested that the otherwise necessary learning examples are not known a priori.

Clustering is performed on data sets which consist of data objects also referred to as records, snapshots or samples. The data objects within the data set have common features against which they are compared. These features can be of numeric or non-numeric type. The numeric features can be continuous (e.g. load), discrete (e.g. tap changer position) or binary (e.g. element's status as on or off).

The following aims not to be extensive but rather a short introduction to the main concepts of clustering and its possible application in the process of the overall electric power system long-term planning.

6.4.2 Data pre-processing

Every data analysis starts with data pre-processing in various aspects: scanning and removing outliers, scanning and filling in missing data, removing noise and so on [Han, 2012]. Normalization is one of these aspects and is worth mentioning because in the context of the work in T4.2 when snapshots of demand in many different buses are clustered, their values might be in completely different ranges leading to that big variation in buses with less installed load might be neglected by small variations in buses with bigger installed load.

Normalization is mainly two types [Han, 2012]:

- Min-max normalization – transforms proportionally a particular value v_i of an attribute A within a given range $[min_A;\ max_A]$ to a new value v' in a new range $[new\_min_A;\ new\_max_A]$:

$$v_i' = \frac{v_i - min_A}{max_A - min_A}\left(new\_max_A - new\_min_A\right) + new\_min_A$$

- z-score normalization – also called zero-mean normalization, because the transformation is based on the mean $\bar{A}$ and the standard deviation σ_A of the attribute values:

$$v_i = \frac{v_i - \bar{A}}{\sigma_A}$$

Reference [Han, 2012][Han, 2012] suggests that z-score normalization has the benefit of being more invariant to outliers and when actual minimums and maximums are not a priori known or might change with new data. Both methods have their application (are in certain situations are even necessary) in the context of the clustering of electric power system data though they should be used with caution with respect to the overall goal of the clustering because they could change significantly the results of the clustering.

6.4.3 Similarity measures

Some clustering algorithms assign each data object to only one cluster (i.e. hard clustering), while others estimate the probability (likelihood, membership degree) that a data object belongs to a cluster (i.e. fuzzy clustering or probabilistic clustering) [Kile, 2014]. In the context of synthesis of (deterministic) credible operating states, the emphasis is put on hard clustering algorithms.

In the case of hard clustering, a measure is necessary to determine the similarity/dissimilarity between two points in the given dataset. In the context of vectors (of coordinates), these similarity measures can

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be interpreted as distances (length, vector norm) – the smaller the distance, the closer (i.e. the more similar) the data objects are.

If a data object has n number of features (properties, attributes), it can be treated as a point in an n-dimensional feature space and the specific values of the features are the point's actual coordinates in this n-dimensional space. This way the data object (record, snapshot, sample) is a vector with size $(1 \times n)$. The clustering problem then translates into finding in this n-dimensional space groups of points which are closer to one another with respect to the other groups of points (regardless of the actual meaning and context of the features, i.e. dimensions).

The most popular similarity measures, which are also implemented in Matlab are listed below. If the data set X is a $(m \times n)$ matrix, then as already explained it might be treated as $m(1 \times n)$ row vectors $x_1, x_2, \dots x_m$ and the various distances (similarity measures) between the vector x_s and x_t are defined as follows [Mathworks, 2016]:

- Euclidean distance

$$d_{st}^2 = (x_s - x_t)(x_s - x_t)^T$$

- Standardized Euclidean distance

$$d_{st}^2 = (x_s - x_t)V^{-1}(x_s - x_t)^T$$

where V is a $(n \times n)$ diagonal matrix whose j^{th} diagonal element is $S(j)^2$, where S is a vector of standard deviations.

- Mahalanobis distance

$$d_{st}^2 = (x_s - x_t)C^{-1}(x_s - x_t)^T$$

where C is the covariance matrix.

- City block metric

$$d_{st} = \sum_{j=1}^{n} \left| x_{sj} - x_{tj} \right|$$

- Minkowski metric

$$d_{st} = \sqrt[p]{\sum_{j=1}^{n} \left| x_{sj} - x_{tj} \right|^p}$$

For the special case of $p = 1$, the Minkowski metric gives the City block metric, for the special case of $p = 2$, the Minkowski metric gives the Euclidean distance, and for the special case of $p = \infty$, the Minkowski metric gives the Chebychev distance.

- Chebychev distance

$$d_{st} = \max_j \left\{ \left| x_{sj} - x_{tj} \right| \right\}$$

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- Cosine distance

$$d_{st} = 1 - \frac{x_s x_t^T}{\sqrt{\left(x_s x_s^T\right)\left(x_t x_t^T\right)}}$$

- Correlation distance

$$d_{st} = 1 - \frac{\left(x_s - \overline{x}_s\right)\left(x_t - \overline{x}_t\right)^T}{\sqrt{\left(x_s - \overline{x}_s\right)\left(x_s - \overline{x}_s\right)^T}\sqrt{\left(x_t - \overline{x}_t\right)\left(x_t - \overline{x}_t\right)^T}}$$

where $x_s = \frac{1}{n}\sum_j x_{sj}$ and $x_t = \frac{1}{n}\sum_j x_{tj}$

- Hamming distance

$$d_{st} = \left(\#\left(x_{sj} \neq x_{tj}\right)/n\right)$$

- Jaccard distance

$$d_{st} = \frac{\#\left[\left(x_{sj} \neq 0\right) \cap \left(\left(x_{sj} \neq 0\right) \cup \left(x_{tj} \neq 0\right)\right)\right]}{\#\left[\left(x_{sj} \neq 0\right) \cup \left(x_{tj} \neq 0\right)\right]}$$

- Spearman distance

$$d_{st} = 1 - \frac{\left(r_s - \overline{r}_s\right)\left(r_t - \overline{r}_t\right)^T}{\sqrt{\left(r_s - \overline{r}_s\right)\left(r_s - \overline{r}_s\right)^T}\sqrt{\left(r_t - \overline{r}_t\right)\left(r_t - \overline{r}_t\right)^T}}$$

where r_{sj} is the rank of x_{sj} taken over $x_{1j}, x_{2j}, \ldots x_{mj}$; r_s and r_t are the coordinate-wise rank vectors of x_s and x_t, i.e. $r_s = \left(r_{s1}, r_{s2}, \ldots r_{sn},\right)$; $\overline{r}_s = \frac{1}{n}\sum_j r_{sj} = \frac{\left(n+1\right)}{2}$; $\overline{r}_t = \frac{1}{n}\sum_j r_{tj} = \frac{\left(n+1\right)}{2}$;

Apart from that, also each feature could be assigned a specific weight coefficient in the calculation of the distance measures.

The choice of appropriate similarity measure is crucial for the outcome of the clustering. This will be illustrated with the simple example from Figure 6-3. It depicts 3 sample points in a two-dimensional space.

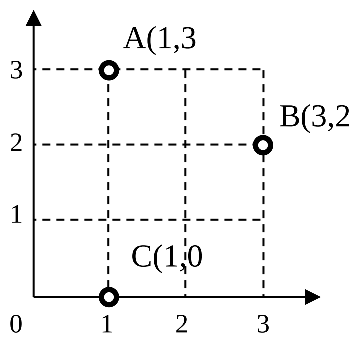

Figure 6-3: Example of 3 points in 2-dimensional space

Table 6-5 shows the distances between the three points expressed in the different distance measures. One can see that they vary in very wide ranges and show completely different trends. This is even more obvious in Table 6-6 that shows the clustering based on the different similarity measures. Altogether, for this simple example, three different clustering outcomes are formed (points A and B belonging to cluster 2 and point C to cluster 1 is essentially the same as points A and B belonging to cluster 1 and point C to cluster 2).

Table 6-5: Comparison of values of different distance measure

	AB	AC	BC
euclidean	2.2361	3	2.8284
seuclidean	1.8516	1.964	2.1712
cityblock	3	3	4
minkowski	2.2361	3	2.8284
chebychev	2	3	2
mahalanobis	2	2	2
cosine	0.21065	0.68377	0.16795
correlation	2	2	2.22e-16
spearman	2	2	2.22e-16
hamming	1	0.5	1
jaccard	1	0.5	1

Table 6-6: Comparison of clustering based on different distance measure

	A	B	C
euclidean	2	2	1
seuclidean	1	1	2
cityblock	1	2	1
minkowski	2	2	1
chebychev	1	1	2
mahalanobis	2	2	1
cosine	2	1	1
correlation	2	1	1
spearman	2	1	1
hamming	1	2	1
jaccard	2	1	2

Altogether, the choice of similarity measure for the clustering should be made with caution, in the context of the data objects being clustered (e.g. snapshots of load consumption, time series, network topology) and the features types (e.g. continuous/discrete/binary, numeric/text/enumeration).

In the context of the electric power system and the work in this deliverable, the authors have applied the Euclidean and Chebychev similarity measures with most success on clustering snapshots and time-series of load consumption.

6.4.4 Types of clustering algorithms

There is a great variety of clustering algorithms, each targeting different types of problems, different types of feature sets, different number of dimensions.

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Reference [Han, 2012] further differentiates the clustering algorithms into four main categories:

- Partitioning methods: one-level of grouping which separates the data into groups with at least one object within the group. Achieving global optimum is usually not computationally feasible and the results converge to a local optimum. To deal with this problem various heuristics are applied. Because portioning methods are usually distance based, they result in grouping the objects into hyper-spheres in the n-dimensional feature space.
- Hierarchical methods: as the name suggests, aims at creating a hierarchical decomposition of the data set. They can be further subdivided into agglomerative (i.e. bottom-up approach) or divisive (i.e. top-down approach).
- Density-based methods: search for regions in the n-dimensional feature space that are denser and thus can find clusters with arbitrary shape and filter out noise and outliers.
- Grid-based methods: the feature space is divided into regions (cells) that form a grid. This way the algorithm's performance is affected little by the number of objects being analysed, however is dependent on the grid resolution.

Reference [Andreopoulos, 2009] gives an extensive overview and classification of various clustering algorithms, their computational complexity, implementation and application.

Maybe the most popular and widely used is the K-means method.

It comprises of the following steps:

Step 1: Choose k initial cluster centroids.

Step 2: Calculate the distances from each data object to all the cluster centroids.

Step 3: Reassign all data objects to the clusters whose centroids are the closest and recalculate the new cluster centroids (i.e. means).

Step 4: Repeat steps 2 and 3 until no data object changes its cluster.

The algorithm has been updated to the K-means++ algorithm [Arthur, 2007] to introduce heuristics in order to improve the convergence issue, mentioned earlier.

K-medoids is a modification of the K-means algorithm so that it does not perform clustering around the cluster means, but around the cluster medoids (the difference between mean and medoid is similar like the difference between mean and median; however median and medoid are not exactly the same). Medoids are always a data object within the data set. This way the clustering is more robust to outliers, the method can be applied on more types of data and thus various distance measures can be applied.

The main drawback is that the number of clusters has to be given in advance.

6.4.5 Evaluation of clustering

The question "What is the right number of clusters?" actually translates into "What is a good clustering?".

The clustering quality is ambiguous and often depends on the particular context of application. In general, if a priori a good clustering benchmark is available, one could use the so-called extrinsic methods. However, this is usually not the case and then one could use the so-called intrinsic methods which evaluates how well the clusters are separated [Han, 2012]. The silhouette coefficient is such intrinsic measure [Han, 2012]. It is a value in the range [-1;1] and evaluates if points within the cluster are closer to other points from other clusters than to the points within the cluster. Silhouette coefficient equal to 1 means that clusters are compact and well separated from each other, but if it is a negative value, it might suggest

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that the clustering is not good. However, this might not be meaningful for continuously spread data because in it the points are not separated in regions but are more or less homogenously spread. In such situation the clustering problems is actually a segmentation problem.

Since in power system analysis usually the data is homogenously spread (load and generation time-series or snapshots), it might be necessary to consider other measures. For example, Figure 6-4 depicts one cluster from the clustering of three year of synchronized records for six load of different type. The box plot shows good clustering because the actual load records are within limited range which means that the cluster centroid or memoid can be used as a good approximation for load flow or contingency calculations.

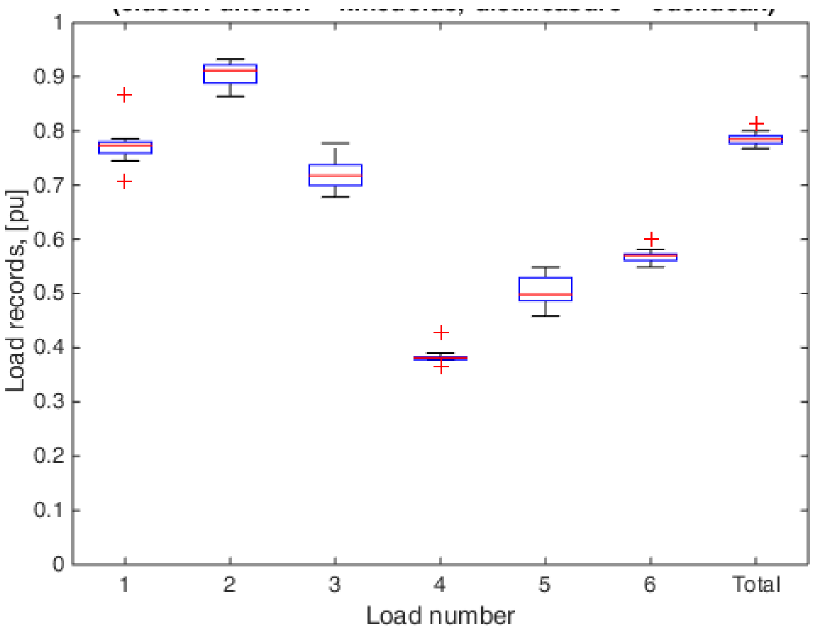

Figure 6-4: Box plot of a cluster of 20 synchronized snapshots for 6 loads

In this case, the assessment of the clustering quality is based on the maximum range of deviation of a load (feature) and if outliers are detected, they might be considered candidates for new clustering.

6.4.6 The "right" number of clusters

Reference [Han, 2012] explains that a general and simple criterion is to set the number of clusters equal to $\sqrt{\frac{n}{2}}$ where n is the number of data points. For example, if $n = 1000$ this equals to about 22 clusters.

The other often mentioned in literature method is the so called "elbow method". It is based on calculation of the "within cluster dispersion" and as the number of clusters increases, this cluster dispersion decreases until it reaches a certain turning point, i.e. the elbow. However, unfortunately, for segmentation problems this is not very obvious.

Reference [Kile, 2014] makes a comprehensive study on the application of different clustering algorithms and setting different number of clusters for the purpose of calculation of reliability indices. One of the main conclusions is that (for all studied clustering algorithms) accuracy of less than 2 % error in the calculation of the reliability indices can be achieved if the number of clusters is about 10 % of the studied snapshots which still means 10 times decrease in the necessary computation time without compromise of the results. Depending on the types of studies, the clustering is going to be applied to, even a further decrease is possible.

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6.4.7 Feature sets

As already explained, an operating state essentially consists of three main components: load, generation and network. Comparing all three at the same time is not meaningful because the same similarity measure cannot be applied for load, generation and network topology at the same time and also because of the so called "the curse of dimensionality" effect (see section 6.4.9). This is why usually the network topology is regarded as different scenarios.

Regarding the load and generation some of the options for feature sets are:

- Power injections per generation and load buses.
- Power flows – one drawback in this case is that a power flow has to be calculated for all samples before clustering can be applied. Also, this feature set is topology dependent meaning that it has to be applied carefully if switching actions or planned outages will be considered.
- Cross-border exchange – unlike the previous three, this is more appropriate for multi-TSO studies.

Usually studies are performed on data for the active power and then power factors are applied to find the reactive and apparent power.

6.4.8 Time-series vs snapshots

Usually, an operating state is treated as a snapshot. This can be enough for contingency studies and for identification of a limited number of operating states to be studied in more detail by the system planner.

The main problem with time-series is, for example, that it is extremely difficult to compare synchronized sequences of load per buses. This is why usually the considered time-series are of aggregated values such as total system load. Then the features are the number of time steps within the considered time window. Most often this means 24 values for 24-hour window with hourly resolution (or 96 for 15-minute resolution).

One such example for the total system load is presented in Figure 6-5 to Figure 6-8. It shows the application of clustering for finding typical (in terms of total system load) days. Figure 6-7 depicts all the cluster memoids (i.e. the typical days) against all days and it can easily be seen that they pretty much cover the whole range of deviation of the total system load for the whole year. Of course, if the number of clusters is increased, clustering will be improved. It is also interesting to notice in Figure 6-6 that seasonality and weekday/weekend dependency is automatically and successfully caught by the clustering algorithm. Similar approach is successfully applied in [Green, 2014].

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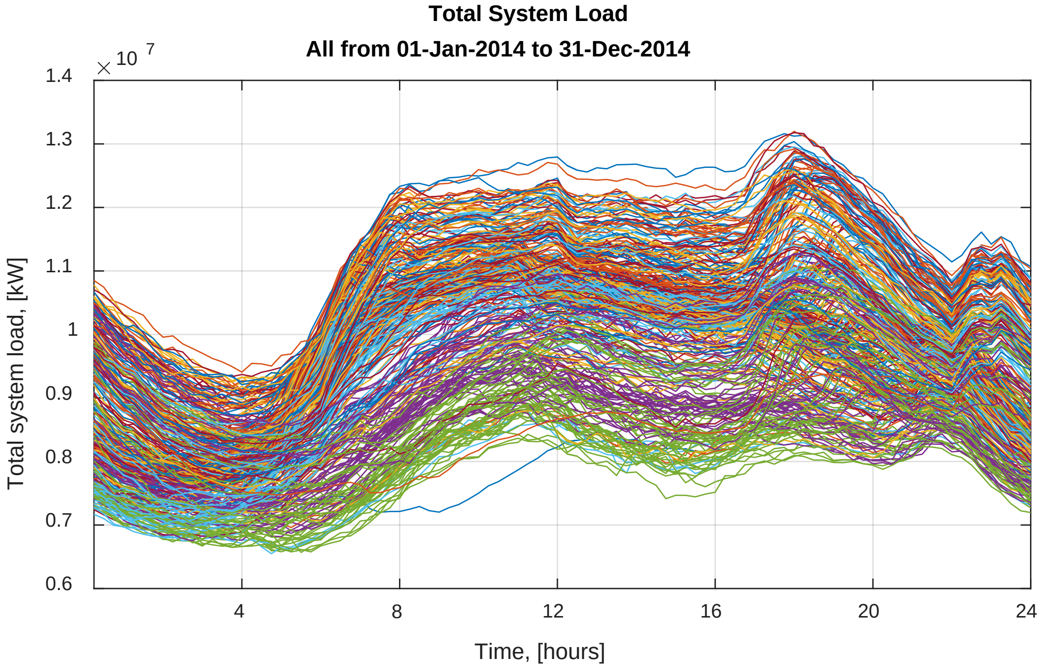

Figure 6-5: Records of the total system load for 2014

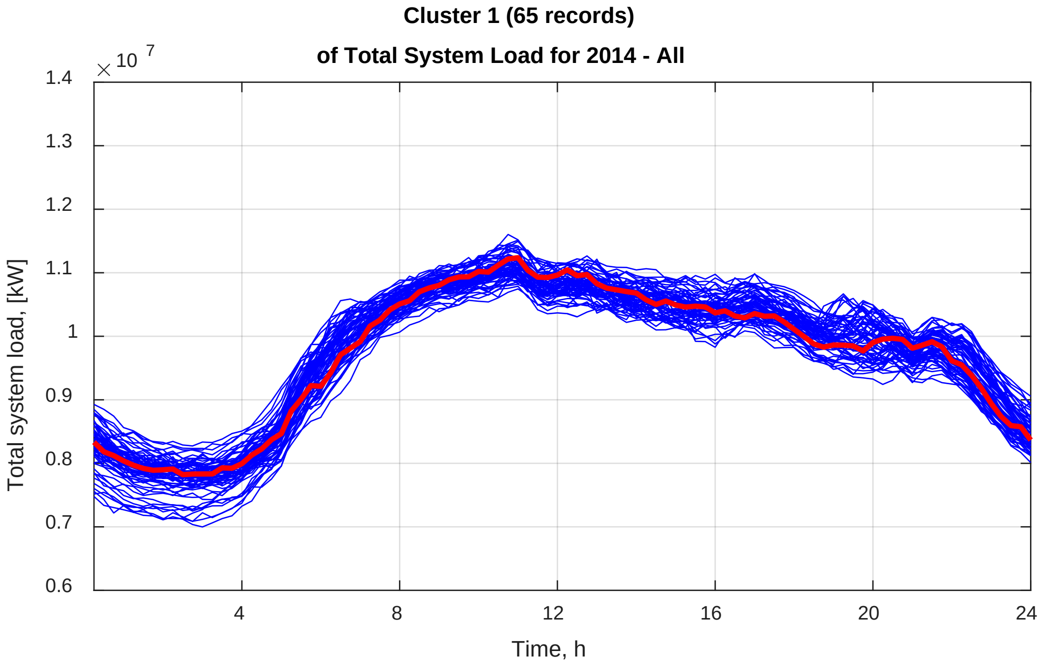

Figure 6-6: Cluster centroid and all cluster member of one of the cluster of recorded days of total system load

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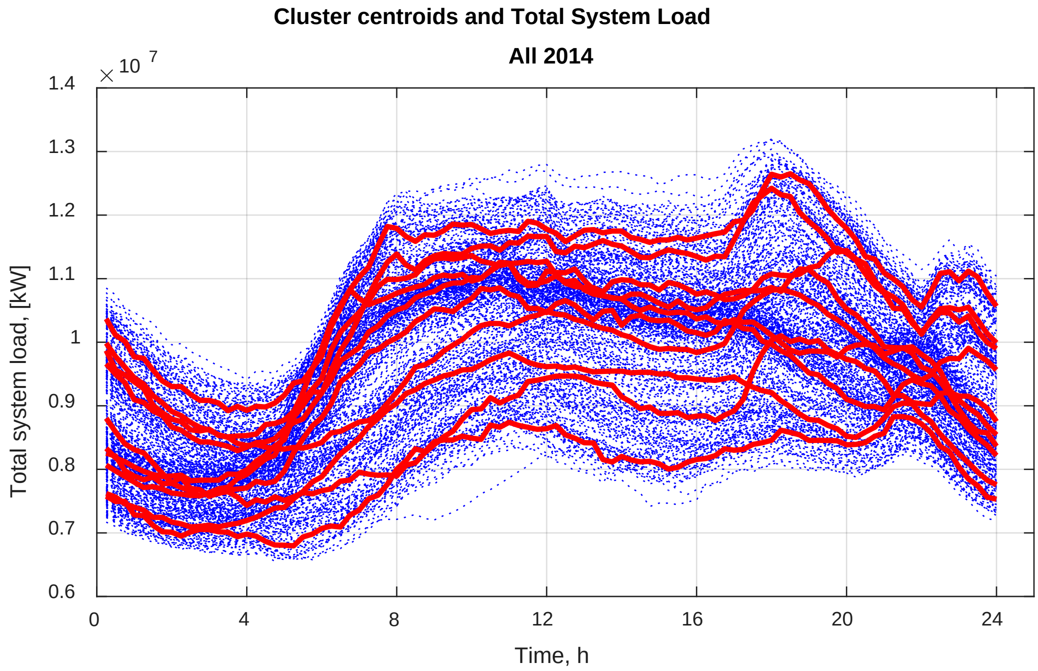

Figure 6-7: All cluster centroids against all recorded days of the total system load for the whole 2014

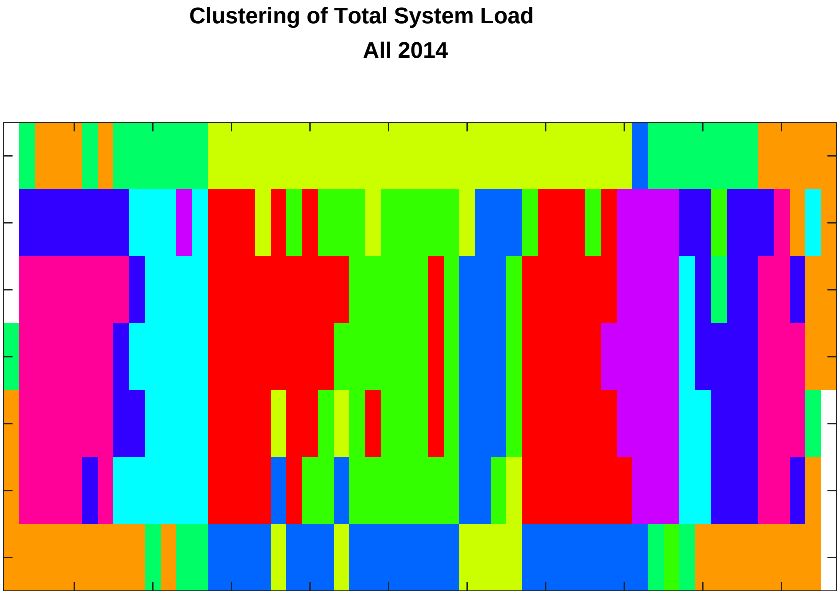

Figure 6-8: Colormap of the clustered recorded days of total system load, for the whole 2014

6.4.9 The curse of dimensionality

If the number of dimensions becomes too large, traditional similarity (distance) measures might start to loose meaning. The following example illustrates this effect [Han, 2012]:

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Table 6-7: Example data illustrating the "curse of dimensionality" effect

	F1	*F2*	*F3*	*F4*	*F5*	*F6*	*F7*	*F8*	*F9*	*F10*
X	1	0	0	0	0	0	0	0	0	0
Y	0	0	0	0	0	0	0	0	0	1
Z	1	0	0	0	1	0	0	0	0	0

The Euclidian distance between all three points is the same:

$$dist(X,Y) = dist(Y,Z) = dist(X,Z) = \sqrt{2} \ ,$$

despite that they are obviously very different from one another. To cope with this problem, besides carefully choosing features and distance measure, one might apply dimensionality reduction techniques before the actual clustering. One of the most popular dimensionality reduction techniques is the so called Principal Component Analysis (PCA) which is based on Singular Value Decomposition (SVD) to remove redundant data. Another option is the discrete wavelet transform (DWT).

6.4.10 Difference between clustering and sampling

Last but not least, it useful to make a clear distinction between clustering and sampling and in what situations is each applied:

1) clustering – ***Analysis is started with the assumption that the demand, PV generation and wind speed samples per bus are already available, synchronized and sufficient!*** *Were these samples actual records or were generated is completely irrelevant*. Then, in the context of WP4, clustering is a reduction technique. It solves basically a segmentation problem by grouping the present samples in ***clusters within which*** the different variates (treated as the sample ***dimensions***, i.e. the features*)* ***vary in small enough ranges so that one can have confidence that by only looking at the centroid of the cluster, conclusions about all the other cluster members*** can be made. This is also a way of dealing with uncertainty in the samples.

   As being a type of unsupervised machine learning algorithm, clustering itself usually does not make use of prior knowledge about the data like for example PDFs (probability distribution functions) of loads.

   It has to be pointed out also that *if extreme operating states are not in the initial set of samples, they will not be in the amongst the final clusters centroids!*

2) sampling – ***Initially samples might not be present*** so a strategy to generate them is necessary. ***Even if some samples are available they are treated as either not sufficient or too many*** and used only for finding PDFs and/or dependencies (correlations) between the different variates of interest. Then, using this additional information about PDFs and/or correlations, a new set of samples is generated. This new set could have much smaller or much bigger size than the original data. Having the same size as the original data (and keeping the same statistical properties) might account for variability in the data but will not bring much benefit to the overall analysis. (It must be noted that in sampling uncertainties are usually treated by introducing additional variation in the sample variates for which a greater number of samples is necessary).

   Sampling is used in two different contexts:

   a. As a reduction technique – *the size of the new set of samples is significantly* ***smaller*** *than the size of the original data.* Basically the idea is to generate or filter out of the original data a new set of samples (but significantly less in number than the original set of data)

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such that it has similar statistical properties (like mean, standard deviation and correlation) as the original big set of data.

Task 4.2 is interested in reductions techniques as a way to cope with the huge number of possible combinations. On the other hand, task 4.2 is also interested in the extremes (for the purpose of understanding the need for 'reliability-drive' investment) and not just in keeping statistical properties of the set of samples (which would mainly be used for estimating the expected cost of system operation and evaluating whether 'economy-driven' investments might be needed). However, the assessments in T4.3 require not just extreme events so such sampling might be more beneficial there.

b. In Monte Carlo simulations – *the size of the new set of samples is significantly **bigger** than the size of the original data.* This is the most often application of sampling. Monte Carlo is used when a certain integral value (measure) has to be calculated with a limited variance in the estimation (degree of confidence) and it is difficult or impossible to use other mathematical (numerical or analytic) methods. In order to speed up the calculations various strategies have been developed to utilize specific knowledge about the problem in order to accelerate the convergence of the assessed parameter within the desired confidence (variance) interval – the so called variance reduction techniques. The "importance sampling" and "stratified sampling" are such type of techniques. Basically they both try to concentrate/prioritize the random sampling within regions which contribute more to the calculated integral quantity in order to speed up the computational time. In this context, an option might be treat the cluster centroids/memoids, identified as leading to overloading or voltage problems in cases of contingencies as stratum for the stratified sampling in the T4.3 evaluation and optimization. It must be noted though that, for example, the different purposes of identifying 'reliability-driven' investment and 'economy-driven' investment might lead to different sampling strategies.

Reference [Li, 2014] proposes a relatively simple way to sample of demand (see the screenshots below). The load duration curve (profile) of the different classes of consumers (such classification algorithms are being developed in T5.2 of the GARPUR project [GARPUR, 2016c]) are separated into several levels (called a multi-step model of the load) and sampling is carried out only on the different possible combinations of the levels in the different load classes with the introduction of random uncertainty.

The report [Rios, 1999] presents a very thorough and practical analysis of various variance reduction techniques in the context of electric power system security assessment. It utilizes importance and stratified sampling mainly in terms of determination of how many contingencies and how deep in the N-x problem to go which is also another important aspect.

The NORTA sampling developed by DTU for wind speeds can be treated in both contexts. However, because usually wind speed records (or samples generated by supercomputers like the one in DTU) are available for many years and because wind can be treated as a stationary random process, its application is more appropriate as a reduction technique. It must be pointed out, though, that, as already demonstrated, the NORTA sampling assumes a single correlation structure. This can be problematic if correlations at high levels are different to correlations in a central part of the distribution. This means that if the number of generated samples is not big enough, extreme events might be missed.

This issue is illustrated in Figure 6-9. It is clearly seen that most of the recorded extreme wind speeds are missing in the NORTA generated samples but are preserved in the clustering.

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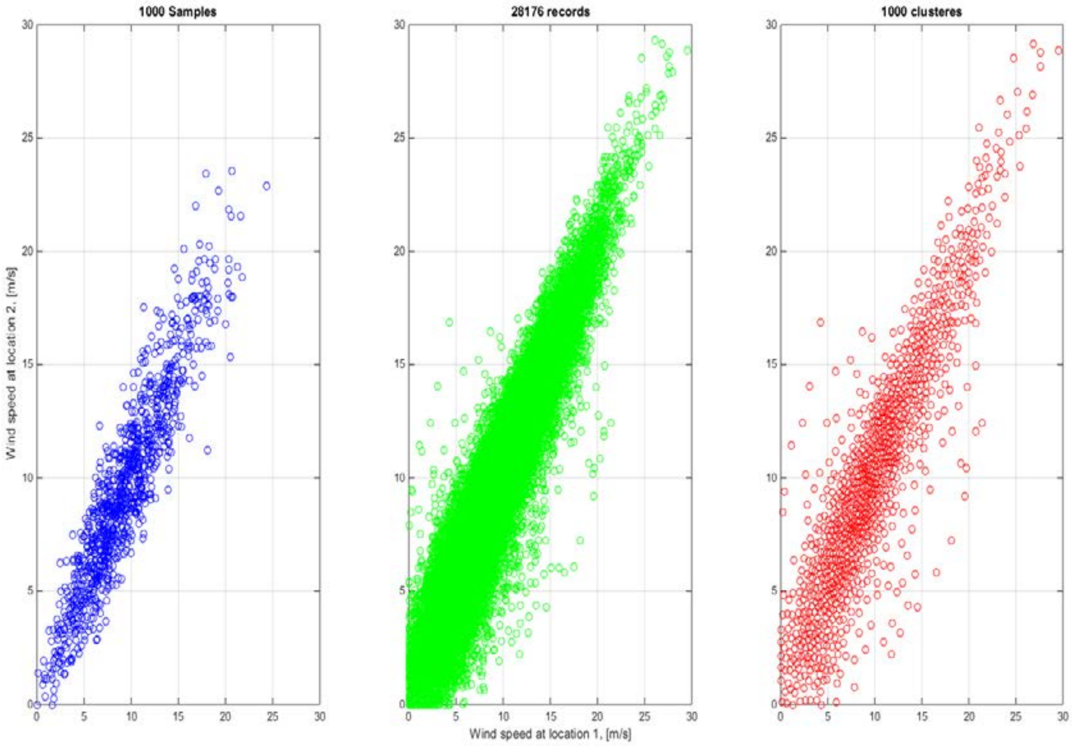

Figure 6-9: Comparison of K-medoids clustering and NORTA sampling.
In the middle (in green) are 28176 re-ordered wind speeds at two different locations for 13 winters.
On the left (in blue) are 1000 NORTA samples,
and on the right (in red) are 1000 clusters memoids of the records.

Meanwhile, if the statistical properties of the recorded, sampled and clustered wind speeds from Figure 6-9 are compared (see Table 6-8) it will be interesting to notice that NORTA samples and the records are much more similar than the clustered records. This is because in the calculation of the data in Table 6-8 the weight of the clusters was not accounted for, i.e. that a cluster might contain only one record, but also might contain much more records. If this is taken into account, then the mean and the standard deviation of the recorded and clustered wind speed practically becomes the same.

Table 6-8: Statistical properties of the wind speed records from Figure 6-9

wind speed	**correlation**	**at location 1**		**at location 2**	
		mean	**std**	**mean**	**std**
recorded	0.9300	9.2149	4.2317	9.4798	4.3881
sampled	0.9246	9.3329	4.1518	9.503	4.2873
clustered (unweighted)	0.8894	10.294	5.678	10.445	5.746

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6.4.11 Conclusion

Data mining techniques (and clustering as such) are already being applied with success in electric power system reliability analyses like the iTesla [iTesla] and SAMREL [Kile, 2014] projects. Clustering can be applied both for snapshots and for time-series and for different feature sets. In the context of credible operating states, it is proposed to be used for two main reasons:

- To decrease the computational burden, i.e. it is not necessary to repeat the analysis for practically similar operating states. These small variations in the analysis results are in line with the notion of proxies and residual risk introduced in WP2.
- To reduce the number of operating states to be studied by the system planner by providing him with a generalization of the main operating states leading to thermal and voltage violations in cases of contingencies.

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