THE GARPUR PROJECT

A transition roadmap towards probabilistic reliability management

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1 INTRODUCTION

Several transmission system operators (TSOs) worked together with research organisations as well as an innovation management company within the **GARPUR research project** in order to design, develop, assess, and evaluate new reliability management approaches to be gradually implemented at the pan-European level over the next decades. Following four years of intense collaboration, GARPUR achieved a major step towards the development and demonstration of the benefits of probabilistic reliability management. The new reliability management approach takes into account probabilities and consequences of different possible events rather than looking only at worst-cases or nominal assumptions. This could provide multiple benefits, such as a more efficient grid use, increased reliance on wind or other variable generation, less capacity given to the reserves and more capacity for power transmission, and finally, more transmission capacity given to the market.

This report provides a high-level summary of the conclusions from work conducted under the GARPUR project, and proposes a transition roadmap to evolve from the current N-1 based reliability management practices to design, maintain, and operate the European electric power system. It gives the necessary information for experts and executives in TSOs, regulators, research organisations, and technology providers to understand the challenges and benefits of evolving towards probabilistic reliability management.

Chapter 2 recalls the basic concepts behind reliability management of power systems as well as the situation regarding its development and use among European TSOs.

Then **Chapter 3** describes the benefits of moving towards probabilistic reliability management based on the conclusions drawn from five tests of the methodologies and tools developed in the GARPUR project which cover both system development and system operation performed with real TSO data. Since the benefits of such a move have been demonstrated, we present the future vision of GARPUR for reliability management in this chapter: a widespread use of probabilistic reliability management. Technical and regulatory challenges still exist and they have to be overcome before a widespread use can be reached.

The report concludes with **Chapter 4,** which provides a description of the transition roadmap to evolve from current N-1 practices. It is formulated on the basis of the results obtained during the project and extensive interaction with external stakeholders. The actions described can be seen as the translation of four years of development within the project into a strategic action plan and a possible starting point for any TSO, regulator, or decision-maker to unlock the societal benefits of probabilistic reliability management.

For further information regarding the project results and its recommendations, the GARPUR consortium recommends **Deliverable D9.1 Results and recommendations towards stakeholders** which extensively describes the work conducted within the GARPUR project, provides pointers to the technical reports produced by the GARPUR consortium, and gives a more technically detailed description of our recommendations for future work.

All the deliverables and publications resulting from the work of the GARPUR project are available on its official web site http://www.garpur-project.eu/deliverables.

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2 RELIABILITY MANAGEMENT OF THE POWER SYSTEM, A CORE TASK OF TRANSMISSION SYSTEM OPERATORS

A secure and reliable electricity supply is essential to drive economic growth and for the welfare of society. In this context, European TSOs play a central role by building the electric transmission system, maintaining its assets, and operating the system, while taking care of all relevant time scales.

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 the society is the purview of *power system reliability management*.

Power system reliability management means making decisions under uncertainty. It is to meet a *reliability criterion*, and minimize the costs of doing so. A reliability criterion is a principle which imposes a standard to determine whether or not 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 the infrastructure with a long-term perspective (say the next 20 years) to operating the system from the control room in real-time. On top of technical complexity, making such decisions involves a trade-off between the costs of providing security of electricity supply[1] and socio-economic costs of power supply interruptions. For example, consider the question of expanding the transmission capacity of the grid. New transmission corridors may mean more redundancy, hence greater security of electricity supply. But it may also mean higher investment costs as well as causing an environmental impact due to construction. On the other hand, not building more transmission capacity may save money in the short run, but it may also mean less security of supply which, in turn, may lead to socio-economic costs due to power supply interruptions. In addition, it may limit the potential to integrate renewable generation resources.

In order to reason around such complex decision-making problems, reliability management is commonly 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 reliability criterion expresses the level of system reliability required by the regulations.

2.1 N-1, Europe's historical approach

Assessing power system reliability (let alone controlling it) is a complex and comprehensive task involving a multitude of factors, dimensions, and uncertainties. Due to the complexity and different needs in different decision-making contexts and time horizons, various methodologies and indicators for reliability assessment have been proposed over the past decades.

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

[1] Here, costs of providing security of 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.

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In the context of real-time operation, this criterion amounts to ensuring that 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 future state of the system over the next hours to days, the scope of the N-1 reliability management concerns ensuring that 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 for the considered target years the system would remain 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.

Even though the current reliability management practice in Europe is based on the N-1 criterion, there are different practical implementations of the criterion, adapted to local conditions. Most of the TSOs in Europe adhere strictly to the N-1 criterion, but there are TSOs that might accept less restrictive limits when consequences are controllable. Some TSOs even use more restrictive limits in situations where the consequences are regarded as less acceptable. The N-1 criterion is used with minor differences for planning, maintenance, and operation.

TSOs have carefully analysed disturbances to understand causes and find possible remedies. As a result, the N-1 principle has continuously been updated with new requirements. The present level of reliability is the result of this process.

2.2 A call to go beyond the current practices

The changing structure of 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, all call for new reliability management approaches. These should improve upon the current N-1 based practice and lead to a better trade-off between the costs of providing security of supply and the socio-economic costs of service interruptions.

In practice, the N-1 criterion does not consider the consequences or the likelihood of contingencies, or its socio-economic impact in terms of power supply interruptions or means of mitigation. Strictly applied, the N-1 criterion results in a system covering the predicted yearly demand peak hours, but that is marginally needed for most of the remaining time. At the same, it fails to capture the risks induced by high impact low probability events. Therefore, under the increasing operational uncertainties driven by higher penetration of renewable energy resources and regional market integration, the current N-1 based reliability management approach could lead to major unforeseen security of supply failures and/or an unnecessary increase in terms of investment and operation costs.

In this situation, it has become clear that the traditional deterministic N-1 criterion has to be gradually replaced by more systematic approaches able to explicitly take into account the 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, maximize social welfare, and ensure a cost-efficient security of supply.

These new reliability management approaches should allow the power system to operate much closer to its economic optimum, which means they should first take explicitly into account:

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- the probabilities of failures of the different system components by carefully modelling their dependence on weather conditions, maintenance history, and real-time conditions
- the uncertainties in forecasted production and load, both in long term planning and short-term operations, by modelling more accurately the forecast errors
- the flexibility available in the grid by using different remedial measures as, for example, special protection schemes and phase shifting transformers
- the flexibility provided by the demand-side, energy storage and distributed electricity generation from renewables
- the possible costs of the power supply interruptions that could occur, by explicitly modelling the socio-economic impact of power supply interruptions on end-users.

Because these approaches take into account probabilities and consequences of different possible events rather than looking only at worst-cases or nominal assumptions, they are called *Probabilistic Reliability Management* approaches. While there is clearly a gap between the theory and practice of probabilistic reliability management, TSOs already collect failure data for primary network components, which is a necessary step to gradually implement probabilistic reliability management in short-term operation as well as in long-term planning. Socio-economic impact assessment, another basis of probabilistic reliability management, is also already used to some extent in the contexts of system development and asset management, but almost absent in the context of system operation.

Furthermore, the existing ENTSO-E network codes (NC) on operational security and System Operation Guidelines[2], the common ground for European TSOs to reliably operate their systems, are already partly in line with the main principles of probabilistic reliability management approach. The Operational Security NC mentions, for instance, that security of electricity supply is sought but not just at any cost. The network code states that "*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 also explicitly states that the TSO shall do its best effort to mitigate exceptional and out-of-range contingencies "*as far as reasonably practical and economically efficient*". Finally, it also points to "*the principle of optimization between the highest overall efficiency and lowest total cost for all involved parties*". The System Operation Guidelines cover key notions related to probabilistic risk management:

- Probabilistic contingency list: *"Classify each contingency on the basis of whether it is ordinary, exceptional or out-of-range, taking into account the probability of occurrence"*

- Long-term scenarios identification: "*When developing the common list of scenarios, TSOs shall take into account*:
    - *the probability of occurrence of the scenarios*
    - *the potential deviations from operational security limits for each scenario"*

- Finally, "*common risk assessment should cover:*
    - *consistency in the definition of exceptional contingencies*
    - *the evaluation of the probability and impact of exceptional contingencies*

[2] Establishing a guideline on electricity transmission system operation. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/SystemOperationGuideline%20final%28provisional%290405 2016.pdf

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- *and the consideration of exceptional contingencies in a TSO’s contingency list when their probability exceeds a common threshold”*.

Several elements already exist both in terms of data as well as parts of regulation as a basis to a gradual transition towards Probabilistic Reliability Management.

However, the implementation of probabilistic methods in real operational conditions is, still, a considerable challenge. The advantages and disadvantages deserve careful consideration and have to be identified and demonstrated in near to real-life conditions so the different stakeholders (System Operators, Regulators, and Policy makers in charge of ensuring the security of supply) will trust these methods.

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3 PROBABILISTIC RELIABILITY MANAGEMENT IS THE FUTURE

New probabilistic reliability standards could provide multiple benefits, such as a more efficient grid use, an increased reliance on wind or other variable generation, less capacity given to the reserves and more capacity for power transmission, and finally, more transmission capacity given to the market.

Yet, probabilistic methods are still perceived as laborious and complex, and as taking too much time to use. To model the consequences of a contingency is seen as challenging. In addition, there may not be sufficient and reliable statistical or other data available for evaluation, and finally, there is reluctance to change and little practical experience to point to.

In this context, the lack of trust in probabilistic reliability management must be overcome by establishing a common framework for these methods, and by demonstrating the benefits of such new approaches to support TSOs in their daily operation activities. GARPUR has worked intensively to satisfy these needs.

3.1 GARPUR, a European Project to improve reliability management

Seven TSOs (from Belgium, Bulgaria, Czech Republic, Denmark, France, Iceland, and Norway), together with twelve RTD performers and one innovation management expert, worked within the 4-year **GARPUR research project** to design, develop, assess, and evaluate new reliability management approaches to be gradually implemented at the pan-European level over the next decades.

Established in 2013 under the European Commission's 7th Framework Program, GARPUR developed a comprehensive probabilistic reliability management framework, and demonstrated its technical feasibility and practical interest to support TSOs in their reliability management activities over all relevant time scales and system areas. This framework targets optimized socio-economic benefits while maintaining the 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 for implementing new reliability management principles for the pan-European electric power system. This framework is designed to be deployable in a consistent way in the different decision-making contexts under the responsibility of TSOs: long-term system development, asset maintenance and replacement planning, mid-term and short-term operational planning, and real-time operation.

In order to adopt these new methods, convincing arguments need to be put forward in terms of how the new methods would indeed improve current practices. The approach of the project has been as follows:

1. A methodology is proposed that allows one to compare 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 uncovers the differences in costs and benefits of the different stakeholders (market participants, power producers, end-users, etc.), and how they are distributed geographically 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, so as to compute the socio-economic indicators over a set of conditions, in order to allow one to carry out 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.

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The results obtained in the GARPUR project are supported by a number of scientific publications, technical reports, and pilot test and extensive interaction with external stakeholders ensuring the soundness and practical interest of GARPUR outcomes as well as their adaptability to the particular situation of different TSOs and regulatory situations.

The following diagram summarizes the overall working approach of the GARPUR project.

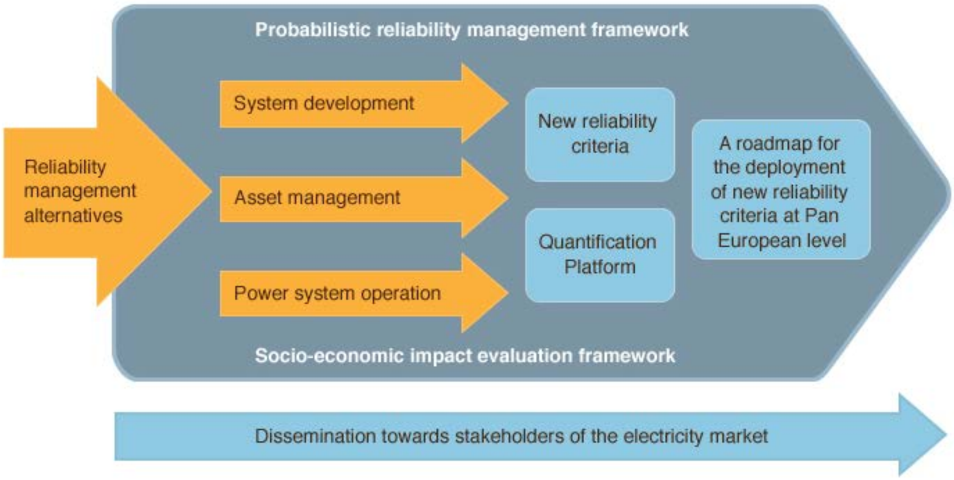

Figure 1: Overall working approach of the Garpur Project.

The GARPUR roadmap presented in the last chapter of this report shows the different steps to unlock the full benefits of probabilistic reliability management within the coming years. The timeframe is dependent on how well the regulation is adapted to the more advanced reliability approach proposed by GARPUR, and how fast system operators can collect the necessary data and implement the respective tools.

3.2 Benefits of moving towards probabilistic reliability management

Due to its transparency and simplicity to be monitored and implemented, the N-1 reliability approach has thus far provided a satisfactory level of security of supply. Nevertheless, this approach presents several shortcomings which limit its benefits in a world with more intermittent generation, ageing assets, and an increased trans-European power exchange.

Within the GARPUR framework, several pilot tests and studies were performed to validate the methodology developed and to understand and quantify the practical benefits of moving gradually towards probabilistic reliability management. They all showed substantial potential for better decision-making and an optimal balance of the costs with security of supply.

A first pilot test was conducted at the control centre of the Icelandic TSO **LANDSNET**. This test concerned the implementation of probabilistic reliability assessment in the context of **real-time operation of the Icelandic system**. In this study, detailed models have been 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 operators in the control room. Based on this test, the probabilistic approach provided useful information, complementary to the result of classical N-1 security assessment, and well in line with operators' experience and intuitions. **This pilot test demonstrated that fostering the development of real-time probabilistic reliability control tools and probabilistic look-ahead mode reliability assessment tools are of value for the Icelandic TSO.**

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Another pilot test concerned the use of a simulation platform developed within the project called the GARPUR Quantification Platform prototype (GQP) in order to compare the probabilistic RMAC and the N-1 criterion. This test was performed by **RTE 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 was 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. **The results showed that the RMAC helps to find a good compromise between preventive and corrective remedial actions with significantly lower global cost.**

A pilot test was also carried out at the planning department of **ELIA, the Belgian TSO**. It concerned an actual **system development study focusing on the year 2030 and on a part of the Belgian transmission system close to the French border**. During this pilot test, GARPUR tools for such long-term studies were first implemented on the Belgian system and used to study a range of conditions representative to identify the main reliability problems to be expected for 2030**. The study showed that the probabilistic approach is applicable in the context of a real system development study**. The results also revealed a need for the development and use of industrial grade probabilistic planning tools in the context of system development. In particular, the need to correctly model outage management and system operation through suitable and computationally efficient proxies[3] was stressed as an important topic in terms of practical acceptability.

STATNETT conducted a study of **system development in Norway**, which included an actual study of two alternatives for expanding 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 it, 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 increase of investment costs significantly outweighs the reduction of the expected interruption cost. **The study shows that large socio-economic savings of about 25% can be achieved, mainly through 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.

A further study on the Nordic system was carried out by **SINTEF**, and used the probabilistic methodology and tools developed in recent years at SINTEF for the purpose of reliability assessment in the context of **long-term planning studies**. This analysis assessed the impact of the amount of transmission capacities given to the market both on the market costs and on the interruption costs. It demonstrated the application of a comprehensive methodology for probabilistic reliability assessment integrated with market analysis for a real case. **The study shows how different aspects can be taken into account, including time dependencies and correlations, utilizing available failure data and interruption cost data, as well as 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.

3.3 The GARPUR vision for the future of reliability management

Altogether, the Reliability Management Approach and Criterion, the Socio-economic Impact Assessment framework, and the Garpur Quantification Platform prototype developed in the GARPUR project, as well as the demonstration of the methodologies and tools in close to real-life pilot test and studies, led to definition

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

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of 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 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 potential new players should also be fostered to possibly align methodologies, data and models.

3.4 Challenges to achieve GARPUR’s vision

Migration towards the systematic use of the developed probabilistic reliability management approaches can only happen in a gradual fashion. To enable and sustain this migration, significant investments and a change of mind-set along several complementary evolution paths are also required. Furthermore, several challenges have to be gradually tackled to make the desired transition a reality and to achieve the full benefits of probabilistic reliability management. The key challenges are mentioned here below.

A regulatory framework not fitted to probabilistic reliability management: The current regulatory framework organising and incentivising the power sector is based on the application of the N-1 criterion. Incentives, remunerations, roles, and responsibilities are defined to ultimately ensure the power system is N-1 secured. Implementing probabilistic reliability management in such a regulatory context would lead to undesired distributional effects of the risk between the areas in a country and in Europe, and between its actors without properly incentivising or remunerating them.

Lack of necessary data and information gathering and sharing: The lack of available data for probabilistic analysis, or their inaccuracy, would lead to interpretation bias of the analysis results. For instance, the absence of statistically relevant reliability data, i.e. failure data, outage times, and cost of power interruptions is clearly a barrier for the implementation of the probabilistic reliability management approach. Finally, the current data and models exchange between actors, and among them in particular TSOs, is not sufficient to ensure practical implementation of probabilistic reliability management.

Lack of tools and competence in the industry: While the theory is beginning to be extensive on probabilistic methods, few methods are implemented in TSO’s practices and in tools and software. A necessary trade-off between practicality and theory has still to be found. Experts responsible for reliability management are neither currently tooled nor trained to be able to understand, criticize, trust, and eventually adopt the new methods and tools. The required computation speed of industrial tools could be an issue, but should be seen as a minor barrier that can be solved with the right algorithms and powerful hardware.

Lack of risk-based mind-set and trust in probabilistic reliability management: A transition towards reliability management based on probabilities and expected consequences requires a change in the mind-set of all main actors in the power sector, and especially in TSOs. System operation has to be based on the balance of costs to provide security of electricity supply on the one hand, and the socio-economic costs of power supply interruptions on the other. This is a large cultural change for TSOs that focus almost solely on achieving high security of supply with whatever measures and costs it takes.

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4 A TENTATIVE TRANSITION ROADMAP TO EVOLVE TOWARDS PROBABILISTIC RELIABILITY MANAGEMENT

Thanks to the work performed over four years by the GARPUR consortium, encompassing the development of methodologies and their testing, as well as interaction with external stakeholders, a roadmap has been developed to reach GARPUR's vision of reliability management.

In order to bridge the gap between knowledge gained by the project and current TSO practices, the GARPUR consortium proposes to make the developed probabilistic reliability management approaches and criteria widely available for further testing and development. To convince more people in the TSOs and other stakeholders of the applicability and benefits of the approach, a main focus has to be on further testing in parallel to the existing N-1 approach.

In addition, it is of paramount importance that the national and historical TSO contexts are considered for further implementation. Different countries and TSOs will possibly prefer different path-ways to gradually implement the GARPUR probabilistic reliability management approaches and criteria depending on the best way to overcome their respective internal challenges and barriers.

The GARPUR consortium recommends that further experience sharing between TSOs (and among the different departments of TSOs responsible for system development, asset management, and system operation) in close cooperation with ENTSO-E should be fostered 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 level and if necessary be coordinated to ensure the swiftest possible progress.

In order to move towards a fully consistent and effective probabilistic reliability management approach, several specific further actions need to be taken in the next decade. Depending on their nature, these recommended actions have been classified in different clusters

- **Regulation and socio-economic considerations**: Actions that are related to the need to change the regulation and to properly anticipate the socio-economic impact of moving towards a probabilistic reliability management approach.

- **Data and models of uncertainties**: Actions that are related to the enhancement of the availability and quality of data and the probabilistic models of uncertainties required by the methods for reliability management and socio-economic impact assessment.

- **Methodologies, algorithms and software**: Actions related to the development of industrial grade implementations of software tools for the probabilistic reliability management approach.

- **Testing and implementation at the operational level**: Actions related to the testing, the implementation and the sharing of knowledge of probabilistic reliability management methods and algorithms that should be initiated by TSOs.

All these actions will require a strong coordination among the different actors of the reliability management decision-chain: regulators, TSOs, research organizations, software developers, and European organizations as ENTSO-E and ACER. Furthermore, the actions have to be taken progressively to ensure a smooth evolution

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towards the adoption of probabilistic reliability management in Europe. A tentative roadmap towards this adoption, the ultimate result of the GARPUR project, is shown in Figure 2, and explained in the rest of this chapter.

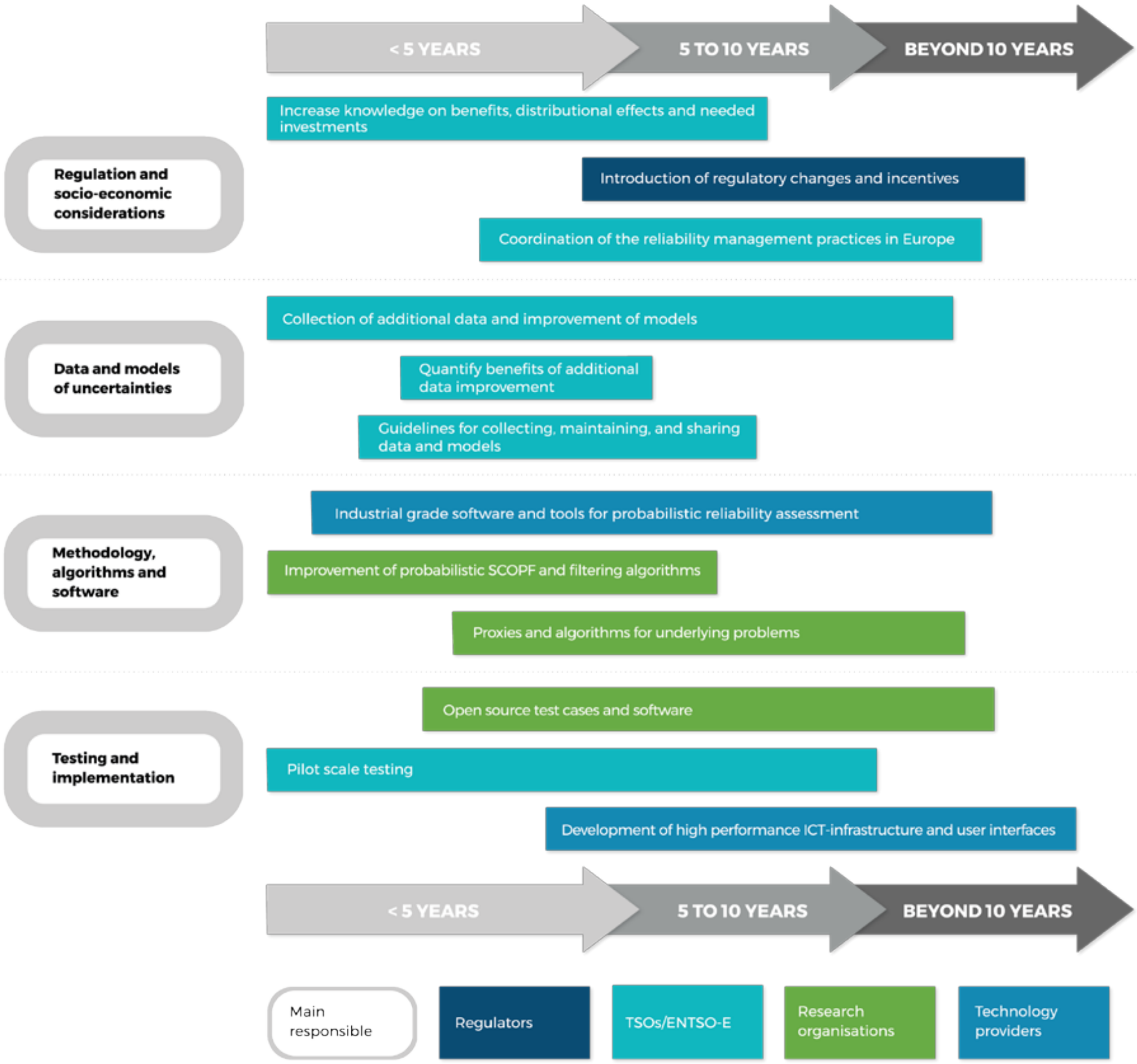

Figure 2: A tentative roadmap towards probabilistic reliability management

The different lines of action displayed in Figure 2 cover a timespan of more than a decade. From a technological point of view, the timeline is realistic, and it also leaves enough flexibility to comply with specific national situations related to the challenges encountered and how quickly the local regulatory rules can be adapted to the more advanced and probabilistic reliability approach proposed by GARPUR, and how fast the concerned TSOs can practically react to implement the respective actions.

Thus, this roadmap can serve as a template for the different stakeholders to determine which lines of actions they should focus on to remain in accordance with the overall advancement of reliability management approaches in the other European countries, and to communicate their plans with their neighbour TSOs and countries.

In the next subsections, we provide further explanations of these different lines of actions displayed in Figure 2.

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4.1 Actions related to regulation and socio-economic considerations

Several main actions must be performed to ensure the regulatory framework is suited for probabilistic reliability management based on socio-economic principles:

- Increase knowledge on benefits, distributional effects, and needed investments
- Introduction of regulatory changes and incentives
- Coordinated level of reliability in Europe

Increase knowledge of benefits, distributional effects, and necessary investments

A better understanding of the benefits and the socio-economic consequences of the probabilistic reliability management approach is needed. This is especially important for sound decisions on future regulations. A main focus should be on the socio-economic benefits, their expected distribution between end-user groups, regions and countries, and the investments necessary to implement the approach. To avoid unwanted consequences or a reluctant a priori perception of the consequences of moving towards probabilistic reliability management, these effects must be well understood upfront. For example, the possible ways to take into account and mitigate the distributional effects by suitable changes in networks tariffs have to be analysed. The understanding of necessary investments for implementation together with the benefits will help prioritize the steps towards probabilistic reliability approach. All these analyses need the support of regulators and Research Institutions to explicitly model the effects and are of main interest to TSOs.

Introduction of regulatory changes and incentives

A next step is the actual introduction of the necessary regulatory changes to clearly specify the new reliability targets and socio-economic evaluation criteria for use by the TSOs. The remuneration mechanisms of TSOs should also be adapted to incentivize the most efficient implementation of the new approach. For this decision-making, the regulators need information based on comparative results of the socio-economic benefits of changes in the reliability criteria.

The regulators determine the choice of policies for reliability management and the regulation of the TSOs. Change in regulations towards probabilistic reliability management should, however, be a matter of discussion between all involved parties, namely TSOs, ENTSO-E, the EC and the regulators. Both EU wide and national scales are recommended to be worked out in parallel to contribute to the evolution of reliability management.

Coordination of the reliability management practices in Europe

A further action should be to reach coordinated reliability management practices throughout Europe. This includes to agree on common principles of reliability management and reliability targets that have a cross border impact. This does not imply an equal level of security of supply for all end users. In the context of interconnected systems, neighbouring TSOs' risk attitude and therewith definition of what an acceptable reliability target is, has an impact on the level of security of supply in both the individual and in the neighbouring TSOs control areas. However, the probabilistic approach should allow one to better assess and document the levels of reliability of supply, and may thus provide guidance in order to coordinate and harmonize the reliability management practices of different TSOs.

Such information exchange already exists in the long-term horizon for the development of the ENTSO-E Ten Year Network Development Plan. In the asset management plan, such information is also exchanged within the workgroup "Annual Maintenance Schedule". A possible way to proceed further towards that topic of

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reliability management in a multi-TSO setting would be to upgrade the existing principles for data exchange between TSOs. 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 Winter package – the draft Risk preparedness regulation refers to regional cooperation in relation to security of supply. The implementation of this recommendation should therefore, in addition to the responsibility of the individual TSOs, lie also in the hand of ENTSO-E.

4.2 Actions related to data and models of uncertainty

Data availability is a major prerequisite for the use of the probabilistic reliability management approach. Several main actions are needed to improve gathering, to exploit and to share data, and to quantify the benefits of additional improvement in data acquisition after the most important key data are in place:

- Collection of additional data and improvement of models
- Quantify the benefits of additional data improvement
- Guidelines for collecting, maintaining, and sharing data and models

Collection of additional data and improvement of models

It is necessary to collect a wide range of data for the probabilistic reliability approach. Related models must also be improved to analyse these data. 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 used generally by the deterministic N-1 based reliability management approaches in place.

The following additional data are absolutely necessary to begin implementation of probabilistic reliability management:

- Failure data to estimate the probability of contingencies
- Restoration rates and outage times of contingencies to estimate the consequences
- Interruption cost data to estimate the expected socio-economic costs of the consequences in terms of power supply interruptions

In addition, GARPUR identified the most important data and model gaps that need to be gradually filled. These are related to the evaluation of power supply interruption costs, to models for the degradation of and the maintenance impact on components, to failure rate models that consider both weather and technical condition, and to models of corrective control failures. Implementation within the next five years should be the goal for getting in place the key data and main models. TSOs should perform this task with the support of Research Institutions.

A good practice to quantify the ***interruption costs*** is an absolute necessity for the probabilistic approach, since otherwise the probabilistic approach cannot be used. Both practices and available data on Value of Lost Load (VOLL) are of varying quality in Europe, dependent on the country. The process to improve the investigation of interruption costs should be based on accepted guidelines for cost estimation studies, such as enhanced CEER guidelines of good practice[4]. The winter package[5] already obligates member states to

[4] 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
[5] COM(2016) 861

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estimate at least a single VOLL for their territory. Regulators and TSOs, with the support of Research Institutions, are the main targeted stakeholders to improve the quantification of the interruption costs.

State-of-the-art in models to predict the ***degradation processes of the assets*** over long time periods, and to predict the beneficial impact on health-condition of maintenance activities, are still in a stage of infancy. Such models are, however, required to objectively conduct a cost-benefit analysis of different maintenance and replacement policies on the future reliability level of the power system. Given the scarcity of the 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. Due to the challenges described above, a successful implementation should not be expected any earlier than 5 years from now.

The exploitation of the gradually collected datasets for the development and validation of enhanced ***component failure rate models*** is an important step. Suitable models must be proposed and validated for the failure rate of power system components, which simultaneously take into account the instantaneous external conditions (primarily weather), the health condition, and current operating condition of the assets. 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 histories. The recommendation is important for these three TSO contexts: system development, asset 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.

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 at the disposal of TSOs. 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 gradually filling in the missing data and models. The first one concerns relying on the current knowledge and expertise of the control room operators. The second possibility relates to inspecting the status of corrective control resources. The collection of these data should be based on the results of the recommended cost-benefit analysis of the value of more data.

Quantify the benefits of additional data improvement

For optimal use of the probabilistic reliability management approach and criteria, processes must be put in place to ensure continuous improvement of data quality, which may include 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. Such analyses could 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. This requires that the most important effects are also modelled in the tool.

Showing 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.

TSOs, with the support of Research Institutions, are the main targeted stakeholders to perform these cost-benefit analyses.

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Guidelines for collecting, maintaining, and sharing data and models

The quality of data and of the inferred models is paramount if the probabilistic reliability management is to successfully improve the actual trade-off between costs of providing security of supply and socio-economic costs of power supply interruptions. Therefore, it is necessary to put in place common guidelines to consistently ensure the collection of data and maintain the databases and the inferred models.

In addition to the individual TSO's use of the data and models pertaining to their subsystem, there is a strong need to share data and models among TSOs in general. Indeed, on the one hand, each TSO must be aware of the reliability status and the socio-economic characteristics of its neighbour systems, and on the other hand, data and model sharing is necessary to ensure that the best practices are used all over the European interconnection. Where observational datasets directly collected by the individual TSOs are too scarce to build accurate enough predictive models, data sharing is urgently needed to improve models of rare events or novel devices.

ENTSO-E should be given the mission to harmonize data collection procedures and model-building approaches needed for probabilistic reliability management, and to define the guidelines for sharing these models and/or raw data among the European TSOs. This recommendation should be applied within the next 5 to 10 years.

4.3 Actions regarding methodology, algorithms and software

When applying the probabilistic reliability management approach, the resulting stochastic simulation and optimization problems are computationally significantly more complex compared to the one used for N-1 based reliability management. Even though GARPUR has developed several methods and prototypes of algorithms for the implementation in large-scale powers systems, it is still necessary to develop a new generation of software tools, methods and algorithms. The next main steps for development are:

- Industrial grade software and tools for probabilistic reliability assessment
- Improvement of probabilistic SCOPF and filtering algorithms
- Proxies and algorithms for underlying problems

Industrial grade software and tools for probabilistic reliability assessment

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

A next generation of reliability assessment and reliability control tools need to be developed that achieve the necessary robustness, efficiency, and availability to support a large community of both industry and academics for the gradual implementation of probabilistic reliability management approaches. These tools must incorporate novel techniques based on recent progress in artificial intelligence, optimization, and statistics, together with suitable physical models in line with the growing complexity of the power system. The knowhow developed within the GARPUR project could serve 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 in order to either enhance existing industrial-grade 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 carry out 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 costs and benefits of all stakeholders. A prototype tool for such off-line studies, called the GARPUR quantification platform, has been developed during the project and used in the context of a pilot test on a real system. 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. The test has also highlighted the fact that further development is needed to allow research centres to perform such analyses with professional tools.

Improvement of probabilistic SCOPF and filtering algorithms

Probabilistic reliability management is a multi-stage decision-making problem under uncertainty, with a probabilistic ***Security Constrained Optimal Power Flow*** (SCOPF) at its core. While the scientific literature on algorithmic approximations to this problem keeps growing, it is necessary to align such research on developing solutions that fit the needs of the tools to be developed. One example is the simulation of system response to contingencies, which is important in order 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, whereas discrete preventive or corrective actions, in particular a change of topology, are rarely captured in existing SCOPF tools. 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. 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 step is directly relevant for real-time and short-term application and also relevant in the form of proxies for the longer-term horizons. Research Institutions with the support of TSOs should drive that task. This task could also be included within future European initiatives.

In probabilistic reliability management, a wide variety of possible operational scenarios need to be considered in order to support decisions. In practice however, it is not feasible to cover all possible scenarios. There is a need to further develop algorithms for the ***automatic selection of subsets of representative scenarios,*** in manageable number while best covering the critical situations. Such methods could be used both for a reduction of the number of computations to be performed and to facilitate interpretation of the simulation results by field experts. The trigger for such developments should come from TSOs while other players, such as research institutes, universities, and industry should take care of the development in close cooperation with TSOs.

Proxies and algorithms for underlying problems

The decision-making process for long-term problems as system development, for example, has to deal with underlying time-horizons and their decisions. This multi-stage decision process has to be modelled with a method of optimum accuracy while keeping an acceptable level of computational complexity. Therefore, GARPUR introduced the notion of proxies for these underlying decision problems. Given its high potential value in reducing the complexity of the corresponding computational problems, the research community

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should further investigate the use of state-of-the-art machine learning methods and algorithms to construct proxies for use in the context of reliability assessment and control. We recommend that academic work on the proxies continue for the short-term decision-making processes. We also recommend to find a sufficiently trustworthy preliminary implementation for the methods that can later be improved upon.

Other areas of improvement are algorithms for day-ahead and week-ahead operational planning. Without such algorithms, optimal decisions cannot be taken in these planning contexts when implementing a probabilistic reliability management. In addition, for long-term studies for grid development and maintenance policy assessment, it is important to explicitly model the fact that the grid must be robust enough to allow the scheduling of component outages needed to carry out scheduled maintenance or replacement activities. All this work should be performed by Research Institutions, with the collaboration and support of TSOs, to ensure meaningful validation and knowledge transfer. RSCs could also be interested in testing such prototype proxies.

4.4 Actions regarding testing and gradual implementation

The approaches, methods, algorithms, and tools for probabilistic reliability management have to be gradually implemented in the operational processes of the TSOs. Prior to implementation, several steps are needed to both prove the benefits and to build confidence:

- Open source test cases and software
- Pilot scale testing
- Development of high performance ICT-infrastructure and user interfaces

Open source test cases and software

The first stage of R&D for probabilistic methods is mainly driven by academic research. It is necessary to proceed in testing on realistic test cases and on the important role of disseminating R&D throughout the community for 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 new method's benefits. 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. In parallel, TSOs should 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.

Pilot scale testing

Pilot scale testing activities provide initial insights into how the probabilistic reliability management approach works in specific use-cases. Such pilot tests have high value for identifying the benefits of a probabilistic approach, but also the challenge of implementation. Ultimately, pilot tests performed with real TSO data are necessary to convince other TSOs and stakeholders of the benefits of probabilistic reliability management. The first practical step for a TSO to take is to calculate the probabilities and risks of the N-1 faults that they are already assessing. This brings into light which data and models are required to develop the probabilistic approaches further and an increased understanding of grid reliability and it's variations over time. In addition, more pilot tests in TSOs have to be started to gain experience beyond the 'theoretical' studies that can be carried out with academic benchmarks and to bring the TSO experts into the validation loop. To convince

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TSOs of the benefits of the new approach, a parallel testing is considered between existing TSO methods and the new methodology.

Development of high performance ICT-infrastructures and user interfaces

The use of practical tools for the probabilistic reliability management relies on the use of massive computing architectures in order to accelerate computations. Therefore, it is recommended to elaborate the needs for the development of an ICT-infrastructure for probabilistic analyses. This includes the necessity to provide data analytics and visualization methods and tools to assist the experts in their decision-making. This task has to be performed in cooperation between TSOs and the industry. In addition, it might be necessary to 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.

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