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Summary

In this project we propose and validate effective forecasting and optimal control algorithms to ensure efficient and secure operation of low voltage distribution grids, as well as flexibility provision from distribution grids toward upstream grids, under uncertainties. To this end, a two-levels rolling optimization framework to ensure optimal and secure operation of distribution grids under uncertainties is developed and experimentally validated in a reconfigurable low voltage distribution grid facility in Yverdon-les-Bains, Switzerland. The first level deals with prescheduling (e.g., day-ahead) of controllable resources in a time ahead basis using a novel distributionally robust programming method, whereas the second level deals with near-real time online scheduling of all the controllable resources. A techno-economic study has been performed to consider both the local and export ancillary services in the proposed optimization framework. Moreover, an appropriate forecasting system is developed to provide day-ahead and near real-time forecast of uncertain parameters, in accordance with the optimization framework to obtain accurate real-time forecasting of PV generation and load (electric vehicle load) focused on both deterministic and probabilistic approaches.

Résumé

L'objectif de ce projet de recherche est de proposer et valider des algorithmes performants de prédiction et de contrôle optimale pour assurer un fonctionnement efficace et sécurisé des réseaux de distribution, ainsi que la flexibilité fournie par des réseaux de distribution vers le réseau moyenne/haute tension, tout en tenant compte des incertitudes. À cet égard, un outil d'optimisation en continue à deux niveaux pour assurer un fonctionnement optimal (le plus économique) et sécurisé des réseaux de distribution tout en tenant compte des incertitudes est développé et validé expérimentalement dans une reseux de distribution reconfigurable à Yverdon-les-Bains, en suisse. Le premier niveau (pre-scheduling optimisation) traite de la pré-planification des ressources contrôlables de manière anticipée (jour à l'avance ou quelques heures à l'avance) basé sur une nouvelle méthode de « distributionally robust programming », tandis que le second niveau (optimisation en ligne) traite de la planification en temps réel de toutes les ressources contrôlables. Une étude technico-économique a été réalisée pour prendre en compte les services auxiliaires locaux et d'exportation dans le cadre d'optimisation proposé. De plus, un système de prédiction est mis au point pour fournir une prédiction au jour avant et en temps quasi réel de paramètres incertains, conformément au modèle d'optimisation pour obtenir des prévisions précises en temps réel de la production photovoltaïque et la charge (y compris charge des véhicules électriques), en se concentrant sur des approches déterministes et probabilistes.

Zusammenfassung

In diesem Projekt schlagen wir effektive Vorhersage- und optimale Steuerungsalgorithmen vor und validieren sie, um einen effizienten und sicheren Betrieb von Niederspannungsverteilnetzen sowie die Bereitstellung von Flexibilität von Verteilnetzen für vorgelagerte Netze unter Berücksichtigung von Unsicherheiten zu gewährleisten. Zu diesem Zweck wird ein zweistufiges, rollierendes Optimierungskonzept entwickelt, das den optimalen und sicheren Betrieb von Verteilnetzen unter Unsicherheit gewährleistet und in einer rekonfigurierbaren Niederspannungsnetzanlage in Yverdon-les-Bains, Schweiz, experimentell validiert wird. Die erste Ebene befasst sich mit der Vorausplanung (z.B. Day-Ahead) der steuerbaren Ressourcen auf Basis einer neuartigen verteilungsrobusten Programmiermethode, während die zweite Ebene die Online-Planung aller steuerbaren Ressourcen nahezu in Echtzeit behandelt. Es wurde eine technisch-ökonomische Studie durchgeführt, um sowohl die lokalen als auch die exportierten Systemdienstleistungen in dem vorgeschlagenen

Optimierungsrahmen zu berücksichtigen. Darüber hinaus wurde ein geeignetes Prognosesystem entwickelt, das in Übereinstimmung mit dem Optimierungsrahmen eine Day-Ahead- und Quasi-Echtzeit-Prognose von mit Unsicherheit behafteten Parametern ermöglicht, um eine genaue Echtzeitprognose der PV-Erzeugung und der Last (Last von Elektrofahrzeugen) zu erhalten, wobei sowohl deterministische als auch probabilistische Ansätze berücksichtigt wurden.

Contents

1 Introduction

1.1 Context and key questions

In the context of energy transition, emerging local power distribution grids are characterized by; a) high penetration of intermittent and variable distributed generation from Renewable Energy Sources (RES), b) active consumers and flexible consumption, and c) interconnection to the local communication and transportation systems. These impose the following challenges to optimal operation and control of distribution grids:

1. High stresses on the low-voltage distribution grids regarding bi-directional power flow that must be addressed, from both static and dynamic aspects;
2. High level of uncertainties concerning the difficulties in the forecast and control of the power generation (caused by the stochastic nature of RES) as well as uncertainties in power consumption (e.g., caused by the stochastic profile of electric vehicle charging).

To address these challenges, it is necessary to improve the observability (by employing the measurement devices and local data acquisition systems), and the controllability (by employing the controllable resources, such as battery energy storage systems) in distribution grids. Moreover, efficient forecasting and optimal control methods are required to ensure that controllable resources are used in the most efficient way with respect to the state of the grid. Note that the involved models/algorithms must be capable of;

1. Analyzing the huge amount of data coming from measurement devices and data acquisition systems, and
2. Creating the control signals (for controllable resources) in very short time-steps, near real-time operation of the system.

This potential capability of low-voltage distribution grids for controlling distributed flexible resources, makes them a suitable choice for provision of flexibility (i.e., ancillary services) to the upstream medium and high voltage grids [1].

In this respect, the main questions that this project will address are:

1. How the flexible resources within a distribution grids should be controlled to ensure secure operation of the grid in real-time?
2. What are the impacts of uncertainties associated with the local generations and demands?
3. What are the potential flexibilities and ancillary services that distribution grids could provide to the upstream transmission grids?
4. What are the technical constraints for utilizing the potential flexibilities in distribution grids?
5. What is the optimal strategy/schedule for controlling the flexible resources within a low-voltage distribution grids?
6. What is the efficient way to handle uncertainties in the development of the optimization problem for optimal scheduling of flexible resources in low-voltage distribution grids?

1.2 Objectives

The first objective of this research project is to develop effective forecasting and optimal control methods to ensure efficient and secure operation of distribution grids, as well as flexibility (i.e., ancillary service) provision from local low-voltage distribution grids to the upstream medium- and high-voltage grids, under uncertainties. The source of uncertainties varies from stochastic distributed power generation (e.g., solar and wind power generation) and demand uncertainties to system model uncertainties (e.g., uncertain parameters of overhead lines and cables). Secure operation deals with satisfaction of technical constraints of distribution grids such as nodal voltage limits, power flow limits of lines/cables, and technical constraints of grid connected resources such as distributed generation and battery storage capacity limits. Efficient and optimal operation deals with both of the technical and economic objectives of local distribution operators such as minimization of voltage deviations and line's losses, maximization of ancillary service provision to upstream medium- and high-voltage grids, and minimization of real-time imbalances with respect to predefined schedules.

The second objective of the project is to implement the above forecasting and optimal control methods in a test case low-voltage distribution grid, and demonstrate the effectiveness of the developed methods for different grid operation scenarios.

1.3 Methods

A techno-economic study has been performed to consider both the local and export ancillary services in the proposed optimization framework. Essentially, the value of those services that allow to avoid network reinforcements are valuated considering the costs of said reinforcements while other services are valuated using a comparison with existing products and their historical development. This study has benefited from a set of interviews with DSOs that helped to steer the services' selection, but also to gather data that is used in the case studies.

The forecasting system is composed of a set of day-ahead forecasting methods as well as a set of near-real time forecasting tools. With reference to the day-ahead forecast, the project resulted in

- The development of a day-ahead probabilistic wind power forecasting based on ranking and combining Numeric Weather Predictions (NWPs);
- The development of a Bayesian bootstrap quantile regression model for probabilistic photovoltaic power forecasting;
- The development of a multivariate approach for probabilistic industrial load forecasting.

With reference to the near-real-time forecast, the development of methods and models able to obtain accurate real-time forecasting of PV generation and load (electric vehicle load) focused on both deterministic and probabilistic approaches. As deterministic approach, two persistence-based methods were proposed. The identification of the best combination type for these underlying models in ensemble approach is also explored. Finally, a comparison with the relevant state-of-the-art benchmarks is carried out. More specifically, the models proposed in the research activity are the:

- derivative-persistence method for real-time photovoltaic power forecasting;
- Caputo-derivative method for real-time photovoltaic power forecasting;
- Bayesian bootstrapping in real-time probabilistic photovoltaic power forecasting;
- hierarchical probabilistic electric vehicle load forecasting.

With reference to the optimization system, to handle the aforementioned uncertain parameters, the pre-scheduling optimization problem is formulated based on a classical stochastic programming approach and a novel distributionally robust programming approach.

This novel approach, unlike robust programming, does not find the worst-case scenario in the objective function. Each scenario of forecast is considered as the sum of the expected forecast and the deviation error around that expected value. The advantages of using distributionally robust programming instead of stochastic programming for pre-scheduling problems are as follows:

The distributionally robust programming is written for the main forecasted scenario, and it needs less computational burden compared to the stochastic programming.

For generating the representative scenarios, which are used in stochastic programming, we need large historical data sets, which are not available most of the time in low-voltage distribution grids. Distributionally robust programming, on the other hand, does not require as much historical data because it only needs the boundaries of uncertain variables.

For LV distribution grids with many control/state variables, solving the stochastic programming with a high number of scenarios is not achievable.

Finally, we validate the proposed methodology and demonstrate its effectiveness under realistic uncertainty sources (e.g., Photovoltaic power generation), for a low voltage distribution grid. In this respect, a live demonstrator is built in the reconfigurable distribution grid laboratory (ReIne) in HEIG-VD, Yverdon-les-Bains, Switzerland. In this grid demonstrator, the forecasting system and the optimization system are integrated within the existing monitoring of the grid and run in a unified platform to control a small test bench that represent the low-voltage grid in La Chappelle-sur-Moudon (Switzerland).

1.4 Final status of the project

The project has been officially started on September 1, 2019 and ended on June 30, 2022. This report presents a summary of the final results of the project and performed research activities. Both milestones of the project have been successfully achieved. To this end, the following deliverables which are annex to this report as separate documents are provided:

D1.1: Description of ancillary services provided within and from distribution grids.

D1.2: Relative costs and benefits of operational and scheduling options for distribution grids.

D2.1: Pre-scheduling forecasting systems and solution algorithms for distribution grids under uncertainties.

D2.2: On-line forecasting systems and solution algorithms for distribution grids under uncertainties for real-time control.

D2.3: Technical report including the validation of the forecasting systems using appropriate test bench and scenarios in a numerical environment.

D3.1: Pre-scheduling optimization model for distribution grids under uncertainties, and its solution algorithm.

D3.2: On-line optimization model for real-time control/scheduling of controllable resources in a distribution grid, and its solution algorithm.

D3.3: Technical report including the validation of the above optimization models using appropriate test bench and scenarios in a numerical environment.

D4.1: Validation case study and grid operation scenarios.

D4.2: Pre-validation report including results of the power grid simulation tool (Simscape Power Systems and PLECS).

D4.3: Validation report including experimental validation of forecasting algorithms.

D4.4: Validation report including experimental test results in the ReIne laboratory.

2 Project organization

This project is organized in four main technical work packages.

WP1: Definition of the ancillary services to be considered by the distribution system operator. These ancillary services will be formulated as relative cost coefficient terms, with respect to techno-economic considerations, in the objective function of the first-level optimization problem.

WP2: Development of appropriate day-ahead and real-time forecasting systems for renewable generation and loads.

WP3: Development of the rolling optimization framework including the formulation of the first-level (scheduling) and online optimization problems.

WP4: Implementation and validation of the proposed methods and algorithms of WP2 and WP3 in a low-voltage distribution grid (ReIne laboratory [2]), and demonstration of their effectiveness under different operational scenarios (test cases).

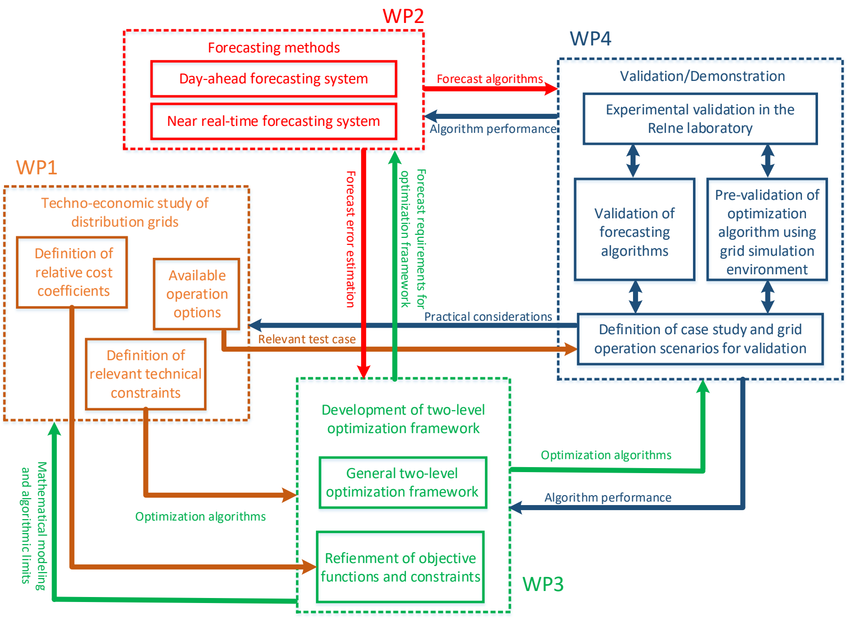


Figure 1 Schematic of the interaction between work packages

Figure 1, schematically shows the interaction between the work packages. WP3 is the theoretical core of the project, in which will first be developed a general two-level optimization framework, including prescheduling and real-time optimization models. This optimization model considers the characteristics of the uncertain parameters (e.g., PV production) that are quantified in WP2. Then, the optimization models (objective functions and technical constraints) based on the outcome of a techno-economic study performed in WP1 will be refined. Afterwards, the result of this techno-economic study of WP1 as well as the requirements of optimization models of WP3, will also be used to define the validation case studies and the grid operation scenarios for WP4. Finally, the developed optimization models according to the results of simulation and experimental tests performed in WP4 will be updated and refined.

The developed methodologies and activities related to the work packages are presented in the following section.

3 Activities and results

3.1 List of activities and organization of the report

Regarding the project planning, the main body of technical developments, as listed below, have been successfully performed in 2020 and 2021.

Task 1.1: Definition of services and degrees of freedom

- Define relevant ancillary services (current and future) for the optimization of the considered grid
- Define relevant ancillary services (current and future) for the provision of services to the upstream transmission grid
- Collect and describe other operational measures (other than ancillary services)
- Collect and describe other scheduling measures (other than ancillary services)

Task 1.2: Analysis and characterisation of available operational and scheduling options

- Description and isolated simulation of each considered option to respond to network constraints
- Comparison of the available options and formulation of relative costs
- Formulation of the relative value of services for the management network constraints

Task 2.1: Data collection, data pre-processing and exploratory data analysis

- Collect the time series of target variables and the time series of predictor variables
- Data pre-processing to eliminate outliers and bad data
- Exploratory data analysis in order to discard uninformative predictors.

Task 2.2: Development of day-ahead forecasting systems for renewable generation and loads

- Development of underlying multiple linear regression and random forests
- Identification of the best combination type for the underlying models in the ensemble approach
- Comparison with relevant state-of-the-art benchmarks

Task 2.3: Development of real-time forecasting systems for renewable generation and loads

- Development of underlying multiple linear regression and random forests
- Identification of the best combination type for the underlying models in the ensemble approach
- Comparison with relevant state-of-the-art benchmarks

Task 3.1: General formulation of the prescheduling optimization

- Setup of the electrical model of the grid
- Definition of the input data and the output optimization variables (state variables, decision variables)
- Definition of the criteria and the constraints
- Choice and setup of the appropriate mathematical formulation (objectives and constrains) complying with uncertainty, in accordance with outcomes of WP2.
- According to the mathematical formulation nature, choice of the solution approach
- Setup the interface with real-time optimization
- Development/Validation using appropriate test bench and scenarios in a numerical environment (e.g., MATLAB or General Algebraic Modelling System - GAMS)

Task 3.2: General formulation of the real-time optimization (on-line)

- Definition of the input data and the output optimization variables (state variables, decision variables)
- Definition of the criteria and the constraints
- Choice and setup of the appropriate mathematical formulation (objectives and constrains) complying with uncertainty and real-time requirements, in accordance with outcomes of WP2.
- According to the mathematical formulation nature, choice of the solution approach
- Development/Validation using appropriate test bench and scenarios in a numerical environment (MATLAB/Python)

Task 3.3: Revisiting and refinement of the optimization tools

- Update the hours ahead formulation according to WP1 and WP2 outcomes
- Update the real-time formulation according to WP1 and WP2 outcomes
- Development and validation of the revisited optimization tools in a numerical environment (e.g., MATLAB or General Algebraic Modelling System - GAMS)

Task 3.4: Definition of the optimization requirement and typical scenarios (i.e., case study and grid operation scenarios) for the validation in WP4

Task 4.1: Definition of case studies and related grid operation scenarios

- Setup of grid configurations and grid parameters to represent typical low voltage distribution grids in Switzerland according to WP1 outcome
- Setup of grid operation scenarios including generation/consumption uncertainties and grid component outages according to the outcomes of WP1, WP2, and WP3

Task 4.2: Pre-validation of optimization using grid simulation environment

- Implementation of pre-validation case studies, according to above setups of Task 4.1 in a time-domain power grid simulation environment
- Definition of success criteria of pre-validation (e.g., level of over/under of nodal voltages as well as over currents of lines)

Task 4.3: Experimental validation of forecasting algorithms developed in WP2

- Data acquisition, data pre-processing and exploratory data analysis
- Implementation of the forecasting systems by means of algorithms run in a statistical programming environment (e.g., MATLAB and R)
- Validation of the outcomes of forecasting algorithms with respect to the realizations of the target variables, in terms of appropriate forecasting errors

Task 4.4: Experimental validation in the ReIne laboratory

- Implementation of validation case studies in the ReIne laboratory
  - Validation of the link between the forecasting algorithms and the optimization algorithms
  - Validation of real-time online optimization regarding grid constraints and controllable source capabilities
  - Validation of link between prescheduling and online optimization regarding grid constraints, communication and computation requirements

The rest of this section is organized as follows: **Subsections 3.2 and 3.3** present a summary of the activities and results of the techno-economic studies in WP1 (Tasks 1.1 and 1.2). The full results are presented as deliverables D1.1 and D1.2, respectively.

D1.1 Description of ancillary services provided within and from distribution grids.

D1.2 Relative costs and benefits of operational and scheduling options for distribution grids

The deliverables D1.1 and D1.2 are annexed to this report as separate documents. They include all the technical details such as literature review, simulation process, interview with DSOs, mathematical formulations and numerical results.

Subsection 3.4 summarizes the activities for Task 2.1 included all the data collection and data pre-processing tasks that were necessary to create a large robust database of variables which could be exploited to develop forecasting systems for renewable generation and loads. **Subsections 3.5 and 3.6** present a summary of the activities and results of the development of forecasting systems in WP2 (Tasks 2.2 and 2.3). The full results are presented as deliverables D2.1, D2.2, and D2.3, respectively.

D2.1 Pre-scheduling (day-ahead) forecasting systems and solution algorithms for distribution grids under uncertainties.

D2.2 On-line (real-time) forecasting systems and solution algorithms for distribution grids under uncertainties for real-time control.

D2.3 Technical report including the validation of the forecasting systems using appropriate test bench and scenarios in a numerical environment.

The deliverable D2.1, D2.2, and D2.3 are annexed to this report as separate documents. They include all the technical details such as literature review, data pre-processing and exploratory analysis, mathematical formulations and specifications of different forecasting models, test bench, scenarios, and numerical results. The deliverables D2.1-D2.3 have been also reported to the Ministry of Education, University and Research (MUIR), Italy by the partners of the project (Università di Napoli Federico II and Università di Napoli Parthenope).

WP3 “Development of the rolling optimization framework including the formulation of the first-level (pre-scheduling) and on-line optimization problems” delivers the models of optimal control for provisioning flexibility and ancillary services from low-voltage distribution grids to the upstream grids under uncertainties. WP3 consists of four tasks:

- Task 3.1: general formulation of the pre-scheduling optimization,
- Task 3.2: general formulation of the on-line optimization,
- Task 3.3: revisiting and refinement of the optimization tools,
- Task 3.4: definition of the optimization requirement and typical scenarios (i.e., case study and grid operation scenarios) for the validation in WP4.

Subsection 3.7 briefly introduces the activities and results of WP3 regarding development of both pre-scheduling and real-time optimization models (Tasks 3.1 and 3.2). A novel distributionally robust programming approach is proposed for the pre-scheduling optimization problem. The pre-validation test results and details of proposed models are presented in deliverables D3.1-D3.3 documents annexed to this report.

D3.1: Pre-scheduling optimization model for distribution grids under uncertainties, and its solution algorithm.

D3.2: On-line optimization model for real-time control/scheduling of controllable resources in a distribution grid, and its solution algorithm.

D3.3: Technical report including the validation of the above optimization models using appropriate test bench and scenarios in a numerical environment.

WP4 “Implementation of the proposed methods and algorithms of WP2 and WP3 in a low voltage distribution grid (ReIne laboratory), and demonstration of their effectiveness under different operational scenarios” shows the performance of proposed methods and models in a real test case environment. WP4 consists of following four tasks:

- Task 4.1: Definition of case studies and related grid operation scenarios,
- Task 4.2: Pre-validation of optimization using grid simulation environment,
- Task 4.3: Experimental validation of forecasting algorithms developed in WP2,
- Task 4.4: Experimental validation in the ReIne laboratory.

The activities and results of WP4 are described briefly in **Subsection 3.8**. The results, structure of test, and gained experiences are explained. The details of tests and results are presented in deliverables

D4.1-D4.4 documents annexed to this report.

D4.1: Validation case study and grid operation scenarios.

D4.2: Pre-validation report including results of the power grid simulation tool (Simscape Power Systems and PLECS).

D4.3: Validation report including experimental validation of forecasting algorithms.

D4.4: Validation report including experimental test results in the ReIne laboratory.

3.2 Description of ancillary services provided within and from distribution grids

This is the initial deliverable for the DiGriFlex project, aiming to “develop effective forecasting and optimal control methods to ensure efficient and secure operation of distribution grids”. WP1 is focussed on (i) defining services and degrees of freedom, and (ii) analysing and characterising available operational and scheduling options. This subsection is covering the first part. The methodology for Task 1.1 is to first classify the services and then to identify how the value of these services will be quantified for the optimization stage planned in subsequent work packages.

Local and export ancillary services have been proposed for consideration. Essentially, the value of those services that allow to avoid network reinforcements will be valuated considering the costs of said reinforcements while other services will be valuated using a comparison with existing products and their historical development. The activities also included a set of interviews with DSOs that helped to steer the services’ selection, but also to gather data (network data and cost information for components) that is used in the case studies planned in Task 1.2.

Flexibility services identified in the literature (30 papers and technical reports are reviewed), expert opinions and DSOs interviews are listed, clustered and discussed in the next chapters. The detailed findings of the literature study are given in a table form in “D1.1 Appendix B”. Two groups of ancillary services have been formed: services for local low-voltage usage and for export to higher voltage level. Then, the actors and technical needs to implement such flexibility systems are listed. The interview reports are given in “D1.1 Appendix A”. In short, the interviews showed that most utilities are aware of the potential for flexibility use in the operation of future systems. The limitations mentioned by the DSOs are in the legal area:

- Can the DSO take unlimited control?
- Can the DSO access directly or via service providers?

Network reinforcement as a conventional means of solving issues of increased PV production are well known, with an increasing number of tap-changers and voltage regulators installed as a consequence of the regulatory requirement to consider active network solutions. The few examples for assets currently managed by the DSO are those that are not PV (e.g., micro-hydro and cogeneration plants). Interesting to note, but outside of the project's scope, a high number of issues linked with reliability and quality of service has been mentioned.

3.2.1 Local services

A local service is an action of resources within a low-voltage network fed by a single medium- to low-voltage transformer that helps to achieve an objective, which is only expressed in terms of quantities (voltages, loadings, total consumption, etc.) of that network. Typically, if an imbalance is solved locally or loadings are adjusted locally, costs can be avoided and therefore a relative value can be assigned to the service. The following paragraphs will discuss these effects. There can however be limitations in using flexibility for several purposes: fulfilling different objectives might lead to contradictory actions. While this is not directly relevant to the optimization approach followed later in this project (where the optimization is performed centrally), such conflicts might arise when several actors of a grid are activating flexibility with incomplete coordination.

In order to facilitate the analysis, the services have been assigned to the service groups that will be sharing several characteristics. Table 1 contains the services and dependencies definitions. A definition for the value of flexibility used for the provision is also proposed. For the purpose of this project, the value definitions in italic will be used later for simulations and comparisons.

As shown, not all services are presently taken into account for a value definition, as not all services have a current direct representation for a local value in today's regulatory setup. For example, local balancing has not a conventional comparison for local use. In this project, an approach taking into account for future developments of local market designs that will be take. Several of these services correspond to standard products known in the transmission system (see, e.g., [3]) that would indeed need some adjustments in order to be used in distribution networks but nevertheless would be produced and used with some similarities:

- Active power balancing: For this service, a remote signal is sent to the resource in order to adjust upwards or downwards the active power fed to or drawn from the network. It is useful to distinguish between positive and negative control reserves, similar to the current situation of corresponding aFRR and mFRR products. In distribution, the intended use of the mechanism would likely mostly be the reduction of unplanned exchanges (this could be interpreted in analogy to the recently launched "integrated market" approach [4]).
- Reactive power control: Reactive power could classically be used in order to control the voltage, although with limited effectiveness in distribution systems. Compensation of non-conform power factors could also be done, but this appears to be a limited necessity at low-voltage level.
- Node voltage control: In the context of distribution network, this is to be understood as a means to increase the hosting capacity in terms of renewable generation, hence this item has been assigned to the service group congestion management (this however does not restrict the use of the service in any optimization algorithm).

Service Group	Service by flexible resource	Service dependencies	Value definition (comparison to alternative)
Balancing	Short-term reserve for local balancing + Short-term reserve for local balancing - (incl. Demand response)	Frequency control Voltage control Reduction of unplanned exchanges	*Historical value of mFRR*[1]
Voltage control	Reactive power control Active power control Voltage quality	Congestion management	*Cost of tap changer* *Cost of voltage regulator*
Congestion management	Node voltage management Line loading management Transformer loading management Peak demand management	Voltage control	*Cost of reinforcement reduced or cancelled* *Avoided increase in cost of network interconnection to upper grid level*
Continuity of service	Black start capability Islanding capability	Voltage control Frequency control	Possibly the cost of the interruption of activity for commercial customers could give an indication for this service.

Table 1 Local services, dependencies and value definition for the flexibility used.

Other services are effectively specific to distribution grids, and therefore not currently used and documented in reference documents:

- Active power control for voltage control: Due to the high R/X ratio of distribution grids, reducing active power flows has beneficial issues on voltage variations.
- Voltage quality: Maintaining required voltage quality characteristics might arise as a service in the future. Other than for maintaining the RMS value of the voltage within defined ranges, this is not further considered in this report.
- Loading management for single branches (line or transformer): In order not to exceed the ratings of a branch element in the network, flexibility could be activated. This would suppress the need to reinforce the network accordingly.
- Peak demand management (peak shaving): The maximum power exchanged with other network levels is limited to a set value. Reasons are not linked to the system considered.
- Islanding and black start capability: These capabilities are often discussed but rarely implemented, also for safety reasons. Therefore, they are not considered in this work.

[1] Previously referred to as tertiary reserve (TRL)

3.2.2 Ancillary services exported to higher network levels

Exported ancillary services are uses of flexibility that are done with the purpose of selling ancillary services to higher network levels. In this project, the focus is on selling to the network level 1, since this is currently the only established market. However, the framework proposed and developed in the project would also allow for exports into intermediate network levels.

Table 2 shows the services that could be exported towards higher grid levels in addition to the benefits of local services to the interconnected network. Obviously, exporting active and reactive power will have an impact on the local system; the voltages will be affected and component loadings will be modified. In an optimization approach, this is covered by adequate constraints. In principle there is no adverse effect on the balancing of the local system, provided that balance group mechanisms are taking the export of ancillary services into account.

The services mentioned in this section correspond to the standard products currently in place in the central European system [3], respectively elsewhere for synthetic inertia [6]. Within this project, their value will be estimated using the current tariffs or historical market prices as indicated in Table 2.

Two ancillary services related to innovative use of storage devices can be considered within the framework of frequency control and congestion management, respectively. With reference to frequency control, the charging of vehicle fleets connected to the local networks can be managed to provide frequency regulation to the upstream grid; this is performed through the services known as V1G (smart charging) and V2G [7], [8]. Regarding congestion management, storage devices connected to the local network can be used to provide load levelling, which allows flattening the power demand at the upstream grid thanks to the appropriate charging/discharging strategies [9]-[11].

Service Group	Service	Service dependencies	Flexibility value definition
Frequency control	Frequency containment reserve Automatic frequency restoration reserve Manual frequency restoration reserve (In the future: synthetic inertia) V1G (smart charging) and/or V2G	Congestion management in the local network	aFRR and mFRR prices (historical)
Voltage control	Reactive power control Active power control	Voltage control in the local network	Only relevant for NL1: tariffs according to Swissgrid voltage management [5][2].
Congestion management	Load Leveling	Congestion management in the local network	Cost of reinforcement of the upstream network reduced or cancelled (this will not be considered coherently with footnote 2)

Table 2 Services, dependencies and value definition for the flexibility used

[2] In this project, this will not be considered: a voltage plan would be needed for the transmission grid. Alternatively, the nominal voltage could be used. This would however require to have a network model for the upstream network, including the load flows, which is not realistic for this study.

3.3 Relative costs and benefits of operational and scheduling options for distribution grids

This deliverable briefly describes the method used to determine the relative value of flexibility and presents the data obtained based on case studies in the western Switzerland distribution network. The different service groups (balancing, congestion management, voltage management and service continuity) have been introduced in deliverable 1.1. Depending on which service is considered and whether export or local use is considered, the relative value of the service is given by: (i) the cost of the equivalent network reinforcement, (ii) the cost of a tap changer distribution transformer, or (iii) the historical value of the corresponding service in the transmission grid. Items (ii) and (iii) are relatively straightforward: The figures have been collected by considering the relevant historical costs. The novelty of the approach is however concentrated on item (i), the relative value of the network reinforcement has been avoided. An ex-ante average value of this relative value for flexibility has been determined by considering a big number of possible network reinforcements within two grid areas (rural and urban) and then computing an average cost of the reinforcement for each kWh that could be additionally injected into the system. The relative value of the flexibility is obtained by discounting the cost for the reinforcements in the entire grid area and computing an adequate average.

Activities for task 1.2 started with the establishment of simulation models of suitable low-voltage networks. The basis for these models was provided by SCCER FURIES related activities where a method for the import of data from the GIS database into a state-of-the-art power systems analysis tool (PowerFactory in this case) had been established. The coverage and degree of detail of the data imported was expanded for the needs of this project: the consumption data measured on the medium-voltage side was broken down into low-voltage consumer profiles approximated using published load profile generators in a manner that the aggregated net consumption corresponds to the measurements. The networks (a rural area network and an urban area network) are used in order to assess the need for network reinforcements if the penetration of solar PV generation (or additional load) is increased in a randomized manner. Using power flow calculations, the cost of upgrading cables and other components in case of capacity or voltage variation violations are used in order to determine the value of the flexibility that would avoid the need for such reinforcement. Two approaches for the determination of the network reinforcement costs have been combined: (i) standard costs published by VSE have been combined with (ii) confidential information obtained from several DSOs for specific projects. The result is a set of aggregated fitted cost curves.

The average value of flexibility has been determined by comparison with the annual costs of the equivalent network reinforcement. For the export of services, methods from other SCCER FURIES activities related to average values of services have been used and the results have been adapted and summarised in this report.

The tables below summarise the results in terms of relative value for the flexibility uses identified in WP1 for further use within the DiGriFlex project.

Local use

Service group	Value for interconnected system			Value for local system Rural area			Value for local system Urban area		
	min	mean	max	min	mean	max	min	mean	max
Balancing in ct/kWh	-11.40	1.36	5.35	4.40	4.82	5.27	5.48	6.11	6.66
Voltage control in ct/kVArh	-	0.26	-	1.70	3.32	17.20	1.70	3.32	17.20
Congestion management in ct/kWh	-11.40	1.36	5.35	4.40	4.82	5.27	5.48	6.11	6.66

Table 3 Values for flexible generation decrease (or flexible consumption increase)

Service group	Value for interconnected system			Value for local system Rural area			Value for local system Urban area		
	min	mean	max	min	mean	max	min	mean	max
Balancing in ct/kWh	1.90	6.43	12.82	3.74	4.12	4.54	3.20	3.58	3.95
Voltage control in ct/kVArh	-	0.26	-	1.70	3.32	17.20	1.70	3.32	17.20
Congestion management in ct/kWh	1.90	6.43	12.82	3.74	4.12	4.54	3.20	3.58	3.95

Table 4 Values for flexible generation increase (or flexible consumption decrease)

Export

Service group	Value for interconnected system		
	min	mean	max
Balancing in ct/kWh	-11.40	1.36	5.35
Voltage control in ct/kVArh	-	0.26	-

Table 5 Values for flexible generation decrease (or flexible consumption increase)

Service group	Value for interconnected system		
	min	mean	max
Balancing in ct/kWh	1.90	6.43	12.82
Voltage control in ct/kVArh	-	0.26	-

Table 6 Values for flexible generation increase (or flexible consumption decrease)

The complete description of the proposed methods for obtaining relative value for flexibility uses as well as simulation process and the detailed numerical results are available in the D2.2 document annexed to this report.

3.4 Data collection, data pre-processing and exploratory data analysis

The Task 2.1 focuses on data collection, data pre-processing and exploratory data analysis activities that are carried out in order to create large, robust databases of variables. It could be exploited to test the performance of the forecasting systems that will eventually be used to predict energy at the site of the installation of the test distribution grid of the ReIne laboratory.

Summarizing, the research activities completed in the Tasks 2.2 and 2.3 resulted in:

- The collection of large, robust datasets of PV power generation and weather variables at the site of installation of the test distribution grid of the ReIne laboratory;
- The collection of large, robust datasets of wind power generation, industrial loads and weather variables available from the relevant literature and from public databases;
- The pre-processing of the collected data, aiming at individuating and correcting missing data, bad data and outliers;
- The exploratory data analysis to reduce the dimensionality of the input datasets, favoring the development of adequate forecasting systems for renewable generation and load.

3.4.1 Data collection

Several datasets are used for the activities related to the forecasting systems (day-ahead and real-time). These datasets are related to the target variables (loads and renewable generated power) and external variables (i.e., weather data) used as additional inputs of the forecasting systems. It includes the data related to the ReIne laboratory as well as public datasets.

Dataset_PVI1: This dataset includes PV power measurements taken at the 30-kWp PV installation (PVI1) equipped with four 8.5-kWp inverters, which is part of the test distribution grid of the ReIne laboratory. Due to its recent installation, the data collection started on August 24, 2019 with a 1-minute time resolution. The utilization of these data for validating and testing the PV power forecasting models is infeasible at the progress stage of the first year of project activities due to the relatively short operation life of the PV system, therefore this dataset is not included in experimental frameworks.

Dataset_PVI2: This dataset includes PV power measurements taken at a second PV installation (PVI2), located close to the test distribution grid of the ReIne laboratory. PVI2 was monitored since January 1, 2016 until December 31, 2018 at a one-minute time resolution. The related data are used for the initial validation of the PV power forecasting systems.

Dataset_PVI3: This dataset consists of zone-1 PV power data published in the framework of the Global Energy Forecasting Competition 2014 [12] at an unspecified location in Australia. Data span April 1, 2012 to June 30, 2014 with an hourly resolution. This dataset is included in the experimental frameworks in order to generalize the performance testing of the proposed forecasting systems.

Dataset_WG: This dataset includes wind power measurements collected at a wind farm located in southern Italy. The wind farm is constituted by ten 3-MVA generators. Wind power was measured at each generator throughout three years, with 10-minute acquisitions.

Dataset_indust_load: This dataset includes industrial load data (active and reactive powers) collected at an Italian factory that manufactures transformers. The factory operates on two work shifts during weekdays (Monday-Friday), on a single work shift during Saturdays, and it is closed on Sundays. Energy meters collect electrical data at fourteen single loads, at four low-voltage power distribution feeders, and at the point of common coupling to the main medium-voltage network (i.e., the aggregate load of the factory). The time resolution of the data metering is 15 minutes.

Dataset_weath_PV: A dedicated weather station is installed at the location of the test distribution grid of the ReIne laboratory. This station collected weather data at the same time resolution and for the same time periods of the PV power data contained in Dataset_PVI1 and Dataset_PVI2, allowing their usage as exogenous variables for PV power forecasting models. 26 variables are monitored in this way.

Dataset_weath_WG: This dataset includes absolute wind speeds and wind directions measured at each of the ten generators related to Dataset_WG. Wind data were collected throughout three years with 10-minute acquisitions, for the same time intervals of those related to Dataset_WG, allowing their usage as exogenous variables for wind power forecasting models.

Dataset_weath_ECMWF: Weather forecast data are gathered from the European Centre for Medium-range Weather Forecasts (ECMWF) [13] for the locations and the time intervals corresponding to Dataset_PVI1, Dataset_PVI2, Dataset_PVI3 and Dataset_WG. Requests are prepared in Python3.7 and sent via the ECMWF Application Programming Interface (API). Forecasts for nine variables are obtained in this way. These data are related to the noon run (i.e., forecasts are issued at 12:00 A.M. of day D-1 for the entire day D) and to the midnight run (i.e., forecasts are issued at 12:00 P.M. of day D-1 for the entire day D). This differentiation in the weather forecast lead time allows developing models diversified for day-ahead control and real-time control of the distributed energy resources. In particular, the forecasts related to the noon run are used for the forecasting models aimed at the pre-scheduling control of the distribution grids, whereas the forecasts related to the midnight run are used for the forecasting models aimed at the real-time control of the distribution grids.

3.4.2 Data pre-processing

The pre-processing of the collected data is carried out in three steps, namely, cleansing, averaging and normalization. Here below, these steps are briefly described. Further details including mathematical formulations, specific treatment of each data set, and numerical illustrations are available in the deliverables D2.1 and D2.2 annexed to this report.

Cleansing

The considered datasets are initially cleaned as an initial analysis revealed some potential outliers, missing and bad data. One of the principal objectives of the pre-processing activity is therefore to correct and remove this harmful effect by cleansing the data. Bad and missing data are easy to be individuated by visual inspection. Potential outliers instead are more subtle, since they cannot be immediately individuated by visual inspection. A slight modification of the Tukey's test [14] has been applied in order to individuate potential outliers. Tukey's test acts by examining and individuating data which lie beyond a specific band of tolerance, in which the null hypothesis can be rejected.

Averaging

In all the considered experimental frameworks for day-ahead forecasting (task 2.2), the time resolution is one hour. An important objective of the data pre-processing activity is therefore to average values collected at different time resolution (for example, 1 minute for the Dataset_PVI2 of 10 minutes for the Dataset_WG) in order to obtain hourly data. Similar process has been carried out for preparing data sets with 10-minutes time resolution required for the development of real-time forecasting systems (task 2.3).

Normalization

The last objective of the data pre-processing activity is to normalize hourly values in the range 0-1. This accommodation is usually necessary when the ranges in which the considered variables are included are very different. Although some forecasting models are insensitive to data normalization, other models may be significantly affected by the lack of normalization. All the data are normalized in order to be used in any case. The normalized value $\tilde{y}_h$ of the generic variable y occurred at hour h is:

$$\tilde{y}_h = \frac{y_h - y_{\min}}{y_{\max} - y_{\min}}, \tag{1}$$

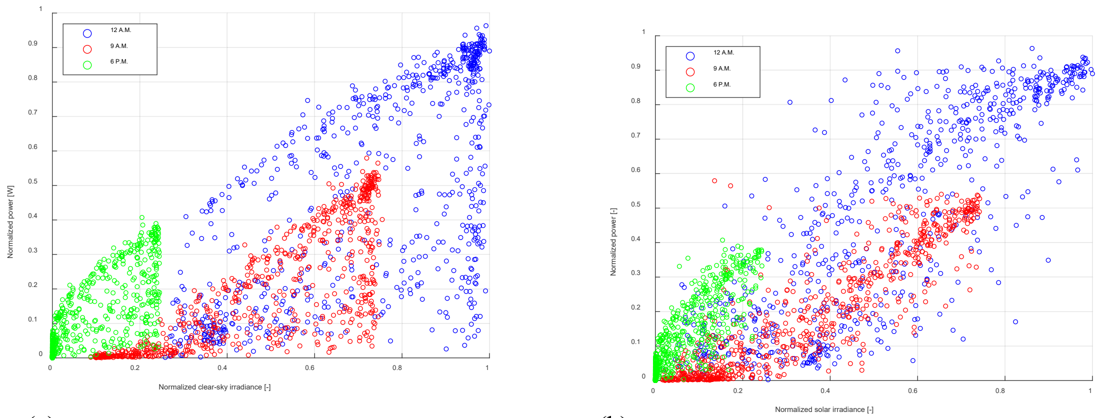
where y_h is the value observed at hour h, and $y_{\min}$ and $y_{\max}$ are respectively the minimum and maximum values observed in the entire dataset.

3.4.3 Exploratory data analysis

The database resulting from the data pre-processing activities consists of hourly observations of several exogenous weather variables and hourly observations of PV power. In order to reduce the dimensionality of the problem, an exploratory data analysis has been carried out to individuate exogenous variables, which are informative for the PV power, and to discard uninformative exogenous variables.

At this progress stage, the exploratory data analysis has been performed only to individuate potential relationship between the PV power of PVI2 and ECMWF weather forecasts. This was performed via graphical inspection of relative scatter plots.

As an example, scatter plots of the normalized PV power versus the normalized clear-sky irradiance forecasts (Figure 2a) and versus the normalized solar irradiance forecasts (Figure 2b) evidence clear relationship among these variables. Nevertheless, this relationship is not steady across the hour of the day, as patterns clearly differ considering, for example, 12 A.M., 9 A.M., and 6. P.M in the figures. From the graphical inspection of Figure 2, it is suggested to add normalized clear-sky irradiance forecasts and normalized solar irradiance forecasts as candidate predictors of PV power forecasting models and to add a dummy variable to differentiate among the hours of the day.



(a) (b)

Figure 2 Scatter plots of the normalized PV power versus the normalized clear-sky irradiance forecasts (a) and versus the normalized solar irradiance forecasts (b) for three different hours of the day.

The exploratory data analysis also allows discarding some variables, which cannot be considered informative for predicting PV power. As significant example,

Figure 3 shows the scatter plots of the normalized PV power versus the normalized forecasts of wind speed at 10 m. No clear relationship can be evidenced from this plot, as the cloud of points is very irregular. Also, there are no clear patterns differentiated among the hours of the day. For this reason, it can be considered safe to discard normalized forecasts of wind speed at 10 m to reduce the dimensionality of the problem.

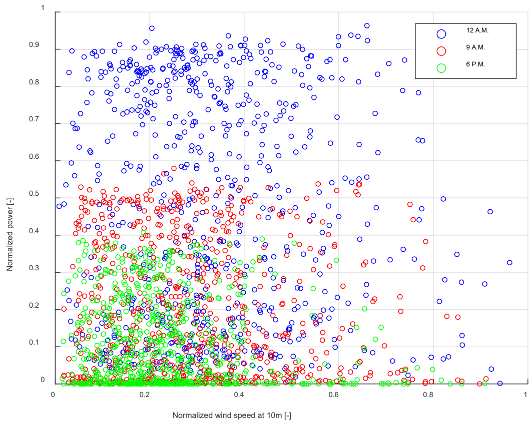


Figure 3 Scatter plots of the normalized PV power versus the normalized forecasts of wind speed at 10 m, for three different hours of the day.

3.5 Day-ahead forecasting systems and solution algorithms for distribution grids under uncertainties

Activities in Task 2.2 included the development of methods and models able to obtain accurate day-ahead forecasting for renewable generation (wind and photovoltaic (PV) forecasting) and loads (active and reactive power). In addition, also the optimal operation of micro-grids in presence of uncertainties is considered and the impact of inputs' forecasting error is analyzed in depth.

The widely spread of the generation systems based on wind and solar primary sources across MV and low-voltage distribution systems lead to the need of methods able to predict the wind and photovoltaic generated power. In fact, since the uncertain nature of the solar and wind energy resource, PV and wind power forecasting models are crucial in any energy management system for smart distribution networks. On the other hand, industrial load takes a big portion of the total electricity demand. Skilled industrial load forecasts allow for optimally exploiting energy resources, managing the reserves, and market bidding, which are beneficial to distribution system operators and their industrial customers. Despite its importance, industrial load forecasting has never been a popular subject in the literature.

Eventually, for both generation and loads, in relevant literature point forecast and probabilistic forecast are proposed. Although point forecasts can suit many scopes, probabilistic forecasts add further flexibility to an energy management system and are recommended to enable a wider range of decision making and optimization strategies. Thus, in our studies probabilistic forecast are considered.

Summarizing, the research activities completed in the Task 2.2 resulted in:

1. The development of a day-ahead probabilistic wind power forecasting based on ranking and combining Numeric Weather Predictions (NWPs);
2. The development of a Bayesian bootstrap quantile regression model for probabilistic photovoltaic power forecasting;
3. The development of a multivariate approach for probabilistic industrial load forecasting.

With reference to (1), the volatility of the wind over large time horizons complicates the generation of skilled, reliable wind power forecasts. Exploiting Numeric Weather Predictions (NWPs) is generally considered mandatory to increase the skill of probabilistic predictions, and forecasts may further be enhanced by adding several spatially-distributed predictions. However, feature selection becomes as more complicated and time-consuming as the number of NWPs increases. In our study, the power generated by a wind farm is predicted developing a new technique based on ranking and combining spatially-distributed NWPs, easing the feature selection and reducing the computational efforts, as well as maintaining high the skill of probabilistic forecasts. Several spatially-distributed NWPs, provided for the area surrounding the wind farm, are ranked for each individual generator, and the ranked NWPs are combined to form an ensemble set of predictors for the probabilistic forecasting model. This ensemble is obtained using three different weighted combination approaches. Gradient boosting regression tree models and quantile regression neural networks generate probabilistic wind power forecasts. The proposed methodology is applied for day-ahead wind power forecasting of individual generators and of the entire wind farm. Numerical experiments carried out on an actual wind farm in southern Italy.

With reference to (2), a probabilistic PV power forecasting based on a Bayesian bootstrap quantile regression model is developed. The Bayesian bootstrap is applied to estimate the parameters of a quantile regression model and a novel procedure is presented to optimize the extraction of the predictive quantiles from the bootstrapped estimation of the related coefficients, raising the predictive ability of the final forecasts. Numerical experiments based on actual data quantify an enhancement of the performance of up to 2.2% when compared to relevant benchmarks.

With reference to (3), most existing methods for industrial load forecasting operate on the active power alone, partially or totally neglecting the reactive power. We developed a multivariate approach to probabilistic industrial load forecasting, which addresses active and reactive power simultaneously. The method is based on a two-level procedure, which consists of generating probabilistic forecasts individually for active and reactive power through univariate probabilistic models, and combining these forecasts in a multivariate approach based on a multivariate quantile regression model. The procedure to estimate the parameters of the multivariate quantile regression model is posed under a linear programming problem, to facilitate the convergence to the optimal solution. The proposed method is validated using actual load data collected at an Italian factory, under comparison with several probabilistic benchmarks.

For the sake of brevity, in the following subsection, we briefly describe and present the selected results of Bayesian bootstrap quantile regression model for probabilistic photovoltaic power forecasting. The complete description of all the above forecasting systems and achieved results are presented in the deliverables D2.1 annexed to this report.

3.5.1 Development of day-ahead forecasting systems for photovoltaic power generation

The proposed PV power forecasting system based on Bayesian Bootstrap Quantile Regression (BBQR) is illustrated in Figure 4. The inputs of the system are Numeric Weather Predictions (NWPs) $\boldsymbol{NW}$ and historical measured PV power data $\boldsymbol{P}$. The proposed forecasting system consists of three stages.

The first stage is model selection, i.e., the selection of the most informative predictors among the available pool of predictors. This is performed by evaluating the performance of multiple Quantile Regression (QR) models having different combinations of predictors, and by picking the model which returns the smallest error. For notation, the underlying QR model selected in this first stage of the system has M^* predictors and M^*+1 parameters.

The second stage consists of applying Bayesian bootstrapping over the selected underlying QR model, in order to estimate the posterior distribution of the parameters of the QR model. Specifically, the Bayesian bootstrap returns R samples extracted from each of the M^*+1 posterior distributions of the M^*+1 parameters of the QR model. As will be shown later, these samples are extracted from a multivariate Dirichlet distribution. A Monte Carlo sampling method then extracts R samples ($\widehat{\boldsymbol{P}}_h^{\langle\alpha_q\rangle}$) of predictive α_q-quantiles of PV power for the target horizon h.

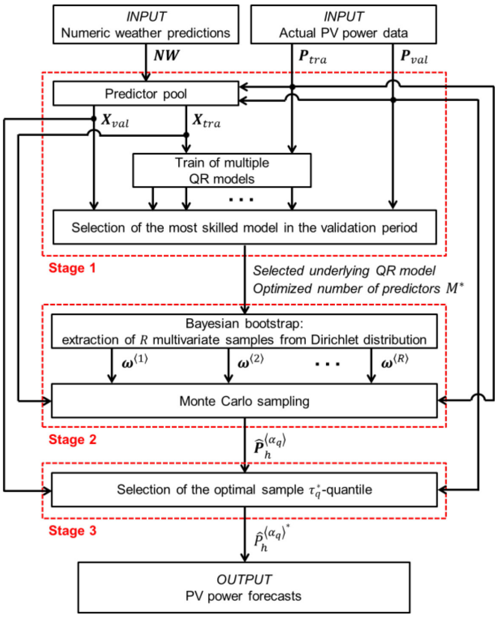


Figure 4 Schematic procedure of the forecasting system based on Bayesian bootstrap quantile regression.

The third and last stage consists of extracting a single value $\widehat{P}_h^{\langle \alpha_q\rangle^*}$ from the R samples of predictive quantiles of PV power for each coverage, in order to generate the prediction of PV power for the target horizon. A procedure dedicated to this purpose, based on the optimization of the sample τ_q-quantile of $\widehat{\boldsymbol{P}}_h^{\langle \alpha_q\rangle}$, is developed and presented here. The entire predictive distribution of the final probabilistic PV power forecasts can be obtained by iteration for Q predictive quantiles.

Five benchmarks are considered to provide a fair comparison of the results.

- Simple QR (SQR)
- Traditional Bootstrap QR (TBQR)
- Quantile regression neural network (QRNN)
- Gradient Boosting Regression Tree (GBRT)
- Seasonal Persistence Model (SPM)

The forecast results for the test set of **Dataset_PVI2** are shown in Table 7 via Normalized Pinball Score - NPS (summed across the $Q = 19$ quantiles and averaged through the test set) and Absolute Coverage Error (AACE). BBQR returns a NPS smaller than SQR, TBQR, QRNN, GBRT and SPM benchmarks by 2.2%, 0.6%, 5.4%, 1.4% and 51.0%, respectively. Bootstrapping increases the accuracy of forecasts, since both the bootstrapped methods (BBQR and TBQR) outperform SQR, although the Bayesian-based procedure slightly outperforms the traditional bootstrapping procedure in terms of NPS.

The technical details of the implementation of the benchmark methods and relevant references, as well as further comparison results are presented in the deliverable D2.1 annexed to this report.

In order to provide a graphical interpretation of the PV power forecasts versus time, Figure 5 shows the BBQR prediction intervals for one week of the test period. Prediction intervals are given for rates 90%, 50% and 10%, and they are plotted together with the actual PV power.

Table 7 Forecast results for the test set of Dataset_PVI2.

Method	NPS [-]	AACE [%]
BBQR	**0.2547**	**2.22**
Simple QR (SQR)	0.2604	5.41
Traditional Bootstrap QR (TBQR)	0.2562	2.38
Quantile Regression Neural Network (QRNN)	0.2692	5.08
Gradient Boosting Regression Tree (GBRT)	0.2583	5.72
Seasonal Persistence Model (SPM)	0.5193	-

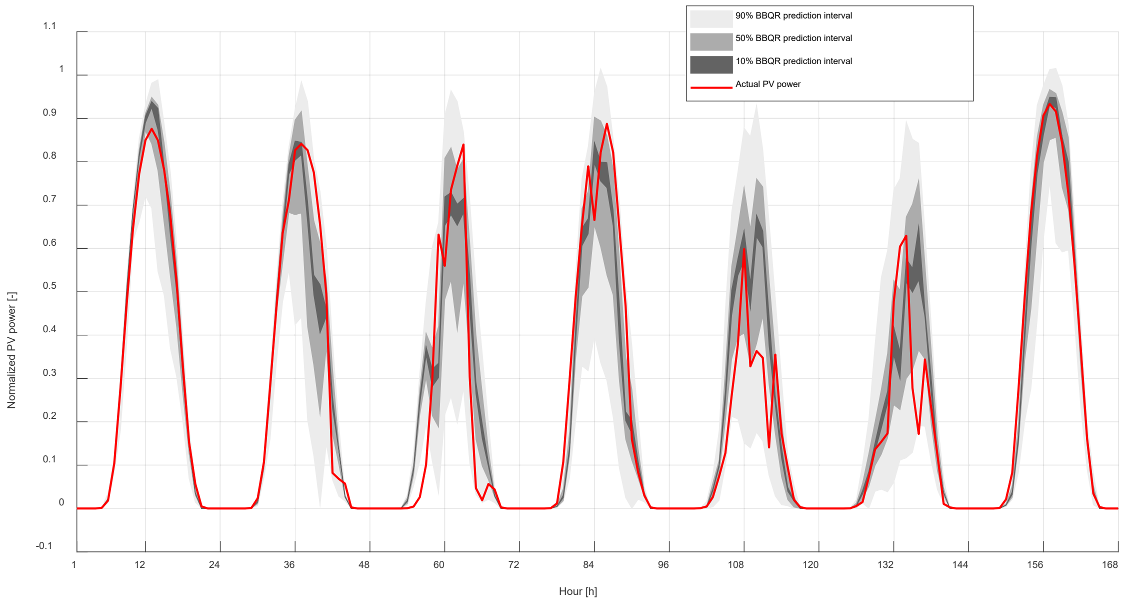


Figure 5 BBQR prediction intervals during one week of the test set of Dataset_PVI2.

3.6 Real-time forecasting systems and solution algorithms for distribution grids under uncertainties for real-time control

With reference to Task 2.3, the development of methods and models able to obtain accurate real-time forecasting of PV generation and load (electric vehicle load) focused on both deterministic and probabilistic approaches. As deterministic approach, a persistence-based method was proposed. Probabilistic methods referred to hybrid physical-statistical models based on multiple linear regression and random forests. The identification of the best combination type for these underlying models in ensemble approach is also explored. Finally, a comparison with the relevant state-of-the-art benchmarks is carried out. More specifically, the models proposed in the research activity are the:

- Derivative-persistence and Caputo-derivative methods for real-time photovoltaic power forecasting;
- Bayesian bootstrapping in real-time probabilistic photovoltaic power forecasting;
- Hierarchical probabilistic electric vehicle load forecasting.

With reference to the derivative-persistence method for real-time photovoltaic power forecasting, we focused to forecasting time horizons ranging from few minutes up to few hours, that are those typically categorized as very short-term and short-term forecasting, and that are included in the intra-day scenarios. A derivative-persistence method has been proposed based on information on measured data of the PV power production in the intervals preceding the forecast horizon.

With regard to the Bayesian bootstrapping in real-time, the research has focused on the application of Bayesian bootstrap in short-term probabilistic PV forecasting. The Bayesian bootstrap was specifically suited up to be applied to three different underlying probabilistic models in order to evaluate potential improvements due to its application. The major aim of this research was indeed to evaluate if the Bayesian bootstrap enabled for better performance and increased skill of the forecasts, compared to the stand-alone usage of the underlying probabilistic models and compared to the application of the traditional bootstrap. Another contribution of the research was the development of the three probabilistic forecasting systems under a new framework that makes the Bayesian bootstrap operate directly on the PV power forecasts, rather than on the parameters of the models. This approach allows reducing the overall computational effort which is particularly important in short-term forecasting, thanks to the fact that there is no need to pass through the sample bootstrap distributions of the parameters since the sample Bayesian bootstrap distribution of the predictive quantile of PV power is directly provided.

The hierarchical probabilistic EV load forecasting is performed by proposing a methodology dedicated to probabilistic EV load forecasting for low-level geographic regions, which implements a hierarchical perspective to forecast the aggregate load of a high-level geographic region. This methodology can provide comprehensive information on electricity consumption at different levels. The hierarchical approach is applied to decompose the problem into lower-level sub-problems which are resolved through standard probabilistic models.

For the sake of brevity, in the following subsection we briefly describe the derivative-persistence method for real-time photovoltaic power forecasting, and present few illustrative results. The complete description of all the above real-time forecasting systems and achieved results are presented in the deliverables D2.2 annexed to this report.

The derivative-persistence method for real-time photovoltaic power forecasting will be implemented in WP4 (ReIne laboratory) thanks to its simple and deterministic nature that fits well with the real-time (online) optimization model.

3.6.1 Derivative-persistence method for real-time photovoltaic power forecasting

The derivative-persistence method deals with a real-time forecasting technique which aims at predicting, on a very-short-term basis, PV power production, based on information on measured data of the PV power production in the intervals preceding the forecast horizon.

The method is based on the idea to conveniently weight information on past data by imposing continuity of the function, of the first derivative and of the second derivative so obtaining three estimates of the function in the forecast interval. The three estimates are then opportunely weighted to provide the forecast.

The derivative persistence forecasting method has been applied to a data set of measured power produced by a PV system installed at the ReIne laboratory. The generation system has a total capacity of 30 kW and includes four AC/DC power inverters. The data considered in this application refer to the measured power at the AC side of one inverter having a capacity of 8.5 kW. Particularly, the data refer to a measurement set recorded in the period August 24, to December 19, 2019. This set of data is useful for testing purposes since it refers to different seasons and represents daily power profiles with different degree of variability. Some examples of daily power production are reported in Figure 6.

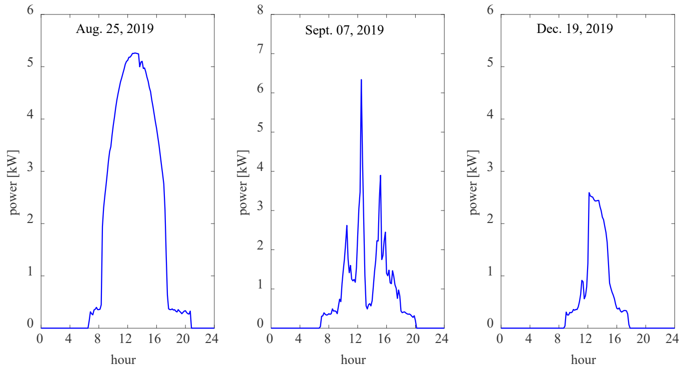


Figure 6 Four days selected among the available measurement data.

To validate the proposed approach and highlight its peculiarities in terms of real-time estimation, the forecasted values of power are compared with those of the persistence method of which the proposal is an improvement and Autoregressive–moving-average (ARMA) method, which is recognized as popular statistical tool for time series analysis forecast. The results are presented in Table 8 based on the following performance index.

Performance index

The mean absolute error (MAE) assesses the average distance between the measured values, $y(k)$ and the model predictions, $\hat{y}(k)$, of the N forecasted values; normalized mean absolute percentage error (NMAPE) evaluates the magnitude of the prediction error normalized with respect to the system capacity (P_n); compared to the MAPE, median absolute percentage error (MdAPE) is used since it is less sensitive to outliers; root mean square error (RMSE) is useful since it penalizes large errors.

Table 8 Performance comparison.

Model	MAE [W]	NMAPE [%]	MdAPE [%]	RMSE [W]
day August 25, 2019				
Persistence	127.36	1.50	3.79	224.94
Proposed	105.92	1.25	2.96	191.54
ARMA	120.26	1.41	3.02	212.55
day September 7, 2019				
Persistence	334.58	3.94	15.13	593.57
Proposed	318.99	3.75	14.94	569.12
ARMA	467.43	5.50	20.40	891.78
day December 19, 2019				
Persistence	108.95	1.28	7.43	249.43
Proposed	104.35	1.23	8.53	240.81
ARMA	221.50	2.61	13.99	540.07

With reference to the day August 25, 2019, the values that all metrics assume in the case of the proposed approach are lower than those assumed by the persistence method. Compared to the persistence model, the NMAPE and MdAPE of the proposed model are 16% and 22% lower, respectively. The values of RMSE and MAE also show better performance of the proposed approach. It is interesting to note that in case of the day August 25, 2019 the ARMA model allows obtaining an accuracy better than the persistence model and worse than the proposed approach. With reference to the other days of the measured data, this generally happens in the days characterized by small variability.

The technical details of the implementation of the benchmark methods and relevant references, as well as further comparison results are presented in the deliverable D2.2 annexed to this report.

3.7 Two-level rolling horizon optimization model

The two-level rolling optimization framework has been developed to ensure optimal (most economical) and secure operation of an active distribution network under uncertainties. The first-level (pre-scheduling optimization) deals with time-ahead scheduling (e.g., day-ahead or a few hours ahead) of the controllable resources, whereas the second-level (on-line or real-time[3] optimization) deals with on-line scheduling of the controllable resources.

The objective of pre-scheduling optimization problem is to minimize the relative expected cost of operation with respect to the estimation (forecast) of the uncertain parameters[4]. This objective function includes the balancing cost minus revenues from provisioning ancillary services or any flexibilities to the upstream transmission system. At this level, the main uncertain parameters are the power generation of renewable energy sources (e.g., PV), and the power demand of consumers in the coming hours. The pre-scheduling optimization problem is solved one day ahead of the target day (day - 1), as we aim to determine the participation of resources in an active distribution network in the energy and ancillary services markets.

The objective of on-line optimization problems is to minimize the deviation of the outputs of controllable resources (e.g., storage) from the pre-scheduled set-points obtained from the first-level with respect to the real-time realization of the uncertain parameters. In this respect, the on-line optimization relies on a very short-term forecast of uncertain parameters in near real-time, which is one of the subjects of WP 2 of this project. The forecasts of PV systems' outputs and the forecasts of demand in the next 10-minutes are done in the very short-term forecasting system proposed in WP2. The on-line optimization problem is solved 10-minutes ahead of the target time instance. Based on the study we had, the best time step (dt) is 10 minutes, which is taken into account in this study. The reason behind using 10-minutes for the time step is that the measurements in distribution grids are normally captured every 10-minutes in standard distribution systems. However, since the market clearance is done every 15-minutes, the participation of active distribution networks in the real-time market is not considered in this project.

The two-level rolling optimization problems are linked together through the technical constraints of the network, as well as the constraints associated with the capacities of the controllable resources (e.g., state of charge limits of the batteries). Moreover, the second-level (on-line) optimization problems will provide deviation feedbacks to the first-level pre-scheduling problem (that will solve for upcoming time windows) to enhance the overall optimality and security of distribution grid operation in a larger time window (e.g., one day). If the deviation from the schedules is more than what expected, some

[3] In this report, the terms "on-line" and "real-time" have been used interchangeably.

[4] The relative cost coefficients are obtained from WP1 and forecasts of uncertain parameters are obtained from WP2.

parameters of the first-level optimization problem should be updated. Figure 7, depicts a simple schematic of the proposed optimization framework.

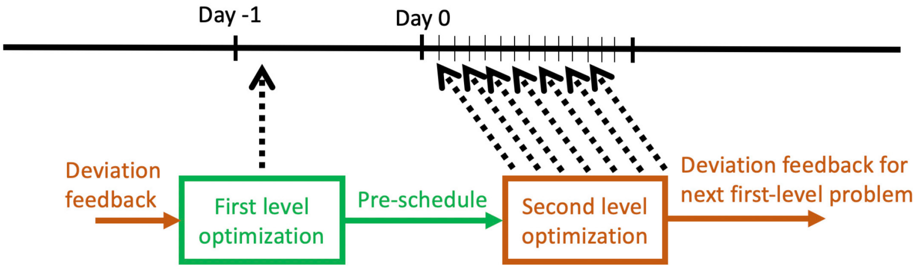


Figure 7 Two-level optimization framework.

The mathematical formulation of the two-level optimization model is presented in the D3.1-D3.2 documents annexed to this report. For the sake of brevity, we only introduce the main components of the model (i.e., input/output variables and the list of technical constraints). Afterwards, two approaches developed for dealing with uncertain parameters in the first-level (pre-scheduling), namely, stochastic optimization and distributionally robust optimization, are briefly discussed and a few selected results are presented.

3.7.1 Definition of state and decision variables of pre-scheduling optimization

The block diagram of pre-scheduling problem (first-level) is depicted in Figure 8. The pre-scheduling set-points and offers to both energy and flexibility markets are optimized on the day-ahead scale by solving either a stochastic optimization or a distributionally robust optimization problem. The proposed optimization problem in the pre-scheduling horizon must be robust against the uncertainties of forecasts. As a result, in the case of deviation from the forecast values in real-time, the resources are optimally controlled to minimize the net deviation. In addition, these deviation experiences are used in the pre-scheduling optimization problem of the next few days by tuning some parameters of robust optimization (which is explained later on). Thus, this feedback in the model is considered to reinforce the proposed model through experiences and bi-directional interaction with the environment. It is worth mentioning that, in addition to this feedback, a high number of operation scenarios are considered in the formulation of the proposed pre-scheduling (first-level) problem to ensure the dispatch possibility of the distribution grid.

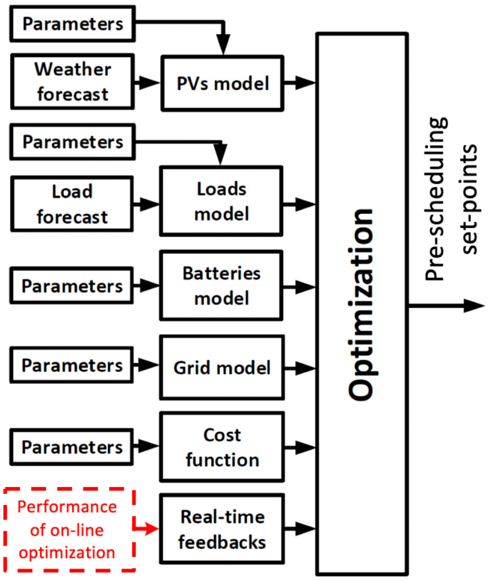


Figure 8 Structure of inputs/outputs of pre-scheduling problem (first-level).

Therefore, the input variables of this pre-scheduling optimization problem are as follows[5]:

- Parameters of PV production systems (grid voltage, converter voltage, and Thevenin reactance), BESSs (charging and discharging efficiencies), distribution grid (resistances and reactance), and voltage magnitude of connection point, i.e., $|V_{nt\omega}|: n \in \mathbb{N}^{(TC)}$.
- Forecast of demands at each time step based on a number of scenarios, i.e., $P_{dt\omega}^{(DEM)}$ and $Q_{dt\omega}^{(DEM)}$.
- Forecast of maximum possible outputs of PV production systems at each time step based on a number of scenarios, i.e., $P_{it\omega}^{(PV,max)}$.
- Cost functions parameters such as $\lambda_{nt}^{(P)}$, $\lambda_{nt}^{(Q)}$, and $\lambda_{nt}^{(f)}: \forall f\{P+, P-, Q+, Q-\}$.
- The asked active and reactive power of upper-layer grid operator from the DSO, i.e., $r_{nt\omega}^{(RT,P)}$ and $r_{nt\omega}^{(RT,Q)}$.

The output variables of pre-scheduling problem are as follows:

- Active and reactive power offers to the day-ahead market at the connection nodes ($P_{nt}^{(SC)}$ and $Q_{nt}^{(SC)}$).
- Active and reactive power flexibility services offered to the day-ahead market at the connection nodes ($R_{nt}^{(SC,f)}: \forall f \in \{P+, P-, Q+, Q-\}$).
- Active and reactive power set-points of PVs at each time step and each scenario of operation ($P_{it\omega}^{(PV)}$ and $Q_{it\omega}^{(PV)}$).
- State of charge and active/reactive input powers of BESSs at each scenario of operation ($\mathrm{SOC}_{st\omega}$, $P_{st\omega}^{(BESS)}$, and $Q_{st\omega}^{(BESS)}$).
- Distribution grid variables including square of currents and voltage ($v_{nt\omega}$ and $l_{nn'_{t\omega}}$), and all variables related to the exact Distflow model.

[5] The full notation is available in the deliverables 3.1 and 3.2 document annexed to this report.

- Real-time injections of active/reactive power at connection node, which may deviate from asked active/reactive power by upper-layer grid operator based on scheduled flexibilities ($P_{nt\omega}^{(RT)}$ and $Q_{nt\omega}^{(RT)}$).

3.7.2 Definition of state and decision variables of on-line optimization

The block diagram of on-line (second-level) problem is illustrated in Figure 9. In real-time, two operation modes are considered since there is a hierarchy of operation in real-time. Here, the hierarchy is due to the fact that the operation of distribution grid must be continued even the solution of on-line optimization problem is not found. To this end, the default set-point values (the set-point in previous time-step) must be used for set-points of flexible resources in the case that the main optimization problem does not find the global optimal solution. To summarize, these two operation modes are defined in the following:

- Mode 1 or main mode: The main optimization problem for finding the set-points of flexible resources in the distribution network considering the commands of upper-layer grid operator or TSO for providing flexibilities is implemented. Note that the command of upper-layer grid operator is considered in the pre-scheduling optimization problem with a boundary; however, in real-time, the exact command is known.
- Mode 2: The default values are used when the outputs of mode 1 are not available (if the solution of optimization problem is not determined in the dedicated time). This mode can be used as backup plan for the proposed control system in real-time.

Using the two modes mentioned, the hierarchy of the proposed control system is kept from the viewpoint of the distribution network's operator because the operation of the distribution grid is not disturbed in the

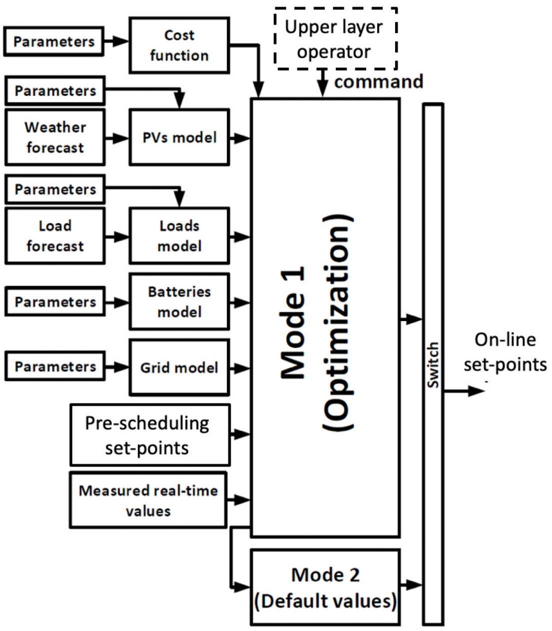


Figure 9 Structure of inputs/outputs of on-line problem (second-level).

case that the on-line optimization problem is not solved in the dedicated time. The block of “switch” in Figure 9 decides the activation of each mentioned mode. The rule of this "switch" is as below: if the solution of mode 1 is not available after a certain time instant, the outputs of mode 2 (which are the default values) are used as the outputs.

Therefore, the input variables of the on-line optimization problem are the same as the inputs of the pre-scheduling problem. In addition, the outputs of the pre-scheduling problem are other inputs of the on-line problem. Finally, the outputs of the on-line optimization problem are as below:

- Active and reactive power set-points of PVs ($P_i^{(PV)}$ and $Q_i^{(PV)}$).
- State of charge or energy content and active/reactive input powers of BESSs (SOC_s, $P_s^{(BESS)}$, and $Q_s^{(BESS)}$).
- Distribution grid variables including square of currents and voltage (v_n and $l_{nn'}$), and all variables related to the exact Distflow model.
- Real-time injections of active/reactive power at connection node, which may deviate from asked active/reactive power by upper-layer grid operator based on scheduled flexibilities ($P_n^{(RT)}$ and $Q_n^{(RT)}$).

3.7.3 Technical constraints

Distribution grid constraints

For pre-scheduling (first-level) problem, the DistFlow (exact version in [15]) is adopted. The reason behind using this version is that the distribution grid is radial in most cases and in addition, there are generation and consumption in active distribution networks. Therefore, the directions of active power are unknown. For the on-line (second-level) problem, the sensitivity-factor based model is used if the exact DistFlow model generates a lot of variables and constraints. The reason behind using this model in the second-level problem is that the problem must be solved in a limited time. Therefore, a linear version of the constraints can be used, which leads us to a LP problem.

Constraints of battery energy storage systems (BESSs)

For the pre-scheduling (first-level) problem, the convex model (the relaxed model described in [16]) is used. For the on-line (second-level) problem, we need a linear model; therefore, the non-linear constraint regarding the capability curve of the converters of the BESS is linearized.

Constraints of PVs

The capability curve of a PV system is defined with the following limitations, which are illustrated in Figure 10:

- The converter’s voltage limit,
- The converter’s current limit,
- Maximum power because of available solar irradiance.

Constraints of connection points

The distribution grids can have multiple connecting nodes to the upper-layer grids, in which these nodes are denoted by index n∈N^((TC)). These nodes are considered slack nodes in both pre-scheduling and on-line problems. In the power flow models (Distflow and sensitivity factor based models), we do not have phase angle variables; thus, the voltage magnitude of these slack nodes should be known as parameters. However, the voltage magnitudes of these nodes depend on the neighbouring distribution networks’ power flows, which are not modelled in this study. As a result, the voltage magnitudes of slack nodes are considered uncertain parameters, since we do not have any information from their probability distributions. We only know the boundaries of these uncertain parameters.

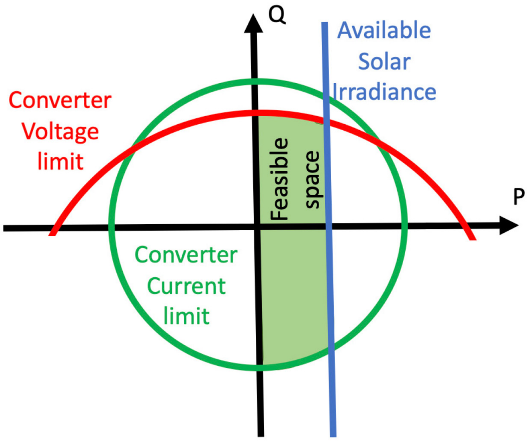


Figure 10 The capability constraints of PVs.

3.7.4 Uncertainty management in the pre-scheduling optimization problem

To handle the aforementioned uncertain parameters, the pre-scheduling optimization problem is formulated based on a classical stochastic programming approach and a novel distributionally robust programming approach.

This novel approach (developed in the course of this DiGriFlex project), unlike robust programming, does not find the worst-case scenario in the objective function. Each scenario of forecast is considered as the sum of the expected forecast and the deviation error around that expected value. For the sake of clarity, in the proposed distributionally robust programming, we linearize all variables and power flow equations around the expectation of forecast value.

The advantages of using distributionally robust programming instead of stochastic programming for pre-scheduling problems are as follows:

- The distributionally robust programming is written for the main forecasted scenario, and it needs less computational burden compared to the stochastic programming.
- For generating the representative scenarios, which are used in stochastic programming, we need large historical data sets, which are not available most of the time in low-voltage distribution grids. Distributionally robust programming, on the other hand, does not require as much historical data because it only needs the boundaries of uncertain variables.
- For LV distribution grids with many control/state variables, solving the stochastic programming with a high number of scenarios is not achievable.

A detailed mathematical formulation of the pre-scheduling optimization problem based on both stochastic programming and the proposed distributionally robust programming is presented in the deliverables 3.1 and 3.2 documents annexed to this report.

A small test bench for validating the performance of the proposed mathematical formulation has been developed based on the low-voltage network in La Chapelle, which is a real low-voltage three-phase radial distribution network (230/400 V, 50 Hz) located in a rural area in Switzerland. By analyzing various numerical results, the following conclusions can be drawn:

- By increasing the confidence-level in distributionally robust programming, the amount of positive active power flexibility will be reduced while the amount of negative active power flexibility is not changed too much. The reason behind this is that the resources for positive flexibility are limited.

- In the case of stochastic programming, more active power is sold to the upper-layer. It is because we need more than 100 scenarios to represent the existing uncertainties in the system.
- The result of distributionally robust programming is more conservative because of the nature of the formulation. By decreasing the confidence-level of the output, we can obtain a less conservative solution.

Pre-validation case studies for both the forecasting and optimization algorithms are carried out and numerical results are reported in corresponding deliverables 2.1, 2.2, 3.1, and 3.2 documents attached to this report.

3.8 Validation tests and experimental demonstration

With reference to WP4, a small test bench based on the low-voltage network in La Chappelle is developed and implemented in the ReIne laboratory in collaboration with Depsys SA. In collaboration with Depsys SA, real-time measurement of GridEye devices installed in La Chappelle, will be used to emulate residential loads in the validation tests in the ReIne laboratory.
The ReIne (RÉseaux INtElligents, French acronym for ``Smart Grids") laboratory (with hardware configuration in Figure 11) has been built at the School of Engineering and Management Vaud (HEIG-VD), Yverdon-les-Bains, Switzerland, to study and plan changes to distribution grids. The details and characteristics of hardware of ReIne will be explained in deliverables 4.1 – 4.4. In this project, the software of ReIne is improved to use the flexible resources, such as battery energy storage systems and PV converters, with controllable commands. Therefore, we are able to run forecast and optimization algorithms automatically.

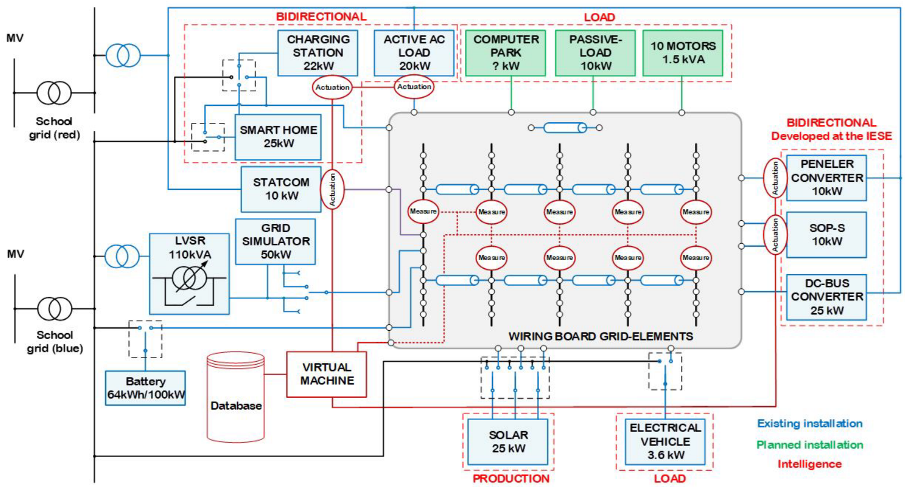


Figure 11: Configuration of ReIne laboratory and connected elements.

The overall view of system configuration and software used for this project is shown in Figure 12. The details of each box are explained in deliverables 4.1–4.4. In summary, the data acquisition, data pre-processing, and exploratory data analysis are done in LabVIEW by measuring voltage, current, and active and reactive power in 200 milliseconds. The LabVIEW code is programmed on National Instruments CompactRIO devices. The implementation of the forecasting systems is by means of algorithms run in R, which is a statistical programming environment. On the other hand, the optimization is run in Python. To this end, the interface between R, Python, LabVIEW, and different controllable devices such as batteries and PV system converters has been implemented.

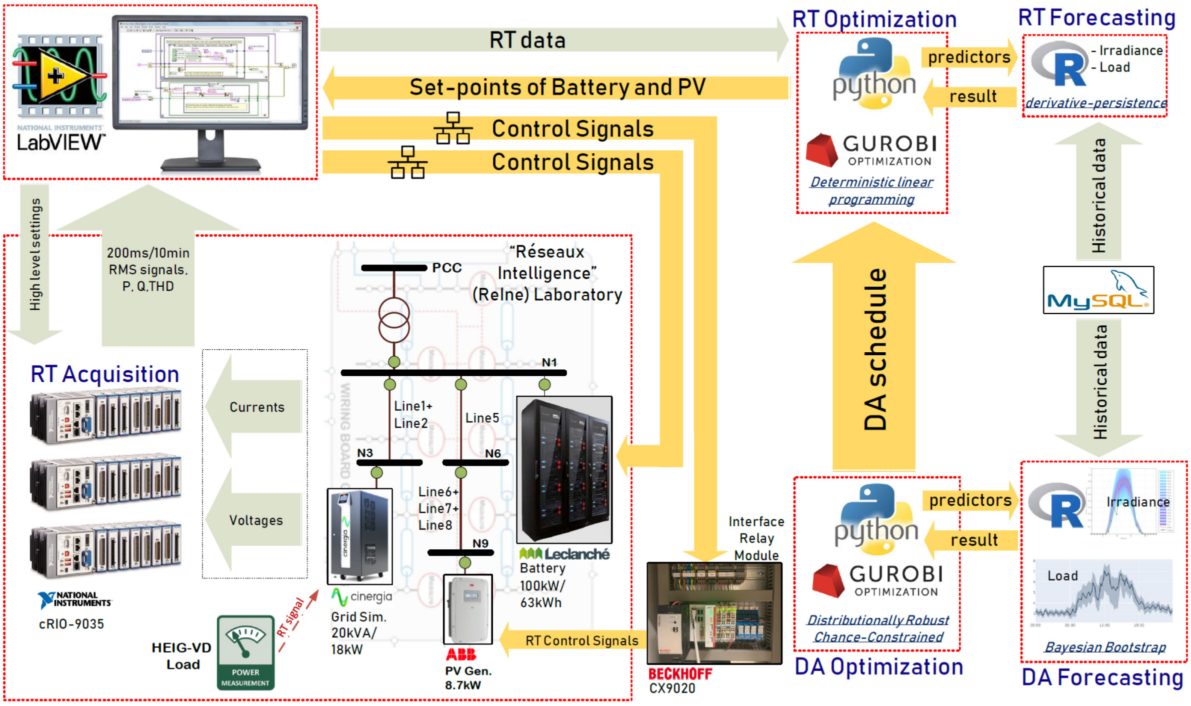


Figure 12: Overall system configuration for a laboratory demonstration platform.

Furthermore, the communication of controllable devices that have a distance from the central command system has been investigated.

Besides validation of proposed forecasting and optimization algorithms in an environment closer to reality, we learned a lot of lessons, which gave us ideas for modifying the proposed algorithms. To this end, the day-ahead and real-time forecasting systems and optimization systems have been revisited. The details of such modifications have been presented in deliverables 4.1 – 4.4.

4 National and international cooperation

At national level, the results of validation work package (WP4) regarding demonstration of the distributed provision of ancillary services in real-time operation of distribution grids, will be presented as a laboratory Demo, in the scope of Swiss Competence Centre for Energy Research-Future Swiss Electrical Infrastructure (SCCER-FURIES) as it is the ultimate goal of WP1 of SCCER FURIES. The Swiss partners of the project, namely, HEIG-VD/IESE, HEIA-FR, and EPFL/Power System Group will be involved in this activity.

At international level, this project is defined in the frame of ERA-NET Smart Energy Systems as a cooperation between industrial and academic partners from Switzerland (HEIG-VD/IESE, HEIA-FR, EPFL, Depsys SA) and Italy (University of Naples Federico II, University of Naples Parthenope).

5 Conclusion and future works

Regarding the project planning, all the following expected results have been successfully achieved.

In particular at technology level,

- A Two-Level Rolling Optimization system in Active Distribution Network (ADN) is developed
    - First level prescheduling (e.g., day ahead) and
    - Second level online control (real-time) of resources in an Active Distribution Network (ADN) with respect to the realization of uncertain parameters.
- Forecasting system that suits the day-ahead and real-time forecasting requirements of the above optimization system.
- Validation tests in reconfigurable distribution grid lab environment

At market adoption level,

- Assessment of potential ancillary service provision from distribution grids with respect to market and regulation frameworks.

Besides validation of proposed forecasting and optimization algorithms in an environment closer to reality, we learned a lot of lessons, which gave us ideas for modifying the proposed algorithms. To this end, the day-ahead and real-time forecasting systems and optimization systems have been revisited.

The laboratory demonstration platform for the DiGriFlex project (real-time distribution grid control and flexibility provision under uncertainties) is running and functional. The platform is created in the ReIne laboratory, which mimics and emulates various distribution grid configurations. For the experiment, a loop of data acquisition, data storage, forecasting uncertainties, optimization, and control activation is implemented. The control loop operates automatically on the day-ahead (DA) and real-time (RT) scales, taking into account the uncertainties in grid operation. The following major lessons were learned from the test results and the demonstration platform that can be applied to related industrial products:

- The accuracy of the Battery Energy Systems (BES) converter in activating set-points in various operating ranges must be considered.
- The proposed solution's scalability in terms of the number of nodes and components must be taken into account.
- The access to historical data and communicating predictors as forecast inputs were the bottlenecks of the proposed algorithms.
- Forecasting and optimization algorithms can be decomposed and parallelized to run on multiple processing units at the same time.

In future work to address the above lessons, a comparative evaluation of stream processing frameworks is needed for the implementation of RT control engines in distribution grids.

6 Communication

- The project objective, methodology, and expected outcomes were presented at the ERA-NET Smart Energy Systems annual conference in Namur, Belgium, in October 2019.
- The results of the intermediary project were presented at the ERA-NET Smart Energy Systems annual conference in August 2019. (Online webinar).
- The DiGriFlex project has been added to the ERA-NET project portfolio's online repository.
- The details of the project, as well as the algorithms proposed within it, were presented at the 2020 virtual working group meetings.
- The project outputs were promoted at the ERA-NET annual Joint Programming Conference on Smart Energy, which was held on November 23–25, 2021, with a 60-minute session.
- On September 27, 2021, the project outputs were demonstrated and tested in real-time in the presence of SFOE representatives in Yverdon-les-Bains, Switzerland.
- From May 29 to June 1, 2022, the project outputs were demonstrated in a poster at the 20th IEEE ICHQP (International Conference on Harmonics and Quality of Power), in Naples, Italy.
- On June 7, 2022, the project outcomes including a live demonstration of the forecasting, optimization, and control system in the ReIne laboratory of HEIG-VD was presented as a side event during the general assembly of the “RIE Association pour la Recherche et Innovation Energétique”, organized in Yverdon-les,Bains, Switzerland.

7 Publications

The following publications are directly resulted from developments in the DiGriFlex project:

1) M. Bozorg, A. Bracale, P. Caramia, G. Carpinelli, M. Carpita, P. De Falco, “Bayesian bootstrap quantile regression for probabilistic photovoltaic power forecasting,” *Journal of Protection and Control of Modern Power Systems*, vol.5, 21, pp. 1-12, 2020.
2) M. Bozorg, M. Carpita, P. De Falco, D. Lauria, F. Mottola, D. Proto, “A Derivative-Persistence Method for Real-time Photovoltaic Power Forecasting”, published in the proceedings of the International Conference on Smart Grids and Energy Systems SGES 2020, Perth, Australia, 23-26 November 2020.
3) M. Rayati, M. Bozorg, M. Carpita, P. De Falco, P. Caramia, A. Baracale, D. Proto, F. Mattola, “Real-Time Distribution Grid Control and Flexibility Provision under Uncertainties: Laboratory Demonstration”, In the proceedings of the 2022 IEEE 21st Mediterranean Electrotechnical Conference - IEEE MELECON 2022, Palermo, Italy, June 14-16, 2022.
4) M. Bozorg, A. Bracale, M. Carpita, P. De Falco, F. Mottola, and D. Proto. "Bayesian bootstrapping in real-time probabilistic photovoltaic power forecasting." *Solar Energy* 225 (2021): 577-590.
5) M. Rayati, M. Bozorg, R. Cherkaoui, and M Carpita. "Distributionally Robust Chance Constrained Optimization for Providing Flexibility in an Active Distribution Network." *IEEE Transactions on Smart Grid* (2022).
6) D. Lauria, F. Mottola, D. Proto, “Caputo derivative applied to very short time photovoltaic power forecasting”, *Applied Energy*, Volume 309 (2022).

The following publications are linked to the technical developments in the DiGriFlex project:

7) A. Bracale, P. Caramia, G. Carpinelli, P. De Falco, “Day-ahead probabilistic wind power forecasting based on ranking and combining NWPs,” International Transactions on Electrical Energy Systems, vol. 30, no. 7, e12325, 2020.
8) A. Bracale, P. Caramia, P. De Falco, T. Hong, “A multivariate approach to probabilistic industrial load forecasting,” Electric Power Systems Research, vol. 187, 106430, 2020.
9) M. Bozorg, A. Bracale, P. D. Falco, F. Mottola and D. Proto, "Incidence of Input Forecast Error in Microgrid Operation," *2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, Sorrento, Italy, 2020, pp. 269-274.
10) O. Galland, L. Eggenschwiler, P. Favre-Perrod, M. Rayati, M. Carpita and M. Bozorg, "Distribution Grid Control and Flexibility Provision Based on Optimal Products Split Selection Method," *2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, Sorrento, Italy, 2020, pp. 257-262.
11) M. Rayati, P. De Falco, D. Proto, M. Bozorg, and M. Carpita. "Generation data of synthetic high frequency solar irradiance for data-driven decision-making in electrical distribution grids." *Energies* 14, no. 16 (2021): 4734.

Finally, the following journal paper is under review for publication:

12) M. Rayati, M. Bozorg, M. Carpita, R. Cherkaoui, “Markov Chain-based Scenario Generation and Stochastic Optimization for Exploiting Underlying Flexibilities of an Active Distribution Network”, Under review in *Sustainable Energy Grids and Networks*, 2022.

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Appendices

- **Deliverable 1.1** Description of ancillary services provided within and from distribution grids.
- **Deliverable 1.2** Relative costs and benefits of operational and scheduling options for distribution grids.
- **Deliverable 2.1** Pre-scheduling forecasting systems and solution algorithms for distribution grids under uncertainties.
- **Deliverable 2.2** On-line forecasting systems and solution algorithms for distribution grids under uncertainties for real-time control.
- **Deliverable 2.3** Technical report including the validation of the forecasting systems using appropriate test bench and scenarios in a numerical environment.
- **Deliverable 3.1** Pre-scheduling optimization model for distribution grids under uncertainties, and its solution algorithm.
- **Deliverable 3.2** On-line optimization model for real-time control/scheduling of controllable resources in a distribution grid, and its solution algorithm.
- **Deliverable 3.3** Technical report including the validation of the above optimization models using appropriate test bench and scenarios in a numerical environment.
- **Deliverable 4.1** Validation case study and grid operation scenarios.
- **Deliverable 4.2** Pre-validation report including results of the power grid simulation tool.
- **Deliverable 4.3** Validation report including experimental validation of forecasting algorithms.
- **Deliverable 4.4** Validation report including experimental test results in the ReIne laboratory.