THE GARPUR PROJECT

Results and recommendations towards stakeholders

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GARPUR

EEGI
EUROPEAN ELECTRICITY GRID INITIATIVE

SEVENTH FRAMEWORK PROGRAMME

Author(s) Name	Organisation	E-mail
Louis Wehenkel	University of Liege	L.Wehenkel@ulg.ac.be
Matthias Hofmann	Statnett	Matthias.Hofmann@Statnett.no
Athanase Vafeas	Technofi	avafeas@technofi.eu
Efthymios Karangelos	University of Liege	e.karangelos@ulg.ac.be
Einar Jordanger	SINTEF	einar.jordanger@sintef.no

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ABOUT THIS REPORT

This document presents the main results and recommendations of the GARPUR project in a transparent manner, organised into three main chapters and an appendix outlined below.

Chapter 1 provides a short introduction to reliability management and recalls the current practice based on the N-1 criterion. It also describes the overall approach pursued in the GARPUR project to develop a general probabilistic reliability management framework that can be used in the different contexts of system development, asset management, and system operation.

Chapter 2 provides an exhaustive account of the results obtained within the different research and testing activities carried out during the project, pointing to the public documents available on the GARPUR website at: http://www.garpur-project.eu/deliverables.

Chapter 3 provides a description of the specific recommendations for further work, organized into four main logical clusters. These recommendations are formulated on the basis of the results obtained during the project and the interview of external stakeholders during the last month of the project.

The appendix recalls the project objectives and R&D strategy, the consortium structure, organization of work, and dissemination activities. It also gives an overview of the public deliverables available from the GARPUR project.

The present report comes with a companion document: The public deliverable D9.2, which describes a roadmap to transition from the current N-1 practices to the vision proposed by the GARPUR consortium.

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EXECUTIVE SUMMARY

A secure and reliable electricity supply is the basis of most societal and economical activities. European Transmission System Operators (TSOs) have the mission to ensure the electricity supply to European citizens and industry by building the electric power transmission system, maintaining its assets, and operating the system while taking care of all relevant time scales and system areas.

Power system reliability describes the degree to which the system can be relied upon to carry electrical energy from the locations wherein it is generated to any location where it is to be consumed. Tuning the reliability level of the power system to the needs of society is the scope of ***power system reliability management***.

Historically in Europe as well as today, power system reliability management is based on the N-1 criterion, with some variations to fit particular characteristics of different control areas of the pan-European system. In general terms, the N-1 criterion means that in case of any fault of one relevant element in the power system, the TSO must still be capable of supplying electricity to all consumers.

The changing structure of the electricity generation due to increasing penetration of intermittent and distributed energy sources, the ageing infrastructure, the growing complexity of the pan-European power system, and the European objective of a single electricity market, call for more effective reliability management approaches to optimize the trade-off between the costs of providing security of electricity supply and socio-economic costs of power supply interruptions.

Over its four years, the GARPUR[1] research project (established in 2013 under the European Commission's 7th Framework Programme) has developed and tested a comprehensive probabilistic reliability management framework aiming at effectively guiding TSOs in their investment, asset management, and operational decisions. This framework targets on optimized socio-economic benefits while maintaining the security of supply at an adequate level, throughout the years and in all regions of Europe, and despite the growing diversity and strengths of threats and uncertainties.

The developed Reliability Management Approach and Criterion framework (**RMAC**) provides the basis for implementing new risk management principles for the pan-European electric power system. To be effective, this framework should be deployed in a consistent way in the different decision-making contexts under the responsibility of TSOs, namely in the contexts of long-term grid development and definition of asset maintenance and asset replacement policies, in the contexts of mid-term and short-term operational planning and control, all these being paramount for a sustainable and secure electricity supply in Europe.

The present report describes the GARPUR RMAC and its use for reliability assessment and control, and it elaborates on how to suitably model shorter-term reliability management processes when focus is on longer-term reliability management problems. These concepts are developed to better exploit the available information, mathematical knowhow, and computational infrastructures than current practice allows, and to cope with TSO specificities and novel technological opportunities.

In order to support arguments of how the new methods improve upon current practice, the approach of the project has been as follows:

[1] General information on the GARPUR project is presented in Appendix A

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1. A methodology was developed to compare the performance from a socio-economic point of view of a power system when the reliability of supply is managed either according to the GARPUR RMAC or according to the N-1 criterion. It aims at finding out the differences in costs and benefits of the different stakeholders (market participants, generators, end-users, etc.), and how they are distributed from a geographical point of view and among end-user groups.

2. A quantification platform prototype was developed to demonstrate how to exploit real data and computational reliability management tools to compute the socio-economic indicators over a set of conditions, and to demonstrate how to conduct a fair comparison of a version of the GARPUR RMAC and a version of the N-1 approach, on a given system and in a given context.

Finally, a significant GARPUR achievement is to have demonstrated, thanks to several pilot tests, the technical feasibility, scalability, and practical interest in the proposed methods to support TSOs in their reliability management activities.

The results obtained in the GARPUR project are documented in detail in Chapter 2 of the present report. Altogether, they strongly support that moving towards probabilistic reliability management in the interconnected pan-European transmission system is not only desirable but also technically feasible. Thus, the GARPUR vision for future reliability management in the Pan-European system emerging from the GARPUR project is summarized as follows:

> ***"An adoption of probabilistic reliability management by all stakeholders dealing with electric power systems reliability management,*** *from experts in the TSO organizations who have the practical responsibility to ensure the security of electricity supply, to the persons in charge at regulators and governments whose responsibility it is to ensure the electric power system performs for the benefit of all parts of society".*

In order to make this vision a reality, complementary actions must be carried out after the end of the GARPUR project. In order to propose priorities, responsibilities, and coordination of these subsequent steps, the present report provides a detailed list of recommendations organized along the four following topics:

1. **Regulation and socio-economic considerations**: These recommendations are related to the identified needs for changing the regulation and for properly anticipating the socio-economic impact of moving towards a probabilistic reliability management approach.

2. **Data collection and models of uncertainties:** These recommendations concern the enhancement of the quality of data and models of uncertainties required by the methods developed in the GARPUR project. They cover the needs to gather more data, to exploit these data to improve models, to share both raw data and models among TSOs, and to assess the additional value of novel data acquisition strategies.

3. **Reliability management methodology, algorithms, and software**: These recommendations concern the further development of industrial grade implementations of software tools for probabilistic reliability management. Industrial use not only means computational efficiency and scalability to continental scale power system models, but it also means robustness of the software, and adaptability to the specifics of each TSO's practices.

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4. **<u>Testing and implementation</u>:** These recommendations concern the efforts that should be made to gain further confidence, develop know-how, achieve wide acceptance, and thus ensure the gradual implementation of the proposed approach in TSOs' practice.

These recommendations, and the process put in place during the GARPUR project to crystalize them, are described in detail in Chapter 3 of the present report.

A separate document summarizes **The GARPUR roadmap**[2] and shows the time-line of the different steps needed to make the use of probabilistic reliability management approaches and criteria a pan-European reality within the next 10 years.

[2] See GARPUR deliverable D9.2 at: www.sintef.no/GARPUR/Deliverables

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1 INTRODUCTION TO RELIABILITY MANAGEMENT

Before introducing the GARPUR methodology, the following subsections provide requisite background concepts and useful context for understanding the results and recommendations of the GARPUR project.

1.1 Basic concepts

Power system reliability describes the degree to which the system can be relied upon to carry electrical energy from the locations wherein it is generated to any location where it is to be consumed. A secure and reliable electricity supply is the basis of most societal and economical activities. Tuning the reliability level of the power system to the needs of society is the scope of *power system reliability management*.

Power system reliability management means making decisions under uncertainty. It aims to meet a *reliability criterion* and to minimize the costs of doing so. A reliability criterion is a principle that imposes a standard to determine if the reliability level of a power system is acceptable. Reliability management refers to a wide range of activities with several timescales, from planning the future development of infrastructure with a long-term perspective (say the next 20 years) to operating the grid from the control room in real-time. Notwithstanding technical complexity, making such decisions involves a trade-off between the costs of providing security of electricity supply[3] and socio-economic costs of power supply interruptions. Consider, by way of example, the question of expanding the transmission capacity of the grid. New transmission corridors may mean more redundancy hence greater security of electricity supply, but they may also mean higher costs, not to mention the impact their construction may have on the natural environment. On the other hand, not building more transmission capacity may save money in the short run, but this also means less security of supply, which in turn may lead to increased socio-economic costs due to more frequent power supply interruptions. It might also limit the potential to integrate renewable generation resources.

In order to solve such complex decision-making problems, reliability management is commonly decomposed into *reliability assessment* and *reliability control*. Reliability assessment concerns quantifying the (anticipated) performance of a system facing uncertainties in its operational conditions over a specified period of time. The complementary step of post-processing the assessment outcomes to select among the available options and apply suitable actions is termed reliability control. In both cases, the level of assurance on the system reliability required by regulations is expressed by means of the reliability criterion.

1.2 Types of reliability management problems

In order to properly manage power systems reliability, decisions can be taken in three main contexts, namely system operation, asset management, and system development.

In *system operation*, decisions may be taken both in real-time and in the context of operational planning. In the real-time context, system topology or generation schedules may be adjusted to prevent component failures from causing line or transformer overloads or instabilities that would eventually result in power supply interruptions. In *operational planning*, decisions are taken about anticipating or postponing maintenance activities and/or reserving flexibility resources (generation and possibly load) to enable reliable operation over a horizon of a few hours to a few days ahead in time.

[3] Here, costs of providing security of electricity supply are defined in a broad sense. The concept includes all socio-economic costs, direct and indirect, of providing a given level of security of supply. Important elements are costs of TSOs, such as costs of investment and maintenance of the transmission system, costs of supplying reserves, as well as congestion costs of suppliers and consumers due to less transmission capacity given to the market.

In power systems *asset management*, the necessary maintenance and replacement activities are scheduled annually to plan maintenance outages at the most favourable moments based on their potential impact on reliable system operation. Furthermore, at much longer timescales, it is also necessary to define adequate maintenance and replacement policies, meaning how much and what kind of activities should be foreseen for the next 20 or 30 years to maintain the reliability of the power system at a proper level.

In the context of *system development*, economically justifiable decisions are made on whether to, and if so where to, build and replace lines, cables, and substations to expand the physical structure for the expected market conditions while maintaining the reliability of supply at an adequate level.

1.3 Current practice

The current practice for reliability management is based on the N-1 criterion, with some variations to fit particular characteristics of different control areas of the pan-European system. In general terms, N-1 means that in case of any fault of one relevant element in the power system, the TSO must still be capable of supplying power to all consumers.

In the context of real-time operation, this criterion ensures the system can withstand at least the loss of any single component, possibly by means of post-contingency corrective controls.

In operational planning applications, while anticipating the near-future state of the system, the scope of the N-1 reliability management ensures the system will be able to withstand any single contingency event under the most likely operational conditions.

In long-term system development and mid-term outage scheduling, the N-1 criterion is currently used to verify that the system remains N-1 compliant, by checking operability and maintainability along a predefined set of usual and extreme conditions, e.g. winter and summer demand peaks and dips.

1.4 GARPUR's approach to reliability management

We are in a period where the European electric power system is, on the one hand, undergoing rapid and profound physical, digital, and organizational transformations driven by economic and environmental concerns, and on the other hand, where adverse human based threats to the cyber-physical and economic integrity of the system have become a major concern all over Europe.

In this situation, it has become clear that the traditional deterministic N-1 criterion has to be progressively replaced by more systematic approaches able to cope with uncertainties and grasp more effectively the trade-off between investment and operating costs and security of electricity supply. This would lead to more transparent decision-making aimed to maximize social welfare and ensure a cost-efficient security of supply.

Over its four years, the GARPUR project developed and tested a comprehensive probabilistic reliability management framework to effectively guide TSOs in their investment and operational decisions. This framework targets on optimized socio-economic benefits while maintaining security of supply at an adequate level, throughout the years and in all regions of Europe, and in spite of the growing diversity and strengths of threats and uncertainties.
GARPUR has developed a new framework called Reliability Management Approach and Criterion (RMAC). The RMAC framework provides a sound basis to implement new reliability management principles for the pan-European electric power system. A detailed description of the framework can be found in the following

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results chapter. To be effective, this framework should be, like the current N-1 based approach before it, applied in a coherent manner by the different European TSOs. The new framework must also be deployed in a consistent way in the different decision-making problems under the responsibility of TSOs, namely in the contexts of long-term system development, asset maintenance and replacement planning, mid-term and short-term operational planning, and real-time operation, all these being paramount for a sustainable and secure electricity supply in Europe.

The GARPUR RMAC, its use for reliability assessment and control, and the choice of shorter-term proxies[4] when using it for longer-term reliability management problems, are intended to use available information and mathematical and computational knowhow in a better way than what is currently possible with the existing N-1 criterion and the corresponding methods.

In order to adopt these new methods, it must be argued convincingly that they improve upon current practices. The approach of the project has been as follows:

1. A methodology is proposed that compares the socio-economic performance of a power system when the reliability of supply is managed either according to the GARPUR RMAC or according to the N-1 criterion. Such a methodology determines the difference in costs and benefits of the different stakeholders (market participants, power producers, end-users, etc.), and how they are distributed from a geographical point of view and among end-user groups.

2. A prototype quantification platform is developed to exploit real data and computational reliability management tools, to be used in the frame of GARPUR, to compute the socio-economic indicators over a set of conditions that allows a fair comparison on a given system and context of a version of the GARPUR RMAC and a version of the N-1 approach.

[4] A proxy is an approximate representation of a shorter-term reliability management context that is used when stating and solving longer-term reliability problems

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2 OVERVIEW OF GARPUR'S MAIN RESULTS

The main objective of GARPUR is to develop a comprehensive probabilistic reliability management framework that in the coming decades can replace the reliability management approaches based on the N-1 criterion. Appendix A of the present report recalls the objectives of the GARPUR project from its description of work, and provides further information about the consortium structure and the organization of the work in different work packages. During the project, various algorithms and software prototypes were developed to implement several versions of the proposed probabilistic RMAC and tested on various academic and real power system models. This important body of collaborative work, carried out over 4 years, has involved high-level expertise made available by 7 European TSOs and 12 research centres and universities. It has already demonstrated the flexibility, the computational feasibility, and the practical interest of both probabilistic reliability assessment and probabilistic reliability control. Pilot tests were conducted at several TSOs to learn about the features of the proposed approaches and to help define pathways for their progressive use in real-life. The following diagram summarizes the overall working approach of the project.

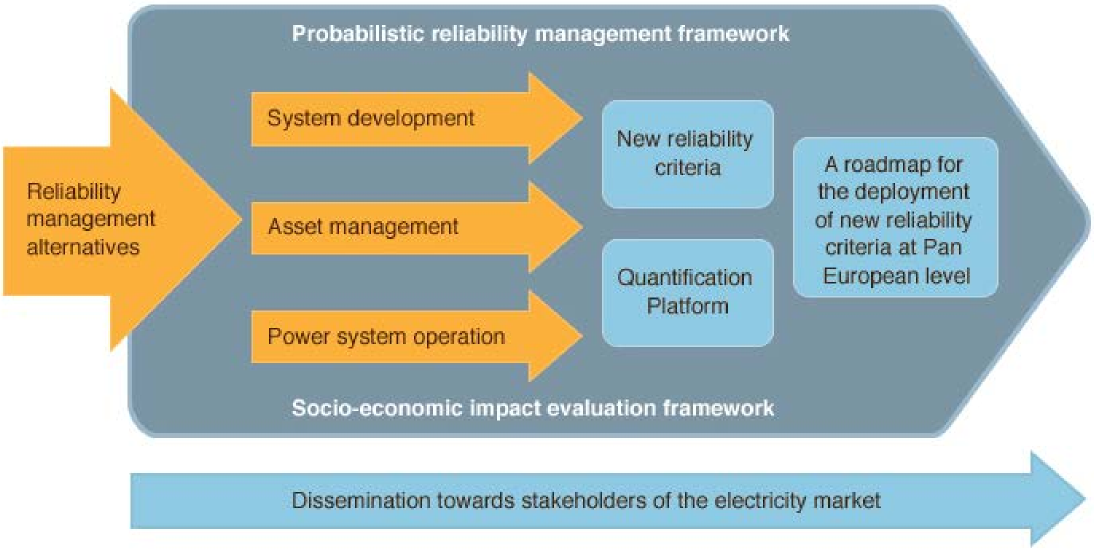

Figure 2.1: Working approach of the GARPUR project

All the work performed, the project results, and the experience gathered on the way are used as input to formulate the recommendations for a transition to probabilistic reliability management. In the next sections, we summarize the results obtained by the different GARPUR activities and provide a more detailed insight into what the recommendations are based on.

2.1 State of the art in theory and practice of reliability management

Preliminary work in the GARPUR project's first year surveyed the state-of-the-art in reliability management both from the scientific literature and from the practical experiences of TSOs via the use of questionnaires. This activity identified strengths and weaknesses of available probabilistic approaches in comparison to the N-1 criterion, and identified the various drivers and barriers for moving towards a probabilistic reliability management approach.

The literature surveys and responses to the questionnaires indicate a gap between existing research literature and what is already practiced by TSOs. Probabilistic methods, including socio-economic impact

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assessment, seem to be used to some extent in long-term planning, in mid-term planning, and in asset management, while being almost absent in short-term power system operations. The TSOs, however, already collect reliability data for primary equipment. A few lessons can be learned from air traffic management, as well as sectors such as nuclear power, gas supply, water supply, and railway, regarding the need for novel probabilistic methodologies. The findings are documented in a report (D1.1)[5], which provides a common basis for the development of probabilistic reliability management approaches and criteria for power systems.

The following items have been identified as **barriers** to the application of probabilistic reliability management methods:

- The methods are perceived as laborious and complex, and to take too much time to use
- Modelling the consequences of a contingency is seen as challenging
- The lack of reliable statistical or other data for evaluation
- A reluctance to change when there is little evidentiary experience
- It may be difficult to understand probabilistic reliability criteria and justify their impact on society.

Regulation can be seen as either a potential driver or a barrier, depending on the contents of the rules. To get an overview of **drivers**, it is interesting to look at the benefits that could be achieved by using a probabilistic reliability management framework. According to the TSO's answers, a new probabilistic reliability standard can give multiple benefits, as shown in Figure 2.2. The TSOs indicated the following benefits:

- Possibility to obtain an estimate for the reliability level of the system
- More efficient grid use
- Increase in wind or other variable production
- Less capacity given to the reserves and more capacity to power transmission
- More transmission capacity given to the market.

A report (D1.2) documents these findings.

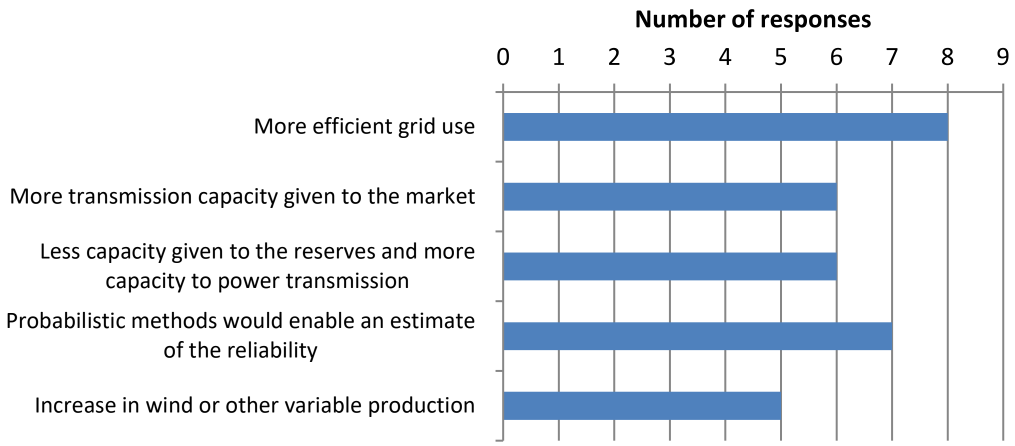

Figure 2.2: Benefits of a new probabilistic reliability standard according to nine TSOs answers

[5] See Appendix B for a complete list with detailed reference to the public reports written by the project.

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2.2 Reliability management and socio-economic impact assessment frameworks

Work on the frameworks for reliability management and socio-economic impact assessment was carried out during the first 3 years of the project. It targeted specifically the objectives recalled below[6].

> **O1:** To **develop** a consistent **probabilistic framework for reliability management** covering the definition of the notion of reliability, the calculation of reliability criteria, and the resolution of optimization problems expressing the economic costs and the desired target reliability levels at the pan-European level and within each individual control zone.

> **O2**: To **develop** a consistent methodology for the quantitative **evaluation of the economic impact on society** of different reliability management strategies, both at the pan-European level and within each control zone.

> **O4:** To **ensure compliance** of the developed methodologies with the **technical requirements** of system development, asset management, and system operations, and to **demonstrate** the **practical exploitability** of the new concepts at the pan-European level and in these decision-making contexts.

> **O6**: To **ensure** general **acceptance** of the proposed methods and tools by **all stakeholders** affected by the reliability management of the pan-European electric power system.

GARPUR focused on the development of a consistent and sound reliability management framework (including theoretical foundations and algorithmic developments) for decision-making in the context of System development, Asset management, and System operation. In addition, GARPUR worked on the necessary methods to evaluate the socio-economic impact of such different decision-making strategies in reliability management within these three contexts.

2.2.1 Probabilistic Reliability Management Framework

The fundamental ingredient of the GARPUR methodology is the concept of **R**eliability **M**anagement **A**pproach and **C**riterion (**RMAC**). For each reliability management activity, a corresponding **RMAC** may be prescribed and mathematically defined by specifying the following six components:

Physical and stochastic model of the decision-making problem under uncertainties: it is defined by the decision-making context, the statement of the space of candidate reliability management decisions, of a probabilistic uncertainty model as an exogenous spatiotemporal stochastic process over the relevant horizon and power system area, and the modelling of the state-transition function of the power system, defining the space of power system trajectories as a function of time, decisions, and stochastic inputs. Thus, the decision-making model can account for uncertainties in weather conditions and in demand and generation in-feeds, for component health-conditions, and for corrective control failure mechanisms (including also uncertainties in the physical behaviour of the power system).

Socio-economic objective function: it measures all costs and benefits to all electricity system stakeholders relevant for the considered reliability management activity, including its impact on the

[6] see Appendix A for the complete list of objectives from the description of work of the project

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market surplus, the CAPEX and OPEX incurred by TSOs due to reliability management decisions, as well as the cost of power supply interruptions potentially incurred by the end-users of the system. The socio-economic objective function balances these different benefits and costs, and explicitly acknowledges the involved uncertainties by blending the present costs of an action with the expectation of the future costs implied by its application. Mathematically, this socio-economic objective function is integrated over the decision-making context relevant for the considered reliability management problem, and computed in expectation with respect to the relevant exogenous uncertainties weighted by their probabilities of occurrence.

Reliability target: it is defined by jointly specifying (a) *acceptability constraints*: to describe the level of functionality the system should maintain, and (b) *a tolerance level*: a maximum value on the probability of not doing so. To exemplify this reliability target in the real-time operation context, acknowledging the possible occurrence of contingencies as well as the possible failure of post-contingency corrective actions, it may be specified as: "ensuring with 99 % probability that no severe power supply interruptions should occur. Thus, the reliability target is mathematically expressed as a chance constraint.

Discarding principle: it allows to discard a subset of exogenous uncertainties from the reliability assessment and control problems, provided that the risk implied by doing so, in terms of expected socio-economic impact of the discarded uncertainties, is bound by an upper limit of a fixed "discarding threshold" expressed in monetary units. Given the large number of possible failure modes and the overall complexity of real power systems, the exact evaluation of the socio-economic objective function and the exact verification of the reliability target are, in practice, unfeasible even with high performance computational resources. Therefore, the GARPUR RMAC includes a discarding principle forming reduced uncertainty sets in a risk-adaptive manner. This principle allows one to neglect a subset of events whose collective risk contribution is low enough, as in lower than a *discarding threshold* value. In the operational context, this principle leads to replacing the static N-1 contingency list with risk-adaptive, dynamic contingency lists. It allows to both (a) consider larger contingency lists under more critical conditions, for instance during adverse weather phenomena, demand peaks, events of national/international interest, etc., and (b) consider shorter contingency lists under less critical conditions, wherein component failures are less probable/harmful, for instance under mild weather conditions. Thus, the discarding principle states with mathematical precision what level of approximation may be accepted in practice when implementing the RMAC in some decision-making context.

Relaxation principle: it complements the GARPUR RMAC by covering the need to handle situations wherein the reliability target turns out in practice to be unachievable. In the context of the shorter-term reliability management contexts, and more specifically in real-time, it may happen, despite all efforts made at previous time-steps, that the space of available candidate reliability management decisions is too small to allow compliance with the set reliability target, despite the aforementioned discarding threshold. If this happens, the latter threshold can be increased in such a way that the control problem becomes again feasible; to be as cautious as possible, this should always be done by determining the minimum sufficient level of relaxation required to make the problem feasible. For example, if meeting the reliability target turns out to be unachievable in a particular instance of real-time operation, the RMAC would be relaxed by further discarding those contingency events that contribute the least to the expected socio-economic costs of service interruptions. Thus, the relaxation principle states in a mathematically transparent and coherent manner how the non-feasible situations should be handled in practice.

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Coherency across time-horizons: the above 5 components can be customized for various reliability management problems, from long-term system planning to real-time operation. For longer-term decision-making problems, the socio-economic objective function should incorporate the expected costs incurred in shorter-term reliability management activities.

The RMAC concept is flexible and general, allowing it to be adapted to the specifics of different TSOs, and to the needs of reliability assessment and decision-making in all contexts, yielding a family of criteria and optimization problem formulations. The complexity of these problems strongly increases when the evaluation horizon increases from short-term to long-term, because the longer-term problems need to incorporate sufficiently accurate models of the shorter-term decision-making of the TSOs. When conducting reliability management in a longer-term context, it is necessary to foresee how reliability would be managed over a certain future evaluation horizon. For example, when managing reliability in the context of operational planning, it is necessary to take into account the impact on real-time operation over the next few hours or days. Therefore, the longer-term reliability management problems can only be solved by encapsulating in their assessment and control parts a suitable model of the behaviour of the subsequent closer to real-time reliability management activities. The need to conduct this encapsulation leads to a complication of the longer-term reliability management problems, both from the modelling and from the computational points of view.

To handle this additional complexity, we introduce the concept of "**proxy**" of a reliability management process. In essence, such a proxy is an approximate computational and mathematical representation of a shorter-term reliability management context that is used when stating and solving the longer-term reliability assessment and control problem. For example, specifying a proxy of system operation when conducting outage scheduling prescribes the way reliability management in operation is taken into account in the outage scheduling activity. The main stake when defining a proxy is to balance the trade-off between computational complexity and degree of accuracy. Machine learning is proposed as a way to automatically build proxies that would be suitable in this respect.

2.2.2 Algorithms and proxies for reliability assessment and reliability control

We recall that **reliability assessment** concerns quantifying the anticipated performance of a system facing uncertainties in its operational conditions over a specified period of time. In terms of the RMAC, this amounts to verifying whether the reliability target is satisfied, and evaluating with sufficient accuracy the value of the socio-economic cost function. In this context, the discarding principle may be used in order to justify that a subset of events that can be assured to have negligible impact on the value of the socio-economic objective function can be neglected in the assessment. Practically speaking, reliability assessment amounts to simulating the expected behaviour of the power system over a representative set of scenarios and computing from this the expected value of the socio-economic objective and the probability of the subset of scenarios that meet the acceptability constraints.

On the other hand, **reliability control** chooses combinations of decisions that maximize the socio-economic objective function while complying with the chosen reliability target. In this problem, the discarding principle again allows to neglect a subset of possible scenarios, which simplifies the computational complexity of the corresponding optimization problem. If the original problem is found to be infeasible, it may be cautiously relaxed according to the relaxation principle.

The following algorithmic schemes were developed to address these problems and their scalability and feasibility issues, from short-term to long-term reliability management problems:

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Probabilistic Security Constrained Optimal Power Flow (PSCOPF) for real-time reliability control: it optimizes joint combinations of preventive and corrective control decisions over a horizon of a few minutes, targeting real-time operation while facing variable weather conditions; it accounts for the possibilities of corrective control failures and minimizes the (expected value of the) total costs of preventive and corrective decision, and power supply interruptions. The method has been tested on an academic benchmark; it is also shown how the same tool can be used both to mimic the application of the N-1 criterion in real-time and to mimic an operator that would follow the GARPUR RMAC. The computational complexity of this method is only slightly higher than that of a classical N-1 based SCOPF, and its implementation in real-life is possible by upgrading existing industrial SCOPF tools.

Probabilistic contingency screening for real-time reliability assessment: it evaluates the expected value of the power supply interruption costs, as well as the probability of meeting the acceptability constraints, while taking into account real-time weather conditions in terms of their impact on probabilities of single and multiple contingencies or failure modes of the control devices, and on the socio-economic impact of power supply interruptions. In order to be applied in practice, this approach calls for upgrading the currently used tools with a suitable proxy to estimate the costs of power supply interruptions implied by a partial loss of system integrity. Therefore, the value of lost load needs to be taken into account, ideally as a function of the actual weather and economic conditions.

Monte-Carlo approach for look-ahead reliability assessment in operational planning: the approach consists of generating possible operating scenarios over a look-ahead horizon of several hours (by sampling from the distribution of forecast errors), and simulating system operation in real-time over the look-ahead horizon and for each one of these scenarios. To do this, a suitable proxy of the real-time RMAC used must be provided as a component of the simulation tool; the proposal is to use the above PSCOPF designed for real-time reliability control or a simplified version of it that would run faster while still giving an accurate evaluation of the different terms of the socio-economic objective function incurred in real-time operation. The output of this look-ahead mode assessment tool is an estimation of the expected value of the socio-economic objective and the probability of meeting the reliability target in real-time operation.

Probabilistic SCOPF for look-ahead mode reliability management in operational planning: the approach optimizes operational planning decisions in the presence of uncertainties on renewable generation and weather conditions that would be faced in real-time operation at some future point. The problem is framed so that operational planning decisions render real-time operation feasible according to its own reliability target.

Building proxies of real-time operation via machine learning: a methodology was designed to apply supervised machine learning to build proxies of real-time operation costs and reliability assessment outcomes. These proxies are designed for use in operational planning contexts to speed up the evaluation and identification of constraining scenarios over a few hours or days.

Cross-entropy based optimization for mid-term outage scheduling: the proposed algorithm uses massive parallel simulations to determine an outage schedule over a period of several months, so that the expected impact on system operation is minimized. To this end, a scenario generator is used to sample exogenous factors over the horizon of several months (market conditions, load and generation realizations, forced outages, etc.) and two proxies are used to model respectively day-ahead unit commitment decisions and real-time preventive and corrective control decisions. A parallelized version of the method has already been tested on a small academic test system benchmark.

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The developed methods and algorithms can also be exploited in longer-term reliability management problems, such as system development and maintenance policy assessment studies, provided suitable models of the longer-terms macro-uncertainties are combined with the models used in mid-term and short-term contexts. For a more detailed explanation of this work, we refer the interested reader to the Guidelines for implementing the new reliability assessment and optimization methodology (D2.2), available at: http://www.garpur-project.eu/deliverables.

2.2.3 Socio-Economic Impact Assessment Framework

In order to develop a methodology for evaluating the socio-economic impact of different reliability management approaches, the underlying principles of social welfare analysis were taken as a point of departure. The proposed evaluation methodology allows a fair comparison among the probabilistic RMAC proposed by GARPUR and the N-1 based reliability management approaches currently in use. It was further elaborated for three time horizons, long-term, mid-term and short-term. Rules to be followed in order to arrive at meaningful social welfare assessment are set forth, as well as possibilities and limitations in ex-post assessment. The choices to be made when setting up a social welfare assessment were outlined.

A **S**ocio-**E**conomic **I**mpact **A**ssessment (**SEIA**) framework, with and without market response, has been formulated. The framework is based on social welfare analysis of the electricity market and allows one to quantify the costs, benefits, and surpluses of all market stakeholder groups: electricity consumers, electricity producers, the TSOs, the government (surplus from taxes on electricity), and the environment (surplus from electricity-related environmental externalities). It details how to calculate power supply interruption costs, TSO costs, producer costs, environmental costs and congestion costs on different time horizons. A general mathematical formulation of these surpluses is given for different nodes, generation technologies, consumer types, time of occurrence and duration of interruptions, and pollutants. It also illustrates how to apply the SEIA framework to a numerical test case in each timeframe. The SEIA framework is then extended to account for the possible responses of stakeholders to changing reliability levels, changing electricity prices, and changing taxes. Furthermore, interactions between multiple TSOs, multiple countries, and the distributional effect on different consumers are analysed.

While developing the SEIA framework, the following recommendations were made:

> **The SEIA is to be used for comparing** economic outcomes resulting from **different RMACs**, such as N-1 and the GARPUR probabilistic RMAC. The SEIA methodology allows one to quantify the costs, benefits, and surpluses of all market stakeholder groups. The calculation of surpluses on a stakeholder level requires an assessment of all flows of goods (e.g. fuel, electricity) and services (e.g. flexibility, transmission) and the corresponding flows of money.
>
> **The SEIA is to be formulated for multiple time horizons**. Since decisions taken at one point in time may have implications later, costs and benefits should be either calculated as net present values (NPV) or should be annualised for inter-temporal assessment.
>
> **In a situation where several countries, regions and TSOs, or multiple consumer groups are to be considered, the SEIA should explicitly differentiate between them**. It is shown that cross-border cooperation increases surpluses and that cross-border flows to other regions must be included in the expression of regional surpluses. Furthermore, the SEIA confirms that reliability management approaches and criteria have distributional effects on the surpluses of different consumer groups and in different locations. Changing the reliability management approach may come at a cost to some consumers and as an advantage to others. Therefore, its acceptability among different consumers may differ. Therefore, the SEIA should explicitly show these distributional aspects.

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Data requirements and data availability are to be considered with care. In general, the SEIA framework requires inputs about physical quantities, such as energy not supplied, TSO actions taken, generation fuel input, and corresponding economic value inputs (value of lost load (VOLL), costs of actions, per unit fuel cost). The VOLL is a central value in the socio-economic analysis. Data availability is a concern. Missing VOLL data can be substituted by data from similar countries, if the correct normalization factor and purchasing power parity are used, but a better approach is to determine them via data collection processes organized in each country.

Finally, a roadmap for further development of the methods is presented. First, the SEIA framework can be extended to analyse possible responses of electricity market stakeholders to changing market variables. Secondly, future research also needs to be directed at the building blocks of electricity market models, in particular the estimation of consumer response to price and reliability. Thirdly, availability of data required to perform SEIA is a necessary condition. Lastly, full adoption of the SEIA methodology would come through its inclusion into handbooks and guidelines for TSOs.

For a more detailed explanation of this work, we refer the interested reader to the report on Recommendations for implementing the socio-economic impact assessment methodology over the pan-European system in a tractable way (D3.2), available at: http://www.garpur-project.eu/deliverables.

2.3 Application in system development, asset management, and system operation

The work on these three subjects was conducted over a timespan of three years. It covers specifically objective **O4** while also ensuring compliance with objectives **O5**, **O6**, and **O7,** also recalled below.

O4: To **ensure** the **compliance** of the developed methodologies with the **technical requirements** of system development, asset management and system operations, and to **demonstrate** the **practical exploitability** of the new concepts at the pan-European level and in these decision-making contexts.

O5: To **validate** the retained alternatives with the help of **pilot tests.**

O6: To **ensure** the general **acceptance** of the proposed methods and tools by **all stakeholders** affected by the reliability management of the pan-European electric power system.

O7: To **define** a **migration path** towards the **use of the new reliability management practices** by defining an **implementation roadmap**.

The overall purpose of this work was to refine the generic **RMAC** and **SEIA** frameworks to make them comply with the practical needs of real-time operation, short-term operational planning, asset management, and system development.
A primary result of this work provides a functional analysis of the system development, asset management and system operation processes and their relationships, which highlights the commonalities and differences among the practices and problems of a representative sample of European TSOs, and defines the practical needs that should be covered by the methods developed in the GARPUR project.

Figure 2.3, below, summarizes the result of this analysis. More details about the different parts of this figure are provided in several reports (D4.1, D5.1 and D6.1) written by the project and available at: http://www.garpur-project.eu/deliverables.

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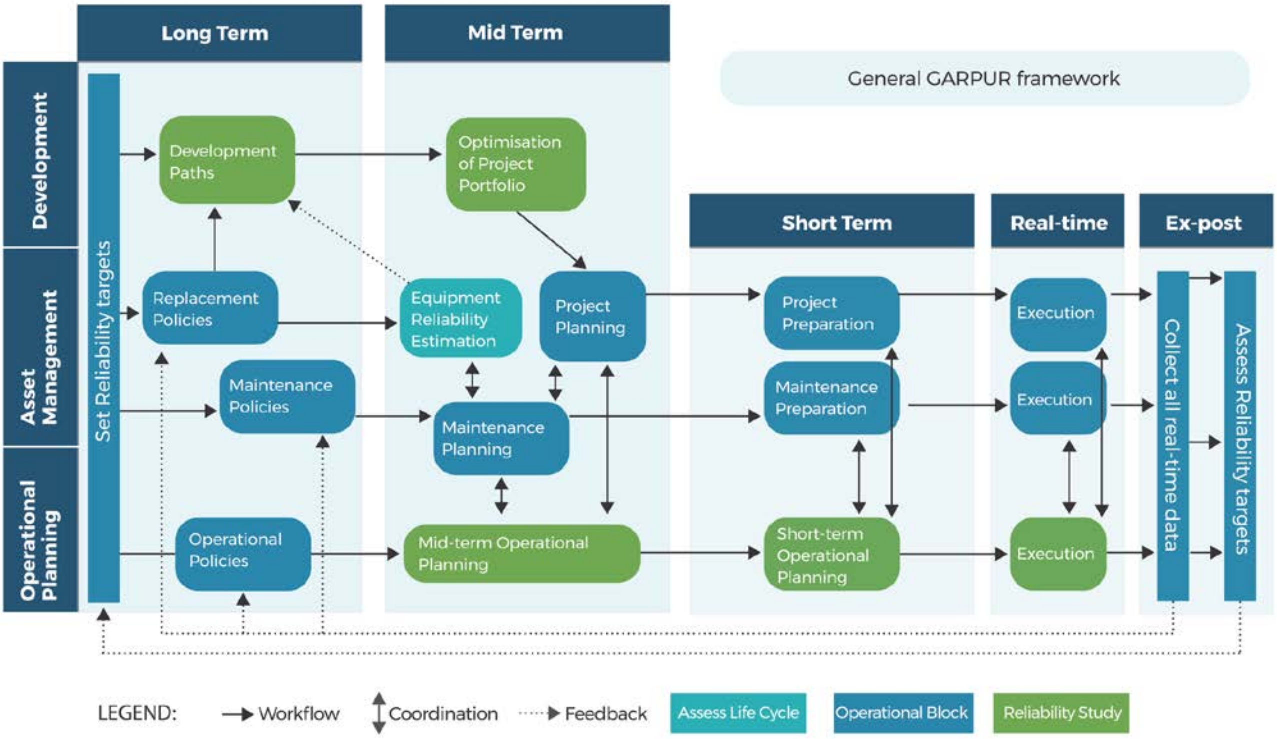

Figure 2.3: Reliability management contexts, tasks and time-horizons faced by TSOs

The next step of the work analysed the specific practical requirements for system development, asset management and system operation, in terms of types of decisions to cover, evaluation horizons to consider, major data and modelling requirements, and practical expectations in terms of the functionalities of decision support tools suitable for enabling power system engineers to exploit the RMAC and SEIA in each one of these contexts.

The last and major part of this work translated the theoretical RMAC and SEIA frameworks proposed in GARPUR into a set of realistic prototype implementations for reliability assessment to define recommendations for further work and real-life testing in subsequent steps. Details about these results, with a proposal of pathways for practical exploitation in TSO reliability management and needs for further work, are provided in severable reports (D4.2, D5.2 and D6.2) available on the GARPUR website at: http://www.garpur-project.eu/deliverables.

2.3.1 Probabilistic reliability assessment in the context of System Development

This work led to the following results:

Target year approach for system development: A framework for system development is proposed for a target year, to determine the main bottlenecks in reliability and transmission capacities and their impact on the electricity markets, and to help engineers propose system development options and assess their impact both on reliability and market performance. Two types of questions are looked at, namely the identification of major transmission bottlenecks and the cost-benefit analysis of upgrades of the transmission system structure.

Scenario reduction: The proposed system development framework is based on Monte-Carlo simulations of the way the system could be operated and maintained during the target year. A two-stage approach is proposed which yields a good compromise between the number of samples and the level of detail of each simulation. In the first stage a set of 'representative scenarios' is identified and then analysed in more detail in the second stage.

Shorter-term proxies: To correctly assess the reliability and socio-economic performance of the system during the target year, proxies have been proposed to assess system operability and maintainability. They are currently based on the experience of TSOs with the N-1 criterion, but can in principle be upgraded to take into account the use of probabilistic RMACs in system operation and maintenance scheduling.

2.3.2 Probabilistic reliability assessment in the context of Asset Management

This work led to the following results:

Maintenance policy assessment: A major question for TSOs is the problem of assessing the impact of maintenance and replacement policies on reliability in operation and component health status over a very long-term horizon of 20-30 years. A Monte-Carlo method simulating the system operation and maintenance activities over so many years has been designed. The main modelling requirements of component ageing and the impact on their fitness of maintenance operations and usage conditions, and their translation to the form of spatially and temporally varying failure rates, have been identified.

Outage schedule assessment: A methodology for assessing outage schedules over a mid-term horizon of several months to a couple of years has been proposed. It is also a Monte-Carlo simulation approach where the impact of placing a particular set of outages at specific moments is evaluated over a sample of possible system trajectories while modelling the resulting costs and reliability levels that can be achieved in system operation. The data and computational infrastructure needed to conduct such studies, as well as the required output information needed to assist engineers responsible for designing and updating outage schedules, are attainable and it is recommended that additional work be carried out in cooperation with field experts to further develop this approach.

Shorter-term proxies: In order to model system operation in the context of outage scheduling studies, and outage scheduling in the context of maintenance policy assessment, proxies have been proposed and developed for modelling the shorter-term reliability management, namely real-time operation, day-ahead operational planning, and yearly outage scheduling. They are currently based on simplified optimization problem formulations (OPF, SCOPF, and greedy search) and were implemented on an academic test system while assuming that the N-1 criterion is still used in the shorter-term decision-

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making environments of TSOs. Migration towards more refined proxies also modelling the GARPUR RMAC in the shorter-term context is possible and recommended as a main step for further research.

2.3.3 Probabilistic reliability assessment in the context of System Operation

This work led to the following results:

Real-time reliability assessment: The implementation of the GARPUR RMAC for reliability assessment in real-time operation was developed by taking into account available data and designing suitable ways to display information to operators; the question of properly modelling corrective control failures and costs of power supply interruptions was analysed in detail. The use of the discarding principle to dynamically adapt the list of explicitly covered contingencies according to real-time weather conditions was shown to be practical.

Day-ahead reliability assessment: A simplified version of the GARPUR RMAC has been developed to enable the assessment of reliability in look-ahead mode while modelling the response of real-time corrective control over a sample of possible scenarios of power injections representative of the forecasting errors and possible weather conditions that could be encountered in the next day.

Algorithms testing and information presentation to operators: Examples of results produced by running the proposed assessment algorithms were generated to gather feedback from operators and design a preliminary graphical user interface that presents the results in a synthetic and meaningful way.

Support to decision-making: The reliability assessment implementations can be a basis for a first-step reliability control approach. For a small set of user-defined actions, the reliability assessment algorithm can be rerun for each action, allowing for comparison between controls. Additionally, comments are provided on how to relax the GARPUR RMAC in cases where the reliability target may be infeasible or too costly to meet.

2.4 GARPUR Quantification Platform

The GARPUR quantification platform aims to facilitate comparison of the probabilistic reliability management approach proposed by GARPUR with an existing N-1 approach, to enable TSOs and Regulators to understand the impact on the socio-economic performance indicators of moving towards the probabilistic approach. The GARPUR consortium invested in this work because it is convinced that such a simulation platform is a valuable tool to foster progress in the field of reliability management and the adoption of new approaches by the stakeholders.

In a nutshell, the idea is to use this platform in the context of off-line studies where the question is to agree on how to move towards the probabilistic approach. Therefore, the platform should enable the comparison of how the same system would perform from a socio-economic point of view when it is either managed by using the N-1 principle or by using the probabilistic approach. This means massive simulations at a realistic temporal and spatial resolution and over several areas of the European interconnected power system. The techniques to be implemented in the quantification platform follow the principles set forward in the previous sections of this Chapter, both in terms of RMAC specification and SEIA methodology.

The specifications and the software development of a first prototype of such a platform were carried out during the last three years of the project. This work targets objective **O3** of the GARPUR project.

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O3: To **develop** a **quantification platform** able to compare different reliability management strategies in terms of their impact on the social welfare in Europe.

2.4.1 Development of the GARPUR Quantification Platform (GQP) Prototype

The first part of this work designed the functional specifications of the quantification platform, together with its software and hardware architectures. Next, the architecture of a first prototype version was specified, developed, and debugged. This prototype uses Matlab, Matpower[7], Python and various other existing software packages. It includes in particular a Common Information Model (CIM) parser to convert input files, and uses DC-OPF modules to simulate day-ahead and real-time reliability management activities, both according to the N-1 criterion and according to the GARPUR probabilistic RMAC. The prototype platform is currently able to simulate the operation of medium sized power systems of a few hundred nodes and lines while explicitly covering a few tens of contingencies. The limiting factor is the time needed for simulation.

2.4.2 Testing and documenting the GQP Prototype

The prototype version has been tested during the GARPUR project pilot tests on a medium sized real power system (see section 2.5.1). The platform prototype has also been tested on smaller academic benchmarks. These tests assess the quality of the computed indicators, and the computational scalability towards real-world uses of the platform.

Information about this work, including recommendations for further upgrade to an industrial version of the platform, is documented in a report (D7.3) available on the GARPUR website at: http://www.garpur-project.eu/deliverables.

2.5 Pilot tests

Within GARPUR, two types of pilot tests were conducted, namely the aforementioned tests using the GQP prototype, and tests about using the GARPUR RMAC in near real-life conditions. The specification and preparation of these pilot tests started during the second year of the project. Most of the testing activities were carried out during the last year of the project, and essentially targeted the following objective:

O5: To **validate** the retained alternatives with the help of **pilot tests.**

Pilot testing methodologies, models, scenarios and validation approach are documented in a report (D8.1) available on the GARPUR web site at: http://www.garpur-project.eu/deliverables.

2.5.1 Pilot test based on the GQP prototype

These tests were carried out on **RTEs system**, and focused on the South-Eastern part of the French power system, an area that is often subject to congestions. In this study, both day-ahead and real-time operation of the power system were simulated while using different reliability management approaches and criteria, in particular one based on the N-1 criterion and two alternative ones based on simplified versions of the GARPUR probabilistic RMAC. While not exhaustive, these tests have compared the features of the GARPUR

[7] http://www.pserc.cornell.edu/matpower/

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RMAC with the N-1 criterion in terms of the preventive and corrective measures suggested and their dependence on the modelling of corrective control failures.

This pilot test has clearly highlighted the interest in using a quantification platform to compare different RMACs with the N-1 criterion, and hence gain a better understanding of their respective strengths and weaknesses. Recommendations were issued for further use of the experience developed in the GQP so the pilot tests can be more realistic and cover a broader spectrum of operating conditions. In particular, it is recommended to upgrade the SCOPF modules to the AC power system model, to optimize the computational efficiency of the most time-consuming modules, and to invest in a massively parallel computing infrastructure for running the future software.

2.5.2 Near real-life pilot tests of the GARPUR RMAC

An initial pilot test was conducted at the **control centre of Landsnet**, the Icelandic TSO. This test concerned the implementation of probabilistic reliability assessment in the context of real-time operation of the Icelandic system, based on system snapshots collected every few minutes from their Energy Management System (EMS). In this study, rather detailed models for system response, VOLL, and weather dependent failure rates were implemented for the Icelandic system and an efficient parallel computing platform was used to ensure computing times compatible with on-line use. Several prototype visualization tools were developed to display the computed indicators in a meaningful way to the control room operators. Based on this test, the probabilistic approach provided quite useful information, complementary to the result of classical N-1 reliability assessment, and well in line with operators' experience and intuitions. In addition, the study highlighted the operational value of system integrity protection and re-dispatch schemes currently used at Landsnet. As a result of this pilot test, recommendations fostering the development of real-time reliability control tools and look-ahead mode reliability assessment tools were also issued.

A second pilot test was carried out at the **planning department of ELIA,** the Belgian TSO**.** It concerned an actual system development study focused on a part of the Belgian transmission system close to the French border with 2030 as the target year. During this pilot test, tools proposed in GARPUR for such long-term studies were first implemented on the Belgian system. These tools were used to study a range of conditions, representative of the target year, to assess operability and maintainability of the system, and identify the main reliability problems to be expected. The study showed that the probabilistic approach is applicable in the context of a real system planning study. It also identified a need for a SCOPF tool for ELIA to assess the risk of various operating conditions, and to simulate the preventive and corrective reliability management actions taken in the context of system operation. The analysis of the results of this pilot test led to recommendations to develop and use industrial grade probabilistic planning tools in system development. In particular, the need to correctly model outage management and system operation through suitable and computationally efficient proxies was stressed as an important topic in terms of practical acceptability.

Two further additional case studies concerned system development studies on the **Nordic system**.

The first one was carried out by **STATNETT**, the Norwegian TSO, and concerned an actual study of two alternatives to expand the transmission network feeding the Stavanger area. The study was based on in-house tools of Statnett and demonstrates how the probabilistic approach can influence investment decisions. The probabilistic approach enabled STATNETT to quantify the value of security of supply and allows, therefore, to properly rank alternative system expansion alternatives according to the highest socio-economic benefit. In this case, it showed that the alternative with a higher level of security of supply was not beneficial since the increased investment costs significantly outweighed the reduction of the expected interruption cost. The study shows that large socio-economic savings of about 25% can be obtained due mainly to lower investment costs compared to the alternative with a higher level of security of supply. In this case, it amounts to approximately 130 million EUR.

The research institute **SINTEF** carried out the second case study**.** It used the probabilistic methodology and tools developed in recent years at SINTEF for reliability assessment for long-term planning studies. The study was performed near real-life by using real system data and applying the same and similar tools as the Norwegian TSOs use. The study assesses the impact of the amount of transmission capacities given to the market, both on the market costs and on the power supply interruption costs. This case study demonstrated the application of a comprehensive methodology for probabilistic reliability assessment integrated with market analysis on a real case. The study shows how different aspects can be taken into account, including time dependences and correlations, utilizing available failure data and interruption cost data, as well as utilizing clustering techniques to increase computational tractability. While the study focused on assessing reliability and socio-economic impact in a long-term perspective, it provides input to the future development of optimisation tools extending the approach to reliability control for a more short-term perspective.

2.6 Recommendations and roadmap for migration

Within the GARPUR project, all results and recommendations from the work performed during the project period and input from a dialogue with external stakeholders were collected to prepare two public reports, namely the present document (D9.1), compiling results and recommendations, and the roadmap towards full implementation of the probabilistic reliability management within the pan-European system (D9.2). The reports are available on the GARPUR website at: http://www.garpur-project.eu/deliverables.

We summarize below the vision and main steps for implementation resulting from this work. A detailed presentation of our recommendations is given in Chapter 3 of the present document.

2.6.1 Vision for future probabilistic reliability management

Over its four years, the GARPUR project has both developed and tested a comprehensive probabilistic reliability management framework to effectively guide Transmission System Operators (TSOs) in their investment, asset management and operational decisions. The results and experiences obtained in the GARPUR project, especially the demonstration of the methodologies and tools in close to real-life pilot tests and studies, show that moving towards probabilistic reliability management in the interconnected pan-European transmission system is possible.

All this defined the GARPUR vision regarding the future of power systems reliability management. The vision can be summarized as follows:

> ***"An adoption of probabilistic reliability management by all stakeholders dealing with electric power systems reliability management,*** *from experts in the TSO organizations who have the practical responsibility to ensure the security of electricity supply, to the persons in charge at regulators and governments whose responsibility it is to ensure the electric power system performs for the benefit of all parts of society".*

While the project focused on the transmission system level of the power system, the GARPUR consortium recommends that the applicability and potential benefits of the project results should also be assessed at the distribution system level. Further, a dialogue with the different stakeholders in the power system and new potential players should also be fostered to align methodologies, data and models.

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2.6.2 Main steps for implementation

While migration towards the systematic use of the developed probabilistic risk management approaches can only happen gradually, it also requires investments along several complementary paths. We highlight below the main changes necessary to implement and sustain this process.

Regulation and socio-economic considerations
The current regulatory framework to organise and incentivise the power sector is not generally fitted to probabilistic reliability management. Incentives, remunerations, roles, and responsibilities are defined to secure the power system with respect to the N-1 criterion. Therefore, a next step should be to expand the regulation to account for the probability of failure and risk associated with the N-1 faults that TSOs' are already assessing, and to encourage the use of the new reliability targets and socio-economic evaluation criteria. The remuneration mechanisms of TSOs should also be adapted to incentivize them to implement the new approach in the most efficient way. For this decision-making, the regulators need information and a better understanding of the benefits and the socio-economic consequences of the probabilistic reliability management approach compared to the existing reliability management.

Data and models of uncertainties
The accuracy of the probabilistic reliability management approach is dependent upon data availability and quality. As a first step, TSOs must collect relevant reliability data, i.e. failure data, outage and restoration times and interruption cost data. Based on the data, improved models must be developed. Gradually these actions will provide the TSOs with more precise results from the use of the probabilistic reliability management approach and supports an iterative improvement of models. Common guidelines should also be adapted to persistently ensure the collection of data and maintain the databases and inferred models.

Methodologies, algorithms and software
When applying the probabilistic reliability management approach, the resulting stochastic simulation and optimization problems are computationally significantly more complex than those used for N-1 based reliability management. Even though GARPUR has developed several methods and prototypes, few have been implemented in TSOs' practices and in industrial grade software. Therefore, a next generation of industrial grade software and tools needs to be developed to achieve the necessary robustness, efficiency and availability to support the large industrial and academic communities for the progressive implementation of probabilistic reliability management approaches.

Testing and implementation at the operational level
A transition towards reliability management based on probabilities and expected consequences requires all main actors in the power sector, especially in TSOs, to adopt a risk-based mind-set. The operation of the grid has to be based on balancing the costs of providing security of electricity supply with socio-economic costs of power supply interruptions, and it should not focus solely on reaching high security of supply at any cost. Pilot scale testing of the new methods and approaches are an important next step to change the mind-set and to simultaneously build trust in probabilistic reliability management. The first practical step for a TSO to take is to calculate the probabilities and risks of the N-1 faults they already assess. This reveals which data and models are required to further develop the probabilistic approaches, and increases understanding of grid reliability and its variations over time. Even though GARPUR has performed several pilot tests with different TSOs, a main focus must be to further test the new approach in parallel to the existing N-1 approach to convince more people in the TSOs and other stakeholders of the applicability and comparative benefits. Such testing also provides more insights into how the probabilistic reliability management approach works in specific use-cases and on challenges for the implementation.

The GARPUR roadmap (D9.2) shows the different steps to make this vision a reality within the next 10 years.

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3 Recommendations for the implementation of the approach

In this chapter, the recommendations for the implementation of the new probabilistic approach are described in detail, and a short description is presented of the process that led to final recommendations.

The first section briefly describes the methodology used to synthesize these recommendations. The resulting set of recommendations is then presented in the next sections. We have divided them into general recommendations to implement the approach in TSOs and more specific recommendations structured in four thematic clusters.

3.1 Methodology used for building the recommendations

The recommendations were developed on the basis of the results from the project R&D activities, the experiences gathered in the various tests carried out in the project, and the feedback from external stakeholders. A sequence in three main successive stages has been followed to gather, to formulate, and to validate the set of recommendations.

- **At the level of the technical work packages** of the project, a series of deliverables and internal technical reports were generated to formulate technical recommendations that enable the application of probabilistic approaches in the various reliability management contexts and time horizons faced by TSOs.
- **At the level of the GARPUR project** these recommendations were collected, ranked, and reorganized in four thematic clusters to form the set of project recommendations proposed to stakeholders beyond the project consortium for consultation.
- **In the broader context of electricity transmission system in Europe through a selection of stakeholders**: In the final months of the project, 8 TSOs, 2 coordination centres, 4 technology providers, 3 regulators, 1 representative of the GARPUR Reference Group, and other representatives of the GARPUR TSOs in planning, system development, and operations were consulted through interviews to enrich, fine tune or amend the proposed draft recommendations.

3.2 General recommendations

3.2.1 A gradual implementation in TSO practice

In order to bridge the gap between the knowledge gained by the project and current TSO practices, the GARPUR consortium recommends the developed probabilistic reliability management approaches and criteria be made available for further testing and development. A main focus must be to further test the new approach in parallel to the existing N-1 approach to convince more TSOs and other stakeholders of the applicability and benefits of the approach. A gradual implementation encourages such testing and building of confidence.

By building on the results obtained within the project, the methodologies and tools can be refined so they can be fully utilised and implemented.

The main benefit of an implementation of the probabilistic approach, as seen by both GARPUR and different stakeholders, is a better trade-off between the costs of providing security of electricity supply and socio-economic costs of power supply interruptions. The new approach offers the possibility of cost saving as, for example, savings in the context of system development or lower re-dispatch costs in short-term operation. The maturity of the approach is an important issue, as well as the question of confidence in the results, especially in the context of system operation. The transfer of responsibility to the operator, and more generally the use of a probabilistic reliability management approach based on a socio-economic principle, is also a political question and decisions from politicians, as well as regulatory changes, are required to achieve it.

In addition, the TSOs see several practical barriers to the implementation of the proposed probabilistic approach:

- The methodological complexity suggests implementing a trade-off between practicality and theory;
- The lack of available data for probabilistic analysis, or their inaccuracy, may lead to interpretation bias of the analysis results;
- The computation speed, even though it can be improved considerably with parallel processing;
- The lack of existing industrial tools for the purposes of probabilistic reliability management that helps the users make the right decisions based on meaningful Key Performance Indicators;
- The required competence and availability of human resources may be barriers in the gradual transition phase;
- The absence of statistically relevant datasets for required reliability data, i.e., failure data and data about outage durations.

A progressive implementation of probabilistic approaches in reliability management allows thorough testing of the approach and the removal of these obstacles one by one. In addition, it is of paramount importance that the national and historical TSO contexts are considered for further implementation.

For example, different TSOs expressed different opinions about the immediate relevance of GARPUR concepts to their respective contexts:

- In some places, the N-1 criterion is currently still strongly supported, at least in short-term and mid-term horizons, despite the economic cost of ensuring N-1 security of supply for smaller areas in regions of low accessibility (e.g., mountains). The focus is then on the increase of capacity by technical optimisation, which allows temporary N-1 criterion violations and which constitutes a way to circumvent limitations of N-1. In addition, a critical question raised is the definition of what a reliability criterion tries to achieve: near 100% security of supply with no power supply interruptions at all or minimisation of the socio-economic impact, which considers the possibility of some power supply interruptions if this allows to increase the overall socio-economic surplus. However, even if these TSOs strongly support the N-1, they are open to alternative approaches, especially in a context of ever increasing volatility of renewable generations, which could make them become necessary.

- In other places, the context is much more mature for a quick implementation of the probabilistic approach. In some cases, a regulation based on socio-economic surplus is already in place, and even an implementation strategy has been established for the full use of probabilistic approaches in the near future, e.g. for grid development, and soon after for asset management. A probabilistic approach is indeed very appealing for some systems for several reasons: high degree of stochastic generation with hydro inflow and wind power, sparsely populated regions, thus a high cost per end customer for excess reliability, and many weather dependent failures in the grid that suits well to probabilistic models.

3.2.2 Implementation in different TSO contexts should occur in parallel

The GARPUR project recommends that the first stages of implementation consist of running the probabilistic methods for reliability management in parallel with the current N-1 based practice to gain experience and

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fine tune the new methods and software tools while assessing the socio-economic benefits that can be achieved by the probabilistic reliability management approaches.

Nevertheless, when asking different TSOs where to start with the implementation of the probabilistic approach, we received different answers, which may also be due to the differences in the various national situations:

- Some TSOs recommend starting implementation at the system development level, benefitting from the ENTSO-E Ten-Year-Network-Development Plan (TYNDP) and adequacy studies in terms of data collection, and allowing for thorough testing and analysis of the new approach;
- Some recommend starting with the mid-term asset management (outage scheduling), since it both allows for enough time to perform the highly intensive calculations and for checking the results thoroughly, and additional benefits can be observed at a faster pace than in system development;
- Some consider the system operation level the most relevant one, since in the operation time-frame most of the probabilistic events and savings will be more clearly visible;
- Some suggest implementing the GARPUR approaches for the three main functions of a TSO (operation, asset management, system development) in parallel, rather than to start by focusing on a single one. One opportunity will then be to directly ensure a consistent adoption of the probabilistic approaches within these three contexts.

These implementation and testing activities can be started in parallel within the system development context, the asset management context, and the system operation contexts to allow use of a consistent criterion in all contexts. The full benefit of the new approach can also only be reached when it is finally implemented in all contexts. For example, would the cost of system operation increase if system operation is performed on the basis of the N-1 criterion while the system is built based on the probabilistic approach? Savings reached in one context could indeed be lost due to higher costs in another context.

The GARPUR consortium recommends that further experience sharing be fostered between TSOs (and among the different departments of TSOs responsible for system development, asset management, and system operation) in close cooperation with ENTSO-E to accelerate the exploitation of the benefits of the probabilistic reliability management approach while circumventing its practical barriers. GARPUR suggests also that the ENTSO-E should play a major role and could initiate and coordinate these activities among different TSOs and Regional Security Coordinators (RSCs), especially in the context of system operation. In principle, all these local, regional, and European initiatives can proceed in parallel, but they need to be monitored at the European scale and, if necessary, be coordinated to ensure the swiftest possible progress.

3.3 Specific recommendations

For a fully consistent and effective probabilistic reliability management approach, several specific further actions need to be taken in the post-GARPUR period.

Function wise, these recommendations are grouped along the following topics:

1. Regulation and socio-economic considerations: Recommendations related to the need for regulatory changes and for properly anticipating the socio-economic impact of moving towards a probabilistic reliability management approach.
2. Data collection and models of uncertainties to enhance the availability and quality of data and the probabilistic models of uncertainties required by the methods for reliability management and socio-economic impact assessment that were developed in the project. They include the need to gather data, the need to process these data as models, the need to share both raw data and models among TSOs, and the need to assess the additional value of better data quality.

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3. Reliability management methodology, algorithms, and software: Further work related to development of industrial grade implementations of software tools for the probabilistic reliability management. Industrial use not only means computational efficiency and scalability to continental scale power system models, but it also means robustness of the software, and adaptability to the specifics of each TSOs practices.
4. Testing and implementation of the probabilistic reliability management methods and algorithms is of paramount importance for the gradual implementation of them and should be mainly initiated by the TSOs.

A common template has been used for each specific recommendation, addressing successively:

- The rationale for each recommendation: **Why** do we propose the recommendation?
- The recommendation itself: **What** should be done?

Each one of the recommendations has also been characterized along three dimensions, summarized in the tables at the start of each subsection:

- Its **targeted stakeholders**, who are expected to take part in the implementation of the recommendation;
- Its **timing**, which relates to estimating an appropriate deadline for its implementation;
- Its **scope**, which refers to the reliability management functions in a TSO concerned by the recommendation.

3.3.1 Thematic cluster 1: Regulation and socio-economic considerations

Several GARPUR recommendations relate to the need for regulatory changes and to properly anticipate the socio-economic impact of moving towards a probabilistic reliability management approach. They rely on the necessity to prove the probabilistic reliability management approach is beneficial, and to understand distributional effects and needed investments. An evolution of policies for the reliability management and the regulation of the TSOs are needed to foster the use of adapted reliability targets and socio-economic evaluation criteria by the TSOs. Last but not least, the coordination of the reliability management principles in the context of interconnected grids constitutes an important recommendation due to ever increasing electricity flows. The acceptable level of reliability of supply can be determined at the country level, but should be coordinated with neighbouring countries.

The research leading to these results has received funding from the European Union
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Table 3.1: The GARPUR recommendations on regulation and socio-economic considerations per stakeholders, time horizon and reliability management context

	Targeted stakeholders					Timing	Context
	ENTSOE	TSOs	Research Organisations	ACER/ Regulators	Technology Providers	Years	System development, asset management, system operation, all
R1.1. Increase knowledge on benefits, distributional effects and needed investments	Contributor	Lead	Contributor	Contributor		< 5	All
R1.2. Introduction of regulatory changes and incentives	Contributor	Contributor		Lead		5 - 10	All
R1.3. Coordination of the reliability management practices in Europe	Lead	Contributor				5 - 10	All

Lead Contributor

R1.1. Increase knowledge of benefits, distributional effects and needed investments

Why?

A change in reliability management will certainly lead to distributional effects between different stakeholders. The political dimension of distributional effects within a country must also be taken into account. These effects must be understood upfront to look into possible counter-measures to avoid unwanted consequences. This knowledge is necessary before implementing the probabilistic reliability management. It should also be expected that stakeholders disadvantaged by a transition to a probabilistic reliability management will try to hamper that transition. Therefore, a better understanding of the socio-economic consequences of the probabilistic reliability management approach is needed.

What?

This recommendation consists primarily of further knowledge building, and targets TSOs, RSCs, Regulators, Governments and Research Institutions. TSOs and Research Institutions need to model these responses explicitly or in a simplified way while regulators and the government need to consider the relevant distributional effect of a new RMAC on end-user groups, regions and countries. A focus should also be on the understanding of socio-economic benefits and the necessary investments to implement the new approach. The understanding of necessary investments for implementation, as well as the benefits, will help prioritize the steps in the path towards probabilistic reliability approach.

The project recommends three specific topics for further study:

1. Analyse possible objections to the probabilistic reliability management approach and criteria due to distributional effects between groups, regions, countries, etc.
2. Incorporate in the analysis the main responses ("feedback effects") of electricity market stakeholders to changed prices and reliability level: (i) change of consumer demand, (ii) change of generation (short term) and generation investment (long term), and (iii) change of TSO revenue and profit.

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3. Analyse the possible ways to take into account and mitigate the distributional effects by suitable changes in the regulation of the power system as, for example, networks tariffs, market models, and ancillary services contracts.

Prerequisites would need the application of the socio-economic impact assessment in a disaggregated form such that the impact on the affected groups, regions, and countries can be analysed. Intensive collaboration between theoretical model development and data collection is needed. Such analyses could be carried out via simulations in tools similar to the GARPUR quantification platform, suitably enhanced to model these effects. Smaller scale studies to assess the probabilistic reliability management approach along with possible objections and unwanted effects might be a first pragmatic step to ensure more knowledge.

R1.2. Introduction of regulatory changes and incentives

Why?

If the probabilistic reliability management approach and criteria are to be implemented by TSOs in practice, the regulations must be adapted to this fact to allow and accelerate such a transition. Regulators in Europe have different opinions about this question. Some point out that control room decisions need clear procedures and, in case of risk-based decision, a no-doubt attitude about the input values or models for the operators are a necessity. Therefore, due to low maturity with respect to data about probabilities and the evaluation of power supply interruption consequences (e.g., in the case of extreme events), incentivizing a pure probabilistic approach seems too early to them, despite an agreement on the concept. Others, however, are more positive and think that regulatory changes can be implemented fast to help the TSOs implement the new approach.

What?

We recommend that the regulation should clearly document the reliability targets and socio-economic evaluation criteria to be used by the TSOs. The remuneration mechanism of TSOs should also be adapted to support the most efficient implementation of the new approach. The national regulators or governments are in charge of the policies for the reliability management and the regulation of the TSOs. However, since such changes are quite sensitive, they should be discussed by all parties involved, namely TSOs, ENTSO-E, EC, governments, ACER and regulators. Both EU wide and national scales should be worked out in parallel to contribute to the evolution of reliability management. For this decision-making, the regulators or governments need information based on results from comparisons of the socio-economic benefits of changes in the reliability criteria.

In the field of operational planning and real-time operation, the existing ENTSO-E network codes on operational security are already partly in line with the main principles of the proposed probabilistic reliability management approaches and criteria. They say that security is sought but not at any cost. The network code states "*Each TSO shall use all available economically efficient and feasible means under its control to maintain in real-time its Transmission System in a Normal State*". It is also explicitly mentioned that the TSO shall make its best effort to mitigate exceptional and out-of-range contingencies "*as far as reasonably practical and economically efficient*". The regulatory aspects (article 3 of the network code) explicitly underline the principles of proportionality, non-discrimination and transparency. They also point out "*the principle of optimization between the highest overall efficiency and lowest total cost for all involved parties*". In the field of long term grid development, ENTSO-e long term adequacy studies and Ten-Year-Network-Development plan are existing processes where probabilistic reliability management approaches and criteria are considered at various level of maturity and methods are defined in collaboration with interconnected TSOs

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in the context of ENTSO-e working groups (i.e. WG European Planning Standards and WG System Adequacy and Market Modelling) and publically consulted on.

R.1.3. Coordination of the reliability management practices in Europe

Why?

The analysis of current TSO practices highlights that, even though all TSOs were following mainly the N-1 criterion, the concrete implementation of this criterion greatly varies between TSOs and may lead to quite different levels of reliability of supply in different areas or countries. Using the probabilistic approach allows one to better assess and document these differences, and may thus provide guidance to reach coordinated reliability management practices throughout Europe. In the context of interconnected systems, neighbouring TSOs' risk attitude and their definition of what an acceptable reliability target is, has an impact on the level of security of supply in the other TSOs' control areas. This is especially true in case of large import, export, or transit flows. In the context of grid development, it is important to identify the trade-off between market-driven cross-border imports or exports and the level of risk taken by neighbouring TSOs that can impact on those transfers. European market integration is an important goal and aims for equal competition. An harmonized approach towards operational security is thus a logical consequence of this integration process.

What?

The probabilistic approach allows one to better assess and document the levels of reliability of supply, and may thus provide guidance to coordinate and harmonize the reliability management practices of different TSOs. As a preliminary step, we recommend that neighbouring TSOs exchange detailed information on the reliability level they achieve in their own system. Such data exchanges already exist in the long-term horizon for the development of the ENTSO-E ten-year network development plan (TYNDP). In the asset management plan, such information is exchanged by workgroup "Annual Maintenance Schedule". A possible way to proceed towards that topic of reliability management in a multi-TSO setting is to upgrade the existing principles for data exchange between TSO.

As a next step, a coordination of principles of reliability management and market capacities should be targeted by the TSOs. The development of grid codes already ensures a certain amount of harmonized practice in Europe. In addition, the draft risk preparedness regulation of the draft Winter package refers to regional cooperation in relation to security of supply.

The implementation of this recommendation should therefore also lie in the hands of ENTSO-E.

TSOs and RSCs are the most impacted stakeholders. The most appropriate implementation level is considered to be European and ENTSO-E appears as an ideal promoter. The current N-1 approach assumes an equal assessment of the reliability from all TSOs. This approach suggests simple and clear criteria which can be verified by any TSO. The application of a probabilistic methodology allows further flexibility for individual planning and operating approaches, and therefore also requires a revision of inter-TSO coordination as well as new rules defined and approved by ENTSO-E.

It might take a long time, however, to reach common principles of reliability management and reliability targets that have a cross border impact throughout the European system because different countries would have different starting points. But adopting the same criteria in the neighbouring systems seems to be desirable. The change of the methodology for reliability assessment along with the reliability data exchange between TSOs will require a transition period when both the existing and the new formats operate in parallel: it is likely that more than 5 years will be needed.

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3.3.2 Thematic cluster 2: Data collection and models of uncertainties

Several GARPUR recommendations refer to data collection and modelling of uncertainties: implementing a probabilistic approach for reliability management is very data intensive and has high expectations on data quality.

During the GARPUR project, extensive work was carried out to identify the data and model requirements of the probabilistic reliability management approach and the additional types of data and models that are not generally used by the current deterministic N-1 based reliability management approaches. Furthermore, the project also analysed the practical availability of these additional data and models, via questionnaires addressed to the TSOs. This identified the most important data and model gaps that need to be progressively filled to maximize the effectiveness of the proposed approaches.

The recommendations[8] are about the work that should be carried out to enhance the availability and quality of data and the models of uncertainties required by the methods for probabilistic reliability management and socio-economic impact assessment that have been developed in the project. They include the need to gather data, the need to construct models based on these data, the need to share both raw data and models among TSOs, and the need to assess the additional value of better data quality.

[8] The methods proposed in GARPUR will also exploit currently used models and data, such as power system physical models, TSO cost functions, market models, forecasting tools, etc. Here, the focus is only on the additional datasets and models that are not yet available and/or exploited by most TSOs in Europe, and/or that need to be documented and shared among TSOs to allow the use of the probabilistic reliability management approach.

Table 3.2: The GARPUR recommendations on Data collection and models of uncertainties per stakeholders, time horizon, and reliability management context

	Targeted stakeholders: ENTSOE	TSOs	Research Organisations	ACER/ Regulators	Technology Providers	Timing: Years	Context: System development, asset management, system operation, all
R2.1. Establish guidelines for collection, processing and sharing key data	Contributor	Lead				< 5	All
R2.2. Establish a trans-European process to harmonise data collection and share data	Lead	Contributor				< 5	All
R2.3. Quantify the value of continuous data quality improvements		Lead	Contributor			5 - 10	All
R2.4. Improve the practice for the investigation of costs of power supply interruptions	Contributor	Contributor	Contributor	Lead		< 5	All
R2.5. Improve modelling of the degradation process and the maintenance impact		Lead	Contributor			5 - 10	System development Asset management
R2.6. Improve component failure rate models based on component condition and weather		Lead	Contributor			< 5	All
R2.7. Gather data and build models for corrective control failure models and probabilities		Lead	Contributor			5 - 10	System Operation

Lead ■ Contributor □

R2.1. Establish guidelines for collection, processing, and sharing of key data

Why?

A wide range of data is needed for the probabilistic reliability approach and must first be collected, and then analysed to improve related models. Probabilistic reliability assessment accounts for both the probability of an event happening and the consequence of such an event. For this assessment, relevant data are necessary especially that relate to equipment reliability data. The practical challenge is the unavailability of detailed historical data that would permit understanding the variability in component outage probabilities as a function of exogenous threats and component health. The main objective of preparing a data collection guideline is to have context dependent data available, which are more meaningful than average data. Data collection usually involves also merging data from several sources. The quality of the recorded information may also vary across time, making it difficult to add up all elements to a single dataset from which to build models. A guideline could ease that process and remove that obstacle.

What?

We recommend to identify at national TSO levels the data collection framework. It is important to target the data quality and availability to move to a probabilistic approach and, thus, it is very relevant to provide simple

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and practical support guidelines for the framework. The data to be collected concerns failure rates, restoration activities, and their durations, as well as correlations between events and the operational context, i.e. on-going maintenance activities, weather conditions, asset loading, age of the equipment, and others. In addition to individual outages and failures related data, it is indeed important to register the correlations between related events and the operational context. As the numbers of failures or malfunctions to be recorded are expected to be small, we recommend that the TSOs collect and structure relevant data about events, i.e. failure cause, outage times, weather condition, and others, with the aim of building up a database that covers as many assets and as many years as possible.

In order to give the maximum information to probabilistic reliability management decisions, a number of data items should be recorded. However, to do so efficiently is very challenging, given the ways in which events are recorded and the possible need for field staff to add additional information. Depending on the present quality of data collection, which can vary from TSO to TSO, the following short-term improvements to data collection procedures are suggested:

- Review consistency of component observation reports (presence and scale of human errors);
- Review and improve the descriptions of maintenance tasks, specifically their guidelines on execution and reporting, to improve future data sets on maintenance activities;
- Review observational data, ensuring that it is as quantitative and granular as possible;
- Assess potential to expand data collection (both component and exogenous data) using remote sensing equipment, or from third parties (e.g. meteorological institutes).

The data collection framework and the related guideline suggested above would be of benefit to all of the following processes: system development planning, asset management, operational planning, and system operation. However, the way they must be prepared for subsequent use may differ for these different processes, e.g. to correctly reflect the appropriate time horizon such as in the difference between short-term and long-term variations of probabilities.

TSOs and ENTSO-E are the targeted stakeholders. It is expected that a deployment of that recommendation could take place within the next five years, however this could be a minimum time horizon for converging at the European level on such guidelines. Confidentiality obligations and lack of TSO resources are implementation barriers that must be tackled. A very first step is to achieve increased awareness of the needs for data collection within TSOs.

R2.2. Establish a trans-European process to harmonize data collection and share data

Why?

Collecting the presently missing data required by the developed methodology will be a time consuming, yet absolutely necessary process. In order to increase the number and quality of the data, it is recommended to share a common structure for incident data and share the collected data between TSOs. The main objective is to increase the data quality by increasing the number of samples without losing the contextualisation identified for a given incident and TSO. Sharing data from a wide area for events and failures that occur rarely can be of special value to get reliable results from probabilistic approaches. However the transferability of failure rates for different countries and different technologies is less straightforward.

Processing the recorded reliability data for further applications in tools for probabilistic reliability assessment, i.e. on a preferably standardized data format as required by the methods is necessary. This will reduce the TSOs barriers against using probabilistic approaches.

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There is also a need for TSOs to collect fault and maintenance data on a sub-component, rather than component, level. In cases where models can be generalized to types or families of sub-components, data sharing and pooling between TSOs should be encouraged. Such cooperation, like the on-going data sharing within Cigré, is essential to build data sets that are large enough to create meaningful maintenance models. ENTSO-E should play a major role in the process of driving this task forward.

What?
GARPUR proposes to combine and align the work of data collection. In order to increase the number of sampled data, it is also recommended to share a common structure for such data collection and to share the collected data among different TSOs. A framework to enlarge the set of collected data without losing the relevance of the data should be defined at EU, e.g. ENTSO-E level, or at international level, e.g. Cigré or IEC level. Because of the heterogeneity of the data, it will probably be necessary to define standards for the exchange of probabilistic data. A common data model and format has to be defined, e.g. via an extension of the CIM format. It is also expected that the existing information about all the events that have already occurred in the past should, to the extent possible, be made available in the same common model and format.

Major challenges include ownership of data, data safety, value of information, and resources for data collection. To address them, it is recommended to implement a full automation of data collection and a process managing aggregated information to avoid displaying any sensitive information. Academic and research centres could support such process to extract characteristic features from raw data. In addition, using already existing data should be a sound foundation to speed up pace of deployment. ENTSO-E should lead such an initiative and TSOs would have the responsibility to provide the data.

The recommendation assumes that Reliability data are collected by the TSOs according to the guidelines described in the previous section. The implementation could be gradual: integrating TSOs with their particularities and a later stage moving towards a pan-European alignment. It is expected that a deployment of that recommendation covering all TSO contexts could take place within the next five years; however, European alignment could also take more time.

R2.3. Quantify the value of continuous data quality improvements

Why?
The accuracy of probabilistic reliability indicator estimation is currently limited by data quality. Specifically, data related to component outage times, corrective control failures, economic and environmental costs, and exogenous uncertainty and correlations between them are of importance. In order to ensure the sustainable use of the probabilistic reliability management approach and criteria, it is necessary to establish processes to ensure continuous improvement of data quality which may include the investment in novel sensors and data gathering infrastructures. To justify such processes and investments, it is necessary to perform analyses that quantify both the costs and benefits of an improvement in data quality and availability.

What?
As a first step, the minimum data quality needed to be able to take decision based on probabilistic reliability indicators must be defined. Further on, research is needed which shows the value of improved reliability data. This type of methodological analysis can be carried out through simulation studies that allow one to assess the economic and technical value of more data and better data quality. Such analyses can be performed with tools for probabilistic reliability management as the quantification platform developed in GARPUR. By changing different input parameters, the importance of the underlying data can be assessed.

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This requires also that the most important effects are modelled in the tool. The impact of changes in input data quantity and quality on the reliability management results could support informed decisions on investments in improved data quantity and quality.

One example is the investment in asset condition monitoring devices. New inspection devices, such as drones and robots, open new perspectives for automatic and additional regular inspection of the assets. However, investing in such technologies would not be free. The question is whether the expected benefits would compensate the purchase and maintenance costs of these assets, as well as the various IT costs to process the information. Asset managers and planners still lack straightforward strategies or frameworks to know what information is required in guiding the selection of an appropriate condition monitoring regime. More data, however, does not necessarily mean better information, or more informed decisions. In fact, many find it difficult to use the data. A sensitivity analysis with a suitable numerical tool could help make informed decisions on these subjects.

The recommendation covers the three TSO contexts: system development, asset management, and system operation and it should be implemented in the next years. TSOs with support of Research Institutions are the main targeted stakeholders to perform these cost-benefit analyses.

R2.4. Improve the practice for the investigation of costs of power supply interruptions

Why?

The estimated consequences of an interruption of power supply has to be taken into account in the decision-making in addition to the probabilities of contingencies. These consequences must be quantified in monetary terms to allow for balancing the security of supply with the cost of different counter-measures. Consideration on the Expected Energy not supplied or the VOLL are missing in the network code, although they are included in the draft of the Winter package[9]. Both practices and available information for VOLL are of varying quality in Europe dependent on the country. However, a good practice for specifying the interruption costs is an absolute necessity for the probabilistic approach.

What?

GARPUR proposes that the estimation of interruption costs must be improved to allow for a high quality estimation of the consequences of a power supply interruption in the probabilistic approach.

This estimation of the consequences in monetary terms is notoriously difficult and includes both the estimation of the power interrupted and the valuation of the lost load for calculating the socio-economic cost of power supply interruptions. In addition, interruption costs vary as function of the customer group, time of interruption, duration of interruption, and total magnitude of interruption. An estimate of the power not supplied could be computed by running OPF methods. Then, it would be necessary to rely on expected load curves and heuristics for the translation into an Expected Energy not supplied. Note that the restoration and repair times of the components are influenced by the weather as well as by the availabilities and location of the crews. The quantification of the socio-economic costs of power supply interruptions must be performed by means of the value of lost load. Despite some exceptions as Norway, where Norwegian regulation describes how to quantify the socio-economic costs of power supply interruptions, data and models describing the impact of power supply interruptions on European electricity consumers are not generally available.

[9] COM(2016) 861

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The process of improving the investigation of interruption costs should be based on Guidelines for cost estimation studies, such as enhanced CEER guidelines of good practice[10]. The current draft of the Winter package[11] already obligates member states to estimate at least a single VOLL for their territory. Member States may establish different VOLL per bidding zone if they have several bidding zones in their territory and they update their estimate at least every five years. Harmonization of the process is thus clearly relevant and has to be seen under the perspective of the on-going discussions of the Winter package and new rules for Risk preparedness.

Regulators and TSOs, with the support of Research Institutions, are the main targeted stakeholders for this purpose of improving the estimation of the interruption costs. Since guidelines for cost estimation studies are already available, such as CEER guidelines of good practice, an implementation within the next five years is likely and should be the goal. The use of aggregated values could be an option to accelerate and simplify the collection and analysis of such data.

R2.5. Improve modelling of the degradation process of components and the maintenance impact

Why?
The state-of-the-art in models allowing one to predict the degradation processes of the assets over long time periods, and taking into account the beneficial impact on health-condition of maintenance activities, is currently in its infancy. Such models are however required to objectively carry out a cost-benefit analysis of different maintenance and replacement policies on the future reliability level of the power system.

What?
We recommend intensifying the research and development of models for the degradation process of power components that also consider the impact of maintenance and power system use of the asset. The modelling of the degradation process in power system components is mostly relevant in long-term studies in system development and asset management.

Given the scarcity of data required for building such models, an alternative approach is to put considerable effort in the creation of prior models. That is, models that are derived from accelerated life tests, numerical and/or physical simulations, vendor models, or expert models/estimates. The scarce real-world data can then be used to test, refine, and validate the prior models.

Maintenance impact models, separate from degradation models, estimate changes in health variables, or even failure rates, following a maintenance activity. These models should allow for improved planning and budgeting of maintenance activities, and enhance existing reliability centred maintenance. In the short-term, maintenance impact models should be heavily dependent upon expert knowledge and laboratory testing.

The validation of degradation and maintenance impact models is inherently difficult. This is largely due to the lack of data on which to train models, and therefore a lack of data outside of the training dataset on which to test and validate the models. This is especially difficult for models that are specific to a particular sub-component and/or health variable or failure mode. Only once the differing models have been adequately tested and compared, and once the data sets are large and consistent, does it become reasonable to attempt validating the models.

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[10] CEER (2010) Guidelines of Good Practice on Estimation of Costs due to Electricity Interruptions and Voltage Disturbances, available at: https://www.ceer.eu/documents/104400/-/-/7dec3d52-934c-e1ea-e14b-6dfe066eec3e
[11] COM(2016) 861

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TSOs are the main targeted stakeholders with the support of Research Institutions. For a successful implementation, an appropriate time horizon ranges from 5 to 10 years, provided that big data technologies bring new knowledge.

R2.6. Improve component failure rate models based on component condition and weather

Why?

The exploitation of the progressively collected data set for development and validation of enhanced component failure rate models is an important step. Indeed, the exercise of generalizing from the observations of component failures to synthesize failure rate models for each component of the power system does not have a trivial solution. Therefore, the proposed models must be validated.

Today's failure rate models calculate mainly average failure rates. However, failure rates are dependent on the component condition and external conditions as the weather, asset utilization, and execution of work in the vicinity of the asset. Reliability assessments that do not account for these factors will therefore give imprecise results. In addition, weather situations are not only correlated with failure rates but also with demand which is correlated to temperature and generation which is correlated to wind and sun and will therefore lead to different grid flows and consequences if failures occur. These correlations are neglected with average failure rates. Therefore, there is a need for failure rate models that provide a probability of failure of sub-components or components that includes these two factors.

What?

The recommendation is to propose and validate suitable models for the failure rate of power system components which simultaneously take into account the instantaneous external conditions, primarily weather, with the health condition and current operating condition of the assets. This will also result in the inclusion of the impact of degradation or maintenance activities and will be heavily constrained by data availability. Therefore, initial models must be quite simple and based heavily upon expert inputs. In addition, the failure data from the TSOs must be correlated with weather records and maintenance or work histories.

Models for linking weather with failure rates are already available and were implemented in GARPUR's work. To link the health and degradation of components with real-time failure rates, there are two possible avenues:

1. Include the health variables as real-time exogenous variables (similar to how weather is treated in some real-time failure rate models, to create failure rate coefficients that are dependent upon weather and health);
2. Use the output of a long-term failure rate model to provide the 'base' failure rate for existing real-time failure rate models.

Both have their advantages and disadvantages. The advantage of the first approach is that it does not require any longer-term failure rate models. The main disadvantage is that such models may become quite complex and, given a lack of data, may not be able to model any meaningful relationships between faults, component health, and weather. The second approach has an advantage in allowing the development of real-time and longer-term models to occur in parallel. By treating the two problems separately, they are greatly simplified, and may therefore be developed sooner. The disadvantage is that interactions between health state and weather exposure may not be possible to capture with this type of model.

The recommendation targets TSOs with the support of Research Institutions and assumes as a prerequisite the availability of failure data from the TSOs and their correlation with weather records and maintenance or work histories. The recommendation covers the three TSO contexts: system development, asset

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management, and system operation. A short implementation time horizon of around 5 years is expected, since several TSOs already have systems in place to describe condition as an index, which can be included in failure rate models.

R2.7. Gather data and build models for corrective control failure models and probabilities

Why?
Acknowledging the potential failure of post-contingency corrective controls is also a modelling novelty of the research and development performed in the GARPUR project. Consequently, the models and data to do so in practice are not presently available at the disposal of TSOs. Moreover, the challenge is aggravated with respect to the previous aspect of outage probabilities since (i) occurrences of post-contingency corrective control failures are much rarer than occurrences of component outages, and (ii) there is hardly any systematic documentation of such events as, understandably, in such occasions operators are more concerned with keeping the system functional while counteracting the effects of a contingency event. Hence, there isn't a generally accepted framework within which to classify and define failures of corrective actions.

What?
Relying only on the lengthy and laborious process of collecting data from observed failures and successful use of post-contingency corrective controls implies progressing at a much slower pace here. We may, however, envision two additional possibilities for progressively filling in the missing data and models. The first one concerns relying on the current knowledge and expertise of the control room operators. Indeed, to a certain extent, control room operators have an intuitive understanding of the possible modes of failure of corrective controls as well as of the probabilities thereof, and use such understanding in prioritising amongst the available post-contingency control actions. Documenting such understanding and expertise can be a first step in identifying how to gather data and build models. This can be translated into a generic, conservatively high, initial value for the failure probability of corrective control to reflect the current practice of favouring preventive control as a more reliable resource. The second possibility relates to inspecting the status of corrective control resources. Indeed, even though corrective control failures are presently revealed only upon the occurrence of a contingency, the failure of the respective resource (e.g. breaker/switch, etc.) may well remain hidden for a considerable period of time. Therefore, inspecting the functionality of such resources at times wherein the system operation is not jeopardized may well provide a solution to the data collection challenge.

This recommendation is mainly for TSOs, and the implementation pace should be based on the results of the previous recommended cost-benefit analysis of the value of more data and higher data quality.

3.3.3 Thematic cluster 3: Reliability management methodology, algorithms, and software

The GARPUR project has developed several methods and prototypes of algorithms to assess the feasibility and determine the computational bottlenecks for the practical implementation in large-scale powers systems of both reliability assessment and reliability control methods based on the probabilistic RMAC.

Clearly, both in reliability assessment and in reliability control, the resulting stochastic simulation and optimization problems are significantly more computationally complex than their already challenging deterministic counterparts suited for N-1 based reliability management. Massive parallel computations using modern high-performance infrastructures and low-cost processors are part of the enablers of these new methods that we recommend exploiting. Even though GARPUR has developed several methods and prototypes of algorithms, for the implementation in large-scale powers systems there is still the need to

The research leading to these results has received funding from the European Union
Seventh Framework Programme under Grant Agreement No 608540.

develop industrial grade software tools. Industrial use not only means computational efficiency and scalability to continental scale power system models, but it also means robustness of the software, and adaptability to the specifics of each TSO's practices.

In the next subsections, we identify the main actions that should be carried out after the end of the GARPUR project to develop the required new generation of software tools, methods, and algorithms. Software tools can be based on the existing software already in use or developed in the context of GARPUR and other previous research projects like, for example, iTesla (http://www.itesla-project.eu), PEGASE (http://www.fp7-pegase.com), and Umbrella (http://www.e-umbrella.eu/).

Table 3.3: The GARPUR recommendations on Reliability management methodology and algorithms per stakeholders, time horizon, and reliability management context

	Targeted stakeholders					Timing	Context
	ENTSOE	TSOs	Research Organisations	ACER/ Regulators	Technology Providers	Years	System development, asset management, system operation, all
R3.1. Develop proxies to reduce the complexity of reliability assessment and control		Contributor	Lead			< 5	All
R3.2. Take into account outage scheduling within long-term studies		Contributor	Lead			< 5	System development Asset management
R3.3. Develop algorithms for the context of day-ahead and week-ahead operational planning		Contributor	Lead		Contributor	5 - 10	System operation
R3.4. Develop scalable and robust algorithms for the probabilistic SCOPF		Contributor	Lead		Contributor	< 5	System operation (All)
R3.5. Handling discrete control actions and non-convexity in the SCOPF algorithms		Contributor	Lead			< 5	System operation (All)
R3.6. Improving the methods for micro-scenario filtering and selection of critical scenarios		Lead	Contributor		Contributor	< 5	System development Asset management
R3.7. Industrial grade software and tools for probabilistic reliability assessment		Contributor	Contributor		Lead	< 5	All

Lead ■ Contributor □

R3.1. Develop proxies to reduce the complexity of reliability assessment and control

Why?

One of the key concepts tackled within GARPUR is the modelling of the multi-stage nature of the decision-making processes, where each stage concerns a specific set of candidate decisions relevant for the time-horizon under consideration. Each stage could be modelled by using an as accurate as possible method such as a SCOPF. However, such an approach is often intractable and, anyway, given the very large amount of uncertainties faced, trying to reach a high level of precision would be irrelevant. Therefore, GARPUR introduced the concept of proxies.

Given their high potential value in reducing the complexity of the corresponding computational problems, state-of-the-art machine learning methods and algorithms to construct proxies for use in the context of reliability assessment and control deserves further investigation by the research community.

What?

We recommend continuing the academic work on the proxies for the short-term decision-making processes, or at least to find a first implementation that, even though imperfect, is deemed sufficiently trustworthy for their intended use. Those proxies also need to be scalable to real systems. Given the tremendous computational complexity of the problem, we had to find an implementation of the proxies that is much faster than massively solving OPF problems. Therefore, we explored in GARPUR the idea of automatically building proxies by exploiting machine-learning methods. Such an approach reduces the computation time by several orders of magnitude, even though its accuracy is not optimal. We see further need to develop proxies that could be based on machine learning or other methods. Today, there is a lack of methodology for transferable machine learning, from one system to another and from one context to another; developing methods that yield transferable proxies is a topic of further research for the machine learning community.

GARPUR has used simplified 'static' models of physical system responses in emergency mode, the so-called 'cascade' simulator, used for real-time reliability assessment. Clearly, if the system dynamics are liable to lead to loss of voltage or transient stability, this model needs to be suitably upgraded. This would lead to a new version of the reliability assessment proxy used in asset management studies as well.

This work could be performed by research institutions, with the collaboration and support of TSOs to ensure meaningful validation and knowledge transfer. ENTSO-E and Regional Security Coordinators (RSCs) could also be interested in testing such prototype tools respectively for short-term and real-time planning, for long term system development, and assessment of investment decisions. The development of proxies is relevant for the implementation of probabilistic reliability management in all contexts: system development, asset management, and system operation.

R3.2. Take into account outage scheduling within long-term studies

Why?

Outage scheduling concerns finding the right moment of component outages on an annual basis, as needed by the maintenance and replacement policies in place, to minimize negative impacts on system operation. In the context of studies covering long-term horizons, such as in system development and in maintenance policy calibration, it is strongly recommended to consider explicitly the fact that the grid must be operated and maintained over many years. In GARPUR, a proxy of the annual outage scheduling process was developed for the purpose of maintenance policy assessment, while no search for optimal maintenance plan was conducted in the framework of system development. In fact, it does not make much sense to define the exact maintenance plan decades in advance because the required outages will be increasingly dependent on renewable energy generation patterns, either directly or indirectly, via their influence on the international flows and generation dispatch, and hence impossible to forecast years in advance. It is, however, a fact that in real-time operation, it rarely happens that all grid components are fully available at the same time, while at the same time each component individually is available most of the time. Therefore, to properly assess the future impact on operation of maintenance policies and grid development decisions, one has to accurately enough model the outage scheduling process over a set of multi-year future scenarios.

The research leading to these results has received funding from the European Union
Seventh Framework Programme under Grant Agreement No 608540.

What?
In the context of long-term studies for grid development and maintenance policy assessment, we recommend explicitly modelling the fact that the grid must be robust enough to allow scheduling of component outages needed to conduct the foreseen maintenance or replacement activities. To this end, a greedy method has been developed within the project for the emulation of the outage scheduling process which heavily relies on further shorter-term proxies, namely a proxy for reliability assessment, a proxy to model the intraday decision-making, and a proxy to model the day-ahead decision-making. We recommend that this outage-scheduling proxy should be further tested and improved to allow its effective use within these long-term studies. We propose also to expand this proxy to take into account the impact of maintenance activities and component outages implied by the execution of system development projects.

A prerequisite for the development of the proxies for the sake of power system development planning and maintenance policy calibration is that sufficient experience from the application of probabilistic approaches is gained upfront. The development of algorithms should be carried out by research centres with the support of TSOs, and should be possible within less than 5 years.

R3.3. Develop algorithms for the context of day-ahead and week-ahead operational planning

Why?
There is a lack of algorithms for day-ahead and week-ahead operational planning for reliability assessment and control. Without such algorithms, optimal decisions cannot be taken in these planning contexts when implementing a probabilistic reliability management.

What?
We recommend the development of tractable algorithms for the implementation of probabilistic reliability management in day-ahead and week-ahead operational planning contexts and to develop tools and methods for optimally taking decisions in these time periods consistent with the real-time operation strategy. This concerns also the calculation of transmission capacities provided to the energy markets, and the preparation of special measures needed to handle extreme weather conditions and/or unexpected extreme situations where several generating plants need to be taken out of operation for safety considerations or because of failures.

Gaining sufficient positive experience from the application of the probabilistic approach is a prerequisite for developing flexible algorithms for probabilistic RMAC for day-ahead and week-ahead. Much information, such as weather forecasts, is available, but data-collection and regulatory aspects must be thoroughly addressed when designing these algorithms. The development of algorithms has to be in the hands of research centres, with the support of TSOs and RSCs, and should be feasible within the next 5 to 10 years.

R3.4. Develop scalable and robust algorithms for the probabilistic SCOPF

Why?
Reliability management is a multi-stage decision-making problem under uncertainty, with a probabilistic SCOPF at its core. While the scientific literature on algorithmic approximations to this problem keeps growing, it is necessary to align such research with developing solutions that fit the needs of the modern industry and build on state-of-the-art computing platforms.

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What?
We recommend developing solutions that fit the needs of the modern industry and are aligned with research on algorithmic approximations of probabilistic SCOPF. For this, we also recommend setting up a benchmark system representative of the set of candidate actions that are to be considered for reliability management by TSOs in system operation, in particular discrete topological manoeuvres. This recommendation is directly relevant for real-time and short-term operational planning, and indirectly relevant as proxies for the longer-term horizons. Research institutions with the support of TSOs should drive that task. Technology providers should also take an important role. This task could also be included within future European initiatives. Main barriers are financial and lack of human resources in TSO organizations.

R3.5. Handling discrete control actions and non-convexity in the SCOPF algorithms

Why?
The simulation of system response to contingencies is important to measure the expected severity of power supply interruptions. In SCOPF tools, the modelling of continuous preventive and corrective actions, i.e. re-dispatch of control targets such as active power and voltage, are well established in solving violations associated with contingencies. Discrete preventive or corrective actions, in particular change of topology, can also be useful and, importantly, can often be carried out at much lower cost than re-dispatch actions. However, they are rarely captured in existing SCOPF tools even though they are often the most efficient and cheapest actions. Also, the AC-SCOPF is inherently a non-convex problem, and iterative solvers may land in local optima or even diverge in the case of stressed system conditions.

What?
Further work is needed to develop efficient and effective SCOPF software to bridge these gaps while building on recent progress published in the scientific literature. This recommendation is directly relevant for real-time and short-term operational planning and indirectly relevant as proxies for the longer-term horizons. Research institutions, with the support of TSOs and technology providers, should implement this task. This task could also be included within future European initiatives. From a technical point of view, this recommendation could be implemented within the next 5 years.

R3.6. Improving the methods for micro-scenario filtering and selection of critical scenarios

Why?
To support decisions in the context of long-term system development and asset management studies, a wide variety of possible future operation scenarios and future macro-economic contexts need to be screened. These include both ‘macro-scenarios’ and ‘micro-scenarios’, the latter representing, for a given set of system parameters, different possible operating conditions. These are affected by, for example, variations in demand and the availability of generation. However, the field experts expect this increase in the number of cases to be difficult to handle. In general, current practice in system development planning does not cover a large set of different operating conditions and, as a consequence, risks either over-investment, because the few conditions that are assessed are onerous and not representative of year-round risks and trade-offs, or under-investment, because some critical conditions might be missed.

What?
The development of an automatic method to select a manageable subset covering the most relevant critical operating scenarios on which to focus detailed analyses and expert work is recommended for use in long-term studies. The development of suitable scenario filtering and clustering methods and criteria using approximate information provided by fast proxies applied to a large number of possible scenarios and

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contexts is recommended to extract from them a reduced number of representative scenarios to be analysed in further detail.

The use of these methods should allow the power system planner to retain control of the proposal of target topologies. It must be noted that these methods could be used either to reduce the number of computations to be performed if the operational constraint is the computing time and automation of a robust impact assessment of each possible hourly snapshot, or to support the post-processing of results to be handed to the power system planner. Therefore, depending on the obtained robustness and computing efficiency of the process, a reliability assessment can be run on all hourly snapshots and used as an input for the clustering or the reliability assessment can be run only on the centroids of the selected clusters. The adoption of suitable scenario filtering and clustering methods should allow a greater but not excessive number of 'micro-scenarios' to be assessed.

A satisfactory result to the clustering process will reveal a sufficiently small number of critical operating states necessary to be studied in detail. The quality of a clustering result might be determined based on a metric of the similarity of different representative operating states or variances of important variables in the set of operating states.

The trigger for such development should come from TSOs while other players, such as research institutes, universities, and technology providers should take care of the development in close cooperation with TSOs. The task should be performed by persons specialized in data mining and optimization. It should be carried out within the next 5 years.

R3.7. Industrial grade software and tools for probabilistic reliability assessment

Why?
Under N-1 driven reliability assessment, operational planning and real-time procedure are already quite complex, and operators must frequently rely on cognitive expertise to manage critical situations. Under a probabilistic framework, a sheer increase of complexity in term data exchange and decision-making (short-term and real-time horizons) is expected. This would require adequate coordination tools and efficient Human Machine Interface capable of translating the complexity of probabilistic reliability dimension into human language input for decision-making.

What?
A next generation of reliability assessment and reliability control tools needs to be developed reaching the necessary robustness, efficiency and availability to support large industrial and academic communities for gradual implementation of probabilistic reliability management approaches. Novel techniques based on recent advancements in artificial intelligence, optimization, and statistics will have to be incorporated in these tools, with suitable physical models in line with the growing complexity of the power system. The knowhow developed within the GARPUR project and during the development of the GARPUR Quantification Platform (GQP) could be used as a basis for such development and be transferred to existing commercial software. The development of these tools calls for a strong and well-targeted collaboration among TSOs, technology suppliers, and research centres either to enhance existing industrial-grade deterministic tools or to industrialize the existing GQP prototype developed in the frame of the GARPUR project.

This new generation of industrial-grade tools would also be used to perform research on the differences between the current N-1 based reliability management approach and the probabilistic ones. It is indeed necessary to conduct a representative set of simulations based on historical or synthetic datasets. In these scenarios both approaches are used, and a socio-economic evaluation is performed to assess differences in

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costs and benefits to all stakeholders. A prototype tool for such off-line studies, called the GARPUR quantification platform, was developed during the project and used in the context of a pilot test on a real system. This pilot test clearly highlighted the interest in using a quantification platform to compare different RMACs with the N-1 criterion, and hence gain a better understanding of their respective strengths and weaknesses. Therefore, industrial development is needed to fill these gaps and to allow research centres to perform such analyses with professional tools.

3.3.4 Thematic cluster 4: Testing and implementation

Several GARPUR recommendations concern the further testing and implementation of methods and algorithms developed within the GARPUR project. These recommendations aim to foster an open-science approach to power systems reliability assessment by sharing data and software among industry and the research community. They also stress the need for further pilot testing activities, and to move gradually towards real-life implementation of the probabilistic reliability management approach. Finally, we stress the need to adapt ICT infrastructures and user interfaces of the developed software, both being necessary for industrial use.

Table 3.4: The GARPUR recommendations on Testing and implementation per stakeholders, time horizon, and reliability management context

	Targeted stakeholders					Timing	Context
	ENTSOE	TSOs	Research Organisations	ACER/ Regulators	Technology Providers	Years	System development, asset management, system operation, all
R4.1. Create open-source test cases and algorithms for broad testing and development		Contributor	Lead			< 5	All
R4.2. Continue and extend pilot scale testing of probabilistic approach		Lead	Contributor		Contributor	< 5	All
R4.3. Implement probabilistic reliability management approaches stepwise	Contributor	Lead				2 - 10	All
R4.4. Develop ICT-infrastructures and user friendly software interfaces	Contributor	Lead	Contributor		Lead	< 5	All

Lead ■ Contributor □

R4.1. Create open-source test cases and algorithms for broad testing and development

Why?

The first stage of research and development for probabilistic methods is mainly driven by academic research. It is necessary to proceed in testing on realistic test cases and to proceed with the important process of disseminating throughout the R&D community the available tools and realistic test scenarios. Open-access of tools, data, and test cases would accelerate the research and make it easier to convince the TSOs of the benefits of new methods.

The research leading to these results has received funding from the European Union Seventh Framework Programme under Grant Agreement No 608540.

What?
In order to ensure that the probabilistic methods proposed by the GARPUR project are adopted and further improved upon beyond the completion of the project, there is a need for making available to the broad industrial and academic research and development communities the available tools and realistic test cases, in open-access format, beyond what is already available in existing reliability test systems and open-source tools. This implies the development of suitable benchmarks, both power system models and datasets with relevant parameters preferably open and in common formats, and a common validation protocol and methodology for developed methods and proxies. The creation of synthetic data sets will also require significant input and insight from TSOs, and a first good starting point could be the data sets of TSOs prepared for the pilot tests performed in GARPUR. In parallel, there is a need for TSOs to continue communicating results and problems to academia to foster good cooperation. In addition, the assessment of potential modelling approaches and the dissemination of the results to TSOs will support the cooperation.

This activity is relevant for all reliability management contexts, and should be carried in a strong collaboration between several TSOs and several research institutions, and within the next 5 years.

R4.2. Continue and extend pilot scale testing of probabilistic approach

Why?
Pilot scale testing activities provide initial insights into how the probabilistic approach developed by GARPUR works in specific use-cases. Such pilot tests have high value not only for identifying the benefits of a probabilistic approach, but also the challenges of its practical implementation. Ultimately, pilot tests performed with real TSO data are necessary to convince other TSOs and stakeholders of the benefits of probabilistic reliability assessment and control. In addition, they are the perfect arena for testing probabilistic concepts and methods and for exchanging knowledge and providing feedback.

What?
Several pilot tests were performed in GARPUR and we recommend further pilot tests to gain further experience beyond the 'theoretical' studies that can be carried out with academic benchmarks, and to bring the TSO experts in the validation loop. As a way to convince TSOs, a parallel testing is suggested between the existing TSO approach and the new methodology. Since only real results will convince TSOs, the comparative benefits resulting from this test should suffice. Smaller scale pilot tests should be performed at the national level not only to assess the probabilistic reliability management approach but also to uncover any possible objections. The results might be a pragmatic first step to ensure progress in changing the mind-sets of the TSO operators. The following pilot tests are proposed:

Outage scheduling assessment
A pilot test on the topic of outage scheduling of a set of transmission lines would consist of submitting an initial tentative outage schedule to a simulation platform, which would compute the expected social-welfare for all the time steps in line with market coupling mechanism (e.g. flow-based). This feedback would help identify the expected difficult periods where the outage schedule might need to be revised. An interesting time-frame would be to cover a full year over the midterm horizon, e.g. 3 years.

Maintenance policies assessment
This test would consist of describing the maintenance/inspection/replacement policies in a tool similar to the GARPUR Quantification Platform, running probabilistic simulation over a very long assessment horizon (20+ years), and then to observe the output indicators on the expected reliability, inspection cost, maintenance

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costs, replacement costs, OPEX, workforce availability, and on the health of the assets at the end of the simulation.

Real-time and short-term

GARPUR has developed different PSCOPF software prototypes for the short-term RMACs and the long-term RMACs. They were tested on academic benchmark systems, with the GARPUR Quantification platform on TSO data in RTE and in the context of the near real-life test case of Elia. We propose to further test these algorithms by integrating them into existing industrial grade tools and applying them on TSO system data, which is similar to the data-sets created for the pilot tests performed in GARPUR. Prerequisites for this test are the availability of realistic "first guess" models and data sets.

Trade-off between preventive and corrective control

TSOs should record the computed value of the expected energy not supplied, as well as the various costs of preventive and corrective control that were triggered. By doing so, they should be able to better appreciate the economic soundness of their decisions, which at some point should contribute to better calibration of the various parameters of the trade-off between preventive-control, corrective-control, and tolerated risk. When possible, one should compare in an ex-post analysis the actual energy not supplied with the predicted values computed in advance.

These pilot tests should be primarily performed by the TSOs with support of academics, technology providers, and research institutes. Such pilots are already on the agenda of some TSOs and should be performed in the next 5 years.

R4.3. Implement probabilistic reliability management approaches stepwise

Why?

Implementation of the ideal GARPUR RMAC is not feasible right after the completion of GARPUR. After pilot tests have successfully shown the benefits, intermediate steps are required to adapt probabilistic reliability assessment by the TSOs.

What?

We recommend TSOs implement probabilistic reliability assessment with two steps; first observation and comparison with the N-1 approach and, if determined to be beneficial, second decision-making based on probabilistic tools.

It seems wise to start the implementation with an observation stage to better understand how risk varies over time on the power system. In practice, the TSO could stick with their usual N-1 practices, but in parallel, test probabilistic approaches. A period of parallel run should be established between the current practices with the current tools and methods, and the new implementation. This stage would also be an opportunity to consolidate the different data collection and modelling issues required by a probabilistic framework. Likely, the practices would evolve in parallel with the knowledge gained by using the new methods. It would also bring interesting feedback on the feasibility for the human operator to interpret and work with probabilistic outputs

After the TSOs have reached a level where they have observed and understood how a probabilistic reliability management strategy could work, they will be in a position to decide whether to start to base their actual decisions on the probabilistic tools.

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The gradual implementation of probabilistic reliability management is under the direct responsibility of the different TSOs, and should take place during the next 5 years. It is obviously relevant for system development, asset management, and system operation, but these contexts might be prioritized in different ways by the different TSOs, according to their specific technical and regulatory context.

R4.4. Develop ICT-infrastructures and user-friendly software interfaces

Why?
The development of practical tools for the probabilistic studies relies on the use of massive computing architectures in order to accelerate computations. The hardware required to parallelize the computation must not be underestimated. In addition, the number of results raises the concern that the output could drown the decision-maker with an overwhelming amount of irrelevant information. To the best of our knowledge, the question of what information should be displayed, as well as the associated graphical interface, has barely been addressed in the literature.

What?
Therefore, it is recommended to determine the development needs of an ICT-infrastructure for probabilistic analyses. This includes the necessity to provide data mining and visualization methods and tools to assist the experts in their decision-making. Some software developers have already developed tools that can perform probabilistic reliability assessment where risk indicators are provided based on the probability and consequence of the contingencies, and which is usually used for off-line planning applications, but also available for real time risk assessment. In addition, there is a need to possibly update existing systems, particularly those embedded within the energy management system (EMS) used by the TSOs, to provide software module interface for new tools, standard formats such as the CIM format, and also to facilitate the display of outputs within the EMS system. The same infrastructures should be usable for both system development studies, asset management, and for operational planning and operation, with suitable ad hoc customizations.

The development should also rely on “big data” methods to exploit the massive datasets formed by the results of Monte-Carlo computations, and correlate them with the data provided as inputs. Modern machine learning algorithms, including deep neural networks, random forests and Gaussian process models, can play a main role in setting up these ICT-infrastructures.

This task has to be performed in cooperation between TSOs, technology providers, and research organisations and should be carried out within the next five years.

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APPENDIX A - THE GARPUR PROJECT IN A NUTSHELL

GARPUR is a four-year project funded by the European Commission FP7 programme (Grant agreement No 608540), which started in September 2013 and is expected to be finished in October 2017. The acronym GARPUR stands for "Generally Accepted Reliability Principle with Uncertainty modelling and through probabilistic Risk assessment". The project is funded under the THEME [ENERGY.2013.7.2.1; Advanced concepts for reliability assessment of the pan-European transmission network].

In this appendix, we first recall the general objectives and research strategy of the project, then we describe the consortium and organization of work and, finally, we briefly discuss our dissemination and exploitation strategy.

A1. Objectives, R&D strategy, and targeted results

Overall, the GARPUR project aims to:

- define new classes of reliability criteria able to quantify the pan-European system reliability in coherence with its evolutions towards and beyond 2020.

- evaluate the relevance of the criteria and compare different reliability management strategies through a comparison of their impacts on the resulting global social welfare, thus pinpointing the most favourable evolutions away from the N-1 criterion in the decades to come.

This general goal translates into the 7 following objectives.

> **O1:** To **develop** a consistent **probabilistic framework for reliability management**, covering the definition of the notion of reliability, the calculation of reliability criteria, and the resolution of optimization problems expressing the economic costs and the desired target reliability levels at the pan-European level and within each individual control zone.

> **O2**: To **develop** a consistent methodology for the quantitative **evaluation of the economic impact on society** of different reliability management strategies both at the pan-European level, and within each control zone.

> **O3**: To **develop** a **quantification platform** able to compare different reliability management strategies in terms of their impact on the social welfare in Europe.

> **O4:** To **ensure** the **compliance** of the developed methodologies with the **technical requirements** of system development, asset management and system operations, and to **demonstrate** the **practical exploitability** of the new concepts at the pan-European level and in these decision-making contexts.

> **O5:** To **validate** the retained alternatives with the help of **pilot tests.**

> **O6**: To **ensure** the general **acceptance** of the proposed methods and tools by **all stakeholders** affected by the reliability management of the pan-European electric power system.

The research leading to these results has received funding from the European Union
Seventh Framework Programme under Grant Agreement No 608540.

O7: To **define** a **migration path** towards the **use of the new reliability management practices** by defining an **implementation roadmap**.

In order to ensure progress beyond the state-of-the-art, the project uses **5 different alternatives** along which progress should be ensured and evaluated. These are defined as follows:

- **A1.** Model the **spatial and temporal variation** of the probabilities of **exogenous threats,** and take into account the **actual criticalities** of service interruptions in the reliability management.
- **A2.** Take into account the increased possibilities of **corrective control** and its **probability of failure** in the reliability management.
- **A3.** Exploit the flexibility provided by **demand-side management** and **energy storage** to achieve the reliability enhancement given the emergence of **decentralized renewable generation**.
- **A4.** Explicitly model the impact of **system development** and **asset management** decisions on the reliability management during **operation**,
- **A5.** Explicitly take into account the consideration of **low-probability, high impact** events like, for instance, the ones originating from extreme weather conditions, possibly through climate change, or those originating from adverse behaviours of external entities.

These **5 alternatives** have been followed systematically throughout the project to reach the **7 objectives** of GARPUR. They were addressed in such a way that the provided solutions are scalable to the multi-actor/multi-zone context of the pan-European system.

The project will deliver **6 compound results** along the **7 objectives**, and will validate them in terms of the progress made along the **5 alternatives**:

- **R1.** A sound probabilistic reliability management approach able to cope in principle with all the expressed needs and ensuring significant progress along the 5 alternatives.
- **R2.** A sound methodology for assessing the social impact of new reliability management approaches.
- **R3.** A prototype version of a quantification platform scalable at the pan-European level, and capable of coping with the 5 alternatives.
- **R4.** Several practical solutions exploiting the 5 alternatives to cover a maximum number of the business objectives of TSOs, from system development to operations, via asset management.
- **R5.** A strong impact of its results on the mind-set of all involved stakeholders to yield acceptance of the new methods along a maximum number of alternatives and players.
- **R6.** A decision from the stakeholders to follow the proposed roadmap and to implement the new methods in real-life practice in the very near future after the end of the GARPUR project.

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Seventh Framework Programme under Grant Agreement No 608540.

A2. Consortium structure and complementary roles of partners

Coordinator: Dr. Oddbjørn Gjerde, SINTEF Energi AS
Scientific Advisor: Prof. Dr. Louis Wehenkel, University of Liège
Partners:

Beneficiary Number	Beneficiary name	Beneficiary short name	Country
1 **(coordinator)**	SINTEF Energi AS	SINTEF	Norway
2	Statnett SF	STATNETT	Norway
3	ELIA System Operator S.A.	ELIA	Belgium
4	RTE	RTE	France
5	Landsnet	Landsnet	Iceland
6	ESO EAD Bulgaria	ESO	Bulgaria
7	CEPS, a.s.	CEPS	Czech Republic
8	Energinet.dk	Energinet	Denmark
9	Reykjavik University	RU	Iceland
10	KU Leuven	KUL	Belgium
11 **(scientific advisor)**	Université de Liège	ULG	Belgium
12	Aalto University Foundation	AALTO	Finland
13	TU Delft	TU Delft	Netherlands
14	University of Strathclyde	Strathclyde	UK
15	University of West Bohemia	UWB	Czech Republic
16	Norges teknisk-naturvitenskapelige universitet	NTNU	Norway
17	Technofi	Technofi	France
18	Universität Duisburg Essen	UDE	Germany
19	Technion R&D Foundation LTD	TECHNION	Israel
20	Danmarks Tekniske Universitet	DTU	Denmark

The seven TSOs (Partners 2 to 8) provide rich expertise in planning and operation practices over a diverse set of areas of the European power system. They contribute by their strong and complementary expertise in system development, asset management, and system operation, to guide the 12 Research Institutions (Partners 1, 9 to 16, and 18 to 20) in their work, and to ensure the validation and exploitation of the results. Jointly, the involved research institutions span high-level expertise in power systems, optimization, machine learning, and economics.

The coordinator (Partner 1, SINTEF Energi AS) has broad experience in European project management, and Partner 17 (TECHNOFI) is a consulting company with recognized expertise in innovation management.

In addition, the project has nominated the University of Liège (Partner 11) as the scientific advisor, with the responsibility to ensure the technical and scientific coherence of the project’s work, and to conduct the required quality control over all the deliverables produced by the project.

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A3. Organization of work

The work is organized in 10 work packages (WPs), as shown in Figure 1, below.

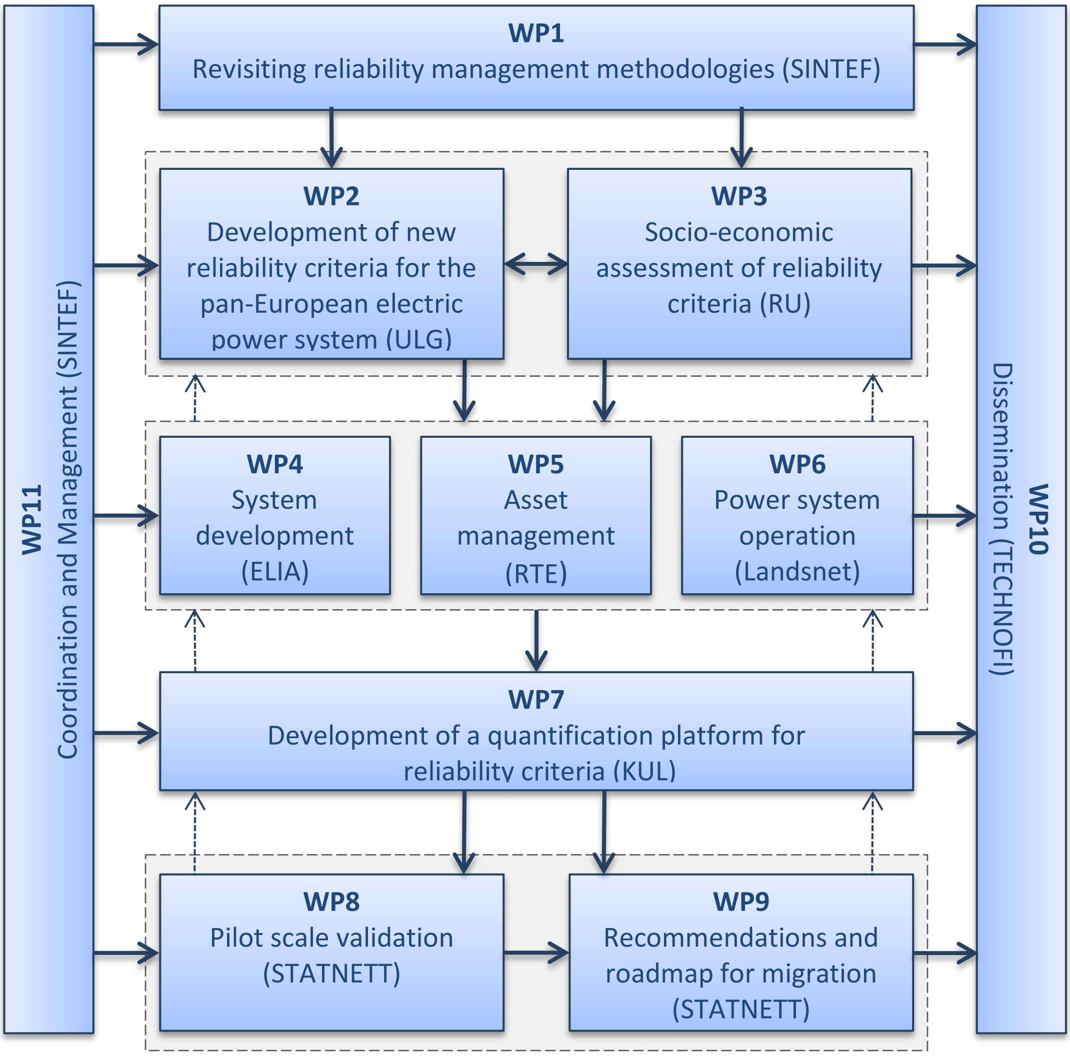

Figure A.1: Main Work package (WP) Structure of GARPUR and WP leader responsibilities

A4. Dissemination of results

Dissemination activities were organized and coordinated under the umbrella of WP10, a work package active for the entire duration of the project (with a specific effort of about 50 man-months). Dissemination was carried out along several complementary channels:

GARPUR Website: the website was created during the first 3 months and enriched all along the project with documents produced by the consortium members as they became available.

GARPUR Workshops: altogether, the project organized 9 works-shops to communicate with relevant stakeholders (TSOs and ENTSO-E working groups, Regulators, DSOs, Generators, Technology

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providers, and other European projects such as iTesla, Umbrella, and Bestpaths) about on-going and planned work.

GARPUR Webinars: the project presented two webinars with Leonardo Energy/ISGAN Academy.

GARPUR final conference and brochure: the final conference will take place on Oct. 17-18 2017, and is expected to gather around 150 specialists. For the broader public, a brochure and a video will summarize the results and vision of the GARPUR project.

GARPUR Special Sessions: two such sessions were organized at IEEE PowerTech 2015 and 2017, where WP leaders presented the main results of the project.

Scientific publications and presentations: the project has led to more than 30 scientific papers and many oral presentations at international conferences, and invited talks at prestigious institutions and workshops.

All the public documents are available on the website: http://www.garpur-project.eu/.

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APPENDIX B - THE GARPUR PUBLIC REPORTS

The table below shows all public deliverables from GARPUR; most of them are referenced in this report. They can be downloaded from the GARPUR website: http://www.garpur-project.eu/deliverables.

ID	Title	Dated
D1.1	State of the art on reliability assessment in power systems	2014-03-11
D1.2	Current practices, drivers and barriers for new reliability standards	2014-06-27
D2.2	Guidelines for implementing the new reliability assessment and optimization methodology	2016-10-10
D3.1	Quantification method in the absence of market response and with market response taken into account	2016-01-19
D3.2	Recommendations for implementing the socio-economic impact assessment methodology over the pan-European system in a tractable way	2016-09-12
D4.1	Functional analysis of System Development process	2015-01-29
D4.2	Upgrading of the decision-making process for system development	2016-10-25
D5.1	Functional analysis of Asset Management processes	2015-02-11
D5.2	Pathways for mid-term and long-term asset management	2016-09-19
D6.1	Functional analysis of System Operation processes	2015-02-11
D6.2	How to upgrade reliability management for short-term decision making	2016-10-10
D7.3	A broader comparison of different reliability criteria through the GARPUR quantification platform	2017-08-31
D8.1	Pilot testing methodologies, models, scenarios and validation approach	2016-02-18
D8.2	Publishable summary of D8.2 Results from Pilot testing using the quantification platform prototype	2017-08-25
D8.3	Publishable summary of D8.3 Results from near real-life pilot testing	2017-08-25
D9.1	Results and recommendations towards stakeholders (this report)	2017-09-25
D9.2	A transition roadmap towards probabilistic reliability management	2017-09-25

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