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Second Report on Project Progress

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Abstract:

This document provides an overview of the results achieved by the RESERVE project which ran for 36 months between 1st October 2016 and 30th September 2019.

Keyword list:

5G, Mobile communications, Renewable Energy Source (RES), Voltage Control, Frequency control, simulation, co-simulation, hardware in the loop, field trial, CSR recommendations, regulatory recommendations, network code, ancillary service.

Executive Summary

The RESERVE project aimed to enable up to 100% RES based power generation (excluding hydro-electric power) and to propose changes to network codes and ancillary services needed to enable the techniques developed in the project to be widely deployed.

RESERVE addressed this objective through its development of new techniques for voltage and frequency stabilisation. RESERVE has undertaken the definition of representative scenarios for the transition to up to 100% RES, has developed the research approach of Linear Swing Dynamics (LSD) and Virtual Output Impedance (VOI) and has developed, tested and internationally deployed the software and procedures needed to enable large scale co-simulation of power networks including the use of 5G-ready hardware in the loop to enable large scale co-simulation. RESERVE created a pan-European multi-site simulation test-bed, bringing together the best simulation facilities in Europe. The use of the RESERVE co-simulation software and approach for the trans-Atlantic co-simulation of frequency balancing between Europe and the US was an early major success story for the RESERVE project and it attracted widespread media coverage, including TV coverage in the US in the early part of the RESERVE project. This success story continued during the project with many more laboratories than expected deploying and using the RESERVE co-simulation environment. Additionally, the ICT implications and the business model implications of the new techniques have been investigated and defined in detail and laboratory experiments were used to verify that 5G meets the requirements of the new voltage and frequency which could be tested with live prototype 5G network infrastructure operating at low power in a laboratory environment. Field trials of voltage control were organised in Ireland and a wide range of stand-alone simulations and co-simulations were organised in Romania, Ireland and Germany to validate the frequency control techniques.

The changes needed to existing definitions of network codes and ancillary services to enable the use of the new techniques have been defined and where needed, the development of new codes and services has been proposed. An innovative programmable inverter was developed as a prototype for use in trials. The structure developed by RESERVE will accompany European utilities in their challenging journey towards the complete de-carbonisation of our energy sector for many years to come.

RESERVE has undertaken a wide range of stakeholder interaction and general dissemination activities, has published three books, numerous papers in peer reviewed journals and in conference proceedings. Furthermore, a professional course on the project concepts, organised in RWTH, Aachen in March 2019, has been made freely available as a MOOC to enable optimal access to project results and learnings. The final event of the project was held at the European Parliament on 10th September 2019 in a highly successful and well attended, project organised public session presenting a set of recommendations highlighting the implications of the project results for decision makers in enterprises, regulatory and political organisations. Lively discussion ensued and project members have taken up a range of invitations they received at this event to present the project results in other upcoming events beyond the end of the project, highlighting the interest in our timely results in the context of discussions on how to combat climate change.

All goals for the project were achieved and all deliverables and milestones due were delivered. Exploitation plans for project results have been finalised and the outlook regarding the large-scale uptake of results is positive.

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1. Introduction

Future energy systems will use renewable energy sources to minimise CO2 emissions. Currently large generators powered by fossil fuel turbines maintain the stability and quality of energy supplies through their inertia. The inertia of these generator-turbine groups gives providers a significant time window for reacting to network events. We urgently need to find ways to stabilise energy systems with up to 100% RES (where inertia is often lost due to power converter mediated energy transfer) to generate "RESERVEs" so that society can relax in the knowledge that it has a stable and sustainable energy supply.

The RESERVE project enables up to 100% penetration of renewables by having developed innovative approaches to system level automation based on innovative ancillary service provision with a close to market level of maturity, supported with validation of the concepts and policies using a pan-European real time simulation Infrastructure, and the anchoring of the approach with the main sector actors in Europe and beyond.

Energy systems with high levels of RES integration will require new distributed energy and ICT system architectures and will need to integrate the use of 5G ICT into the design of ancillary services to ensure system stability. The focus of the RESERVE project has been to prepare the way for new harmonised ancillary services with harmonised network codes, which are needed to operate RES based energy systems. We did this by developing new concepts to ensure system stability and undertaking feasibility studies and trials of elements of these concepts and their implementation in 5G ICT-enhanced solutions.

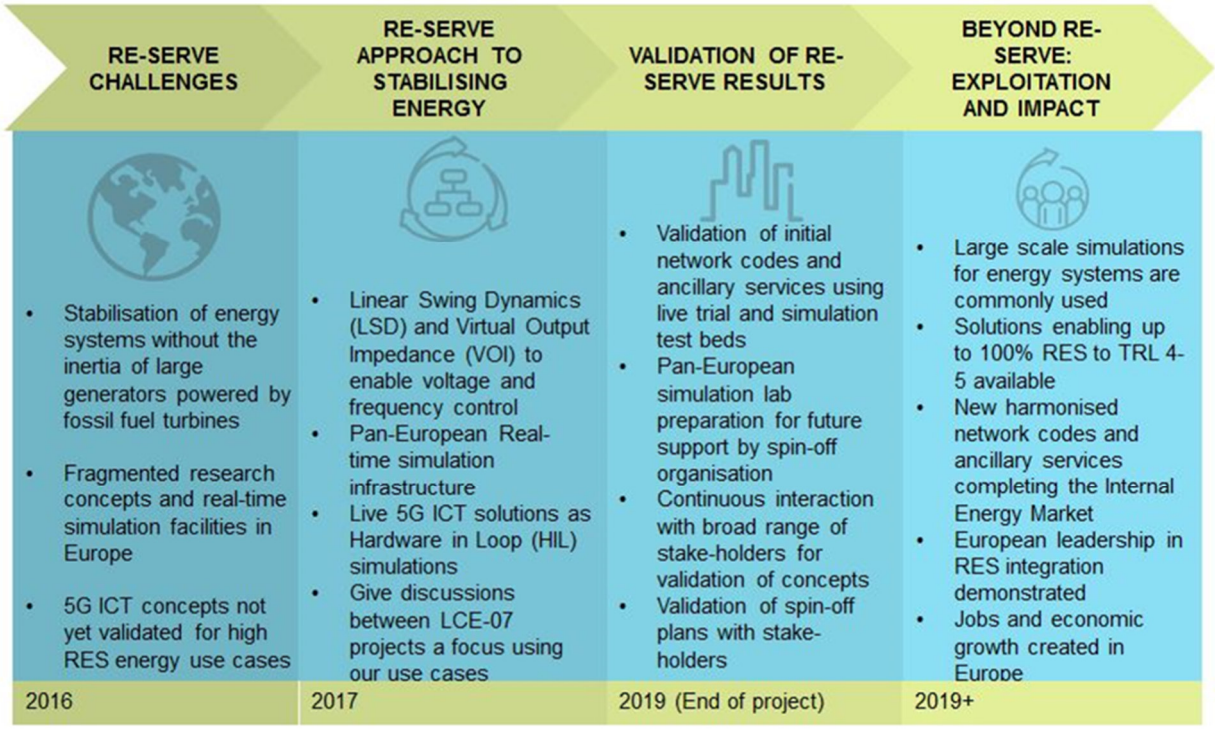

Figure 1 - From challenges through to preparing exploitation of results

1.1 The RESERVE approach to addressing the RES challenge

RESERVE addressed this challenge by researching new energy system concepts, implemented as new system support services enabling distributed, multi-level control of the energy system using pan-European unified network connection codes. Near real-time control of the distributed energy network is enabled by innovative 5G ICT. Energy system use case scenarios supplied by energy providers formed the basis of energy system models. Performance characteristics of the new control mechanisms were investigated through integration of energy simulations and live 5G communications. We created a pan-European multi-site simulation test-bed, bringing together the best facilities in Europe.

RESERVE achieved its strategic objective of enabling the integration of up to 100% penetration of renewables into the energy generation mix by

- Developing the novel research concepts of Linear Swing Dynamics (LSD) and Virtual Output Impedance (VOI),
- Validating the concepts through an innovative pan-European real time simulation infrastructure and
- Developing a set of harmonised regulations and network codes, supported by the sector actors and realised as field trials.

RESERVE addressed the RESERVE strategic challenge through:

- Putting dynamics both for voltage and frequency control, taking into account the role and characteristics of power electronics, at the centre of our research,
- Basing work on a bottom up approach and fully decentralised approach. Such an approach follows the characteristics of the decentralised future energy system and also means that the approach can be progressively adopted supporting transitions in energy systems,
- Proposing a new way to address the transition, monitoring the evolution of the system, using advanced real-time modelling, capable of supporting future decision-making processes,
- Incorporating innovative and social responsible innovation using to a Corporate Social Responsibility approach as a complement to technical studies,
- Involving all the key-stakeholders in the process from the beginning,
- Proposes a vision of exploitation that shows clear impact well beyond the duration of the project creating new opportunity for competitivity for the energy sector in Europe, and
- Proposes the right mix of laboratory and field trial to get immediate, concrete and realistic information on the real-life implementations enabling the immediate application of the knowledge generated in the project in the day to day work of utilities.

The RESERVE concepts take the energy community from today's traditional dispatchable generation energy systems through research, simulations and field trials and the preparation of enhanced definitions of network codes and ancillary services for consideration as potential harmonised European codes and services, to an energy system based on the use of up to 100% RES generation, as illustrated in the figure below.

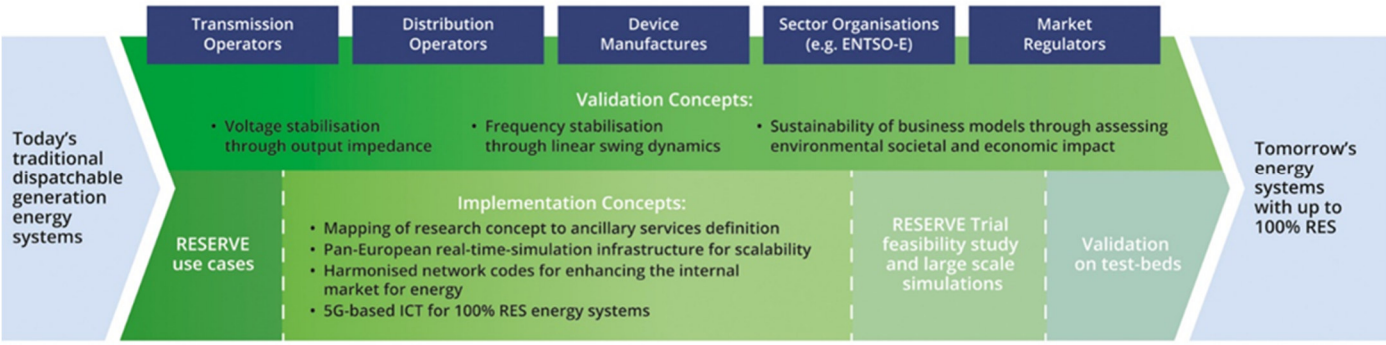

Figure 2 RESERVE concepts and approach

RESERVE has prepared and run a field trial of voltage control in Ireland. Tests using this infrastructure have been completed. A laboratory trial of frequency control in Romania and the use of the RESERVE co-simulation software for co-simulation, including 5G-ready hardware in the loop has been used to evaluate frequency control techniques. The figure below illustrates the key locations preparing the field trials and testing the initial co-simulation infrastructure.

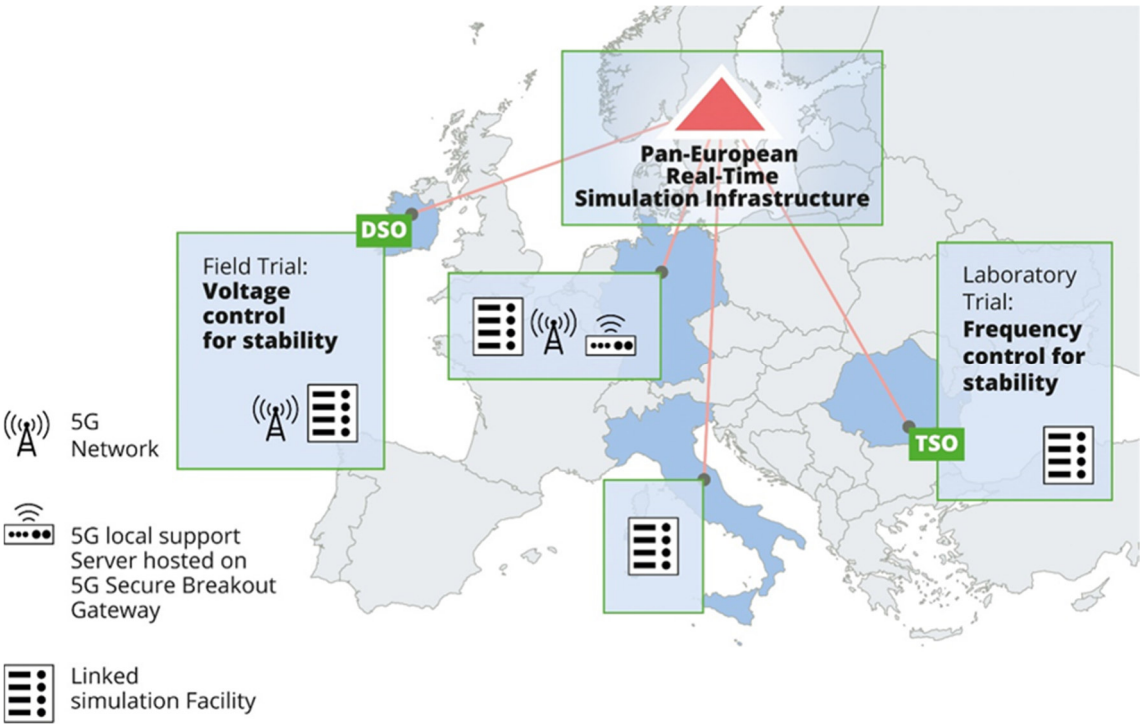

Figure 3 - RESERVE Field and Lab Trials

1.2 Results at the end of the RESERVE project

RESERVE produced a framework for stabilising energy systems with up to 100% RES integration, expressed as:

- A set of new research concepts for fast voltage and frequency control,
- A pan-European real-time simulation infrastructure, implemented as the interconnection of facilities at 4 universities, to validate the fast frequency and voltage control concepts during the project, and to support, after the end of the project, regulators and energy stakeholders in general in defining the energy transition process,
- Guidelines on the implementation of a new structure for Ancillary Services together with the corresponding measurements required to enable the European Internal Energy market to the completed,
- Development of a new Wideband-frequency Grid Impedance (WFZ) device,
- Requirements on 5G ICT for supporting energy systems with up to 100% RES integration, for promotion in standards bodies in the energy and communications sectors,
- An adaptation and harmonisation of today's network codes to support the implementation of the new structure of Ancillary Services,
- Demonstration of fast voltage control in a live field trial on the Irish power network, which shall show increased overall distribution system utilisation, supporting an increased penetration of distributed renewable energy sources (increasing load –> reduce wind curtailment),
- Feasibility study of fast frequency control based on real time hardware in the loop experimentation, and laboratory small-scale demonstration emulating the Romanian network use-case, and
- New ethical business models to support 100% RES integration in today energy systems.

All goals for the period were achieved. All deliverables and milestones due were delivered.

1.3 Impact of project results

RESERVE research concepts, implemented using the latest 5G ICT technologies, and promoted as ancillary service definitions to ENTSO-E/ACER. The RESERVE research concepts provide input to the definition of harmonised network codes which will help the energy sector to provide a

stable power supply with very high levels of RES integration and without the availability of hydro-electric generation station."

RESERVE new ancillary service definitions will enable energy providers to integrate high levels of RES to complete the European Internal Energy market as defined in the SET plan of the European Commission.

RESERVE is providing the software needed to connect to our novel pan-European real-time simulation platform and our Dynamic Phasor solver as Open Source code creating the capability of capitalising on the availability of computational resources across Europe to create a unified virtual simulation environment, enabling much larger scale energy system simulations than are currently possible.

RESERVE demonstrations of research results at TRL levels 4 and 5 in laboratory experiments and in field trials are creating confidence in the energy sector community that our techniques are applicable to today's and future energy systems.

RESERVE contributions to regulations and network codes will provide the basis for scalable deployment of solutions and demonstrate European leadership in RES integration internationally.

RESERVE results will create jobs in the service operations of the partner organisations and contribute to job creation in European based energy sector actor organisations, in the ICT and energy sectors.

RESERVE results will unlock new markets, mostly for innovative SMEs, in implementing new energy services based on the innovative RES integration concepts and the new automation and monitoring concepts, and

Partner organisations aim to increase their revenue streams and market shares by providing new innovative services to the energy sector which leverage the results of the RESERVE project.

The contribution RESERVE makes to society, the economy and integration, at EU level, is illustrated in the figure below.

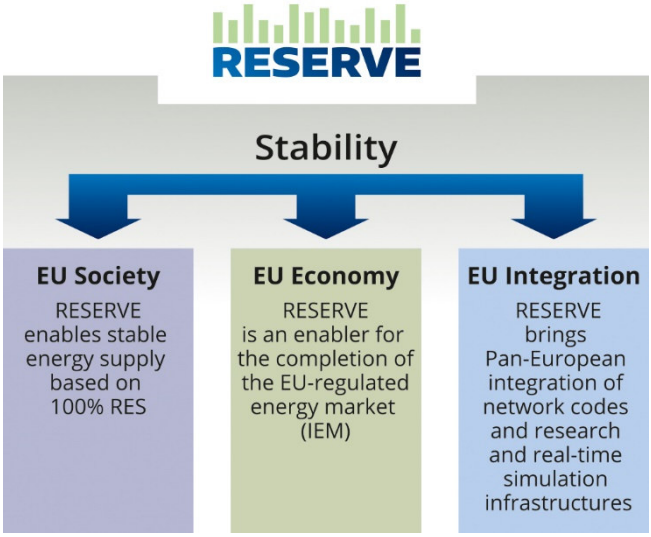

Figure 4 - The RESERVE strategic impact targets at EU level

2. Main achievements

2.1 System Level Work for RES integration

The objectives of this work are the definition of future scenarios with high level of RES penetration, enabling to highlight the most important aspects for the voltage and frequency control in the future power system. The definition of the scenarios needs the deep understanding of the features composing the scenarios, such as:

- Components
- Functions
- Information
- Communications

During the second period, the activity has focused on updating D1.5 (whose final version D1.6 was delivered at month 36), by reporting the variations occurred in the scenarios' definition due to the actual implementation of simulation and field trials.

Regarding the frequency control, two scenarios have been defined in the first period of the project, namely, Sf_A (Mixed Mechanical-Synthetic Inertia) and Sf_B (Fully Synthetic Inertia).

For Sf_A, only minor changes occurred (the inclusion of fossil and nuclear power plants for the transition phase to 100% RES and DC only at transmission level). The tests carried out for validation were based on offline simulations using a variety of platforms such as Dome, Simulink and Eurostag. Beyond the Romanian and the Irish grid (expected to be used already in the first period), the New-England system has been used for studying grid connected microgrids. The main results reached and summarised as achievements in D1.6 are the full implementation of the grids and the different components in three simulation platform (Dome, Simulink and Eurostag), which allowed to carry out simulation investingating the different aspects of the frequency control (i.e., inertial, primary and secondary frequency control). Also, the definition of frequency taker and maker have been reached. Furthermore, a model of battery storage was successfully tested in Eurostag and applied to the Romanian transmission system. The battery participated both to primary and secondary control. A model of Virtual Power Plant (VPP) was also introduced based on battery storage systems.

For Sf_B, different changes have been reported. The developed LSD-control scheme for RES and HVDC did not require communication system because only local information are needed. Only the adaptive frequency control for HVDC required communication system, based on optic fiber. The test for multi-machine LSD control were carried out on the 9-bus system, and hybrid ac/dc network have been also tested.

Regarding the voltage control, two scenarios have been defined in the first period of the project, namely, Sv_A (Dynamic Voltage Stability) and Sf_B (Active Voltage Management).

With reference to Sv_A, the changes maily referred to technical aspects of the implementation of the control. Three real time experiments have been carried out and the major achievements was the implementation of the developed control on a real device (completely built and developed in RESERVE) that was installed in the field trials.

Furthermore, a focus group on Static Solid Transformers (SSTs) was created. The idea behind this was the investigation about how this technology (that was demonstrated to be promising for future applications microgrids and storage deployment, of interest for RESERVE) could be used in the framework of the RESERVE scenarios. In particular, the scenario Sv_A was the ideal scenario where to apply this technology and the work focused on the list of the characteristics that the SST device should have to guarantee the proper implementation of the control proposed in the project (such as the topology, the integration of the impedance measurement and so on).

For Sv_B, the major change registered was the focus of the objective function on losses minimization or voltage unbalance, and the use of the current in the AVM strategy, Four separate

field trials have been used to validate the proposed methodology using batteries, vehicle-to-grid charge, photovoltaics and air-source heat pumps.

More information is available in Deliverable D1.6 which is provided on the web page www.reserve.eu.

2.2 Frequency Stability by design

The objective of this work has been to develop, through mathematical solutions and simulations, new frequency control strategies that allow increasing the share of generation from renewable and power converter-based distributed energy resources (RCB-DERs). The main achievements during the project have been the development and validation of the novel concepts of "Frequency Divider Formula (FDF)" and "Linear Swing Dynamics (LSD)" as new techniques that allow to overcome the actual inconveniences in the frequency control systems. The work done aimed also at identifying specific characteristics of the ICT systems required to achieve coordinated and fast control of RCB-DERs as a need to ensure the stability of the future power systems, which rely less and less on conventional power plants. Finally, the work done has resulted in the draft of several recommendations for Network Code (NC) definitions and Ancillary Services (ASs) to be evaluated, harmonised and promoted for international adoption by WP6.

The contributions to frequency control are thus threefold: a new definition of frequency in transient conditions, new frequency control strategies of non-synchronous devices; and a variety of proposal of solutions for the improvement of the stability of systems with low to zero inertia. Each contribution is briefly outlined below.

The definition of frequency as proposed by ENTSO-E network codes has been critically revised and a new definition has been provided. This new definition takes into account the fact that frequency, in the first instants after a contingency, is not the same in every point of the grid. These variations, even if small, may be crucial for the stable frequency control of the grid, especially if such a control is fast and provided by non-synchronous devices.

The work on the definition of frequency has been based on the development of two novel concepts: the frequency divider formula (FDF) and the rate of change of power (RoCoP). The former is a linear expression that links the rotor speeds of the synchronous machines with the frequency of the network buses. If one knows the rotor speeds of synchronous machines, then the bus frequencies can be calculated exactly, and vice versa, if one measures the bus frequencies, the rotor speeds can then be measured accurately. This formula is useful to define the "ideal" values of the bus frequencies and to compare such values with those estimated by conventional devices (i.e., phase-locked loops and PMUs). The validity of the FDF has been validated experimentally by means of the real-time digital simulators and physical PMU devices in the lab facilities made available by RTWH. The latter concept developed, i,e., The definition of RoCoP, is a direct consequence of the FDF and enables the determination of whether a device connected to the grid is regulating the active power injection/consumption and, consequently, quantifying its contribution to the frequency control of the system. The works on the FDF and RoCoP have been presented at several international workshops and conferences and have received very encouraging comments from other academics and practitioners. A patent has been filed on the RoCoP concept and UCD is currently contacting TSOs and aggregators to discuss the implementation of the RoCoP for metering purposes.

The linear swing dynamics (LSD) is a control strategy for power electronic converters that has been developed by RTWH and has two objectives: (i) replicating the dynamic response of synchronous machines with power electronic converters; and (ii) removing the idiosyncrasies of the synchronous machines (non-linearity). The result is an intrinsically stable control that, if systematically implemented in distributed energy resources, can help operating the systems with very low to zero physical inertia in the system.

Finally, several frequency control strategies have been discussed and tested. These include the utilisation of energy storage systems and microgrids. Both primary and secondary frequency controls have been considered. The results are a set of recommendations for network codes and ancillary services which, if put in place, will enable the increase of the penetration of non-synchronous devices and, in particular, of renewable energy resources. The requirements in

terms of both power systems and communications systems (including but not limited to 5G ICT) have been duly considered and discussed in the deliverables of WP2. All recommendations have been developed in strict collaboration with Transelectrica, CRE and EDD, thus ensuring that the proposals are both relevant for stakeholders and implementable in practice with, in most cases, a time scale shorter than a year.

Main achievements

During the second part of the project, the main achievements have been the following:

- The validation of the concept of LSD through simulations considering a multi-machine system with 100% non-synchronous renewable generation;
- The development of several applications of the FDF developed in the first part of the project, which include applications for dynamic state estimation of synchronous machine rotor speeds and local bus frequencies, and a formula to evaluate whether a device connected to the grid is performing frequency regulation, and to quantify the amount of frequency regulation being provided by the device for the purpose of properly remunerating the ancillary service provider;
- The identification of the specific characteristics of ICT systems required to achieve coordinated and fast control of RCB-DERs as a need to ensure the stability of the future power systems with little to no conventional synchronous machine-based generation;
- A thorough and comprehensive analysis of the role of converter-interfaced energy storage systems in future electric power systems;
- A thorough and comprehensive analysis of the role of grid-connected microgrids on the frequency control of the overall grid; and
- The drafting of recommendations for NC definitions and ASs.

More information is available in Deliverables D2.5, D2.6 and D2.7, which are provided on the web page www.re-serve.eu

2.3 Voltage Stability by design

The main objectives of the work are to define system level decentralised voltage control and monitoring solutions for futuristic low voltage (LV) distribution grids. Due to large penetration of renewables, dynamic problems such as interaction among converters due to impedance overlap, parallel resonances and constant power loads are on the rise. Steady state problems such as over/under voltage and voltage unbalance are also arising due to the distributed nature of power generation and due to the presence of single-phase inverters, which may result in unequal power generation across phases.

Dynamic Voltage Stability Monitoring (DVSM) was the proposed solution for handing dynamic voltage stability problems. Under DVSM technique, an impedance-based stability monitoring technique was developed, a grid impedance measurement concept based on Wideband System Identification (WSI) was developed and a Virtual Output Impedance (VOI) control technique was developed for grid integrated converters to mitigate harmonic instability problems. Working on the DVSM technique provided a pathway for building a low power, low cost and high bandwidth programmable inverter which can be used a Wideband Frequency grid Impedance (WFZ) measurement device.

Active Voltage Management (AVM) technique was the proposed solution for handing steady state voltage problems. In the first half of the project, AVM was formulated as a single objective optimisation problem, where the objective was either to minimise power losses or unbalances. In the second half of the project, multi-objective AVM was introduced which considers both power loss and unbalance minimization objective. The proposed methodology is exploiting the reactive power support capability of inverter based connected RES to distribution level.

To enable the implementation of the AVM across the trials a set of ICT architectures based on the characteristics of the network conditions from a topological and communications perspective were developed in D3.6. This was done to ensure the interoperability of the solution across a wide range of scenarios. To fully appraise the AVM implementation from an ICT perspective a full set of validated and tested ICT requirements were developed for each of the three ICT

architectures so as to inform the design and development of the software components of the base requirements needed to ensure the AVM is implemented as intended. The software components to receive the readings from the relevant inverter endpoints and execute the VVC in order to receive a reactive power setpoint that is sent to the inverter was developed and packaged to ensure the viability of its deployment in a heterogenous way across multiple platforms. From a monitoring perspective the readings from the inverters upon which the AVM was deployed is sent to SERVO Live, along with the VVC and the reactive power set points, so that the impact of the AVM on the RES device can be assessed.

Main achievements

- Developed a generalised framework for VOI design considering the measurement of grid impedance
- Defined and specified DVSM
- Defined and specified Multi-objective AVM : Considering both active power loss and voltage unbalance
- ICT requirements for both DVSM and AVM were updated
- Two implementation schemes were identified for DVSM where the ICT requirements are different:

  o WSI tool within inverter: requires high computational capability at the inverter end and low communication message size

  o WSI tool in SSAU: requires larger data size and low computational requirements for the RES inverter.

- Developed a low power programmable inverter prototype, which acts as a real-time impedance measurement and stability-monitoring device. The proposed device is low cost, mobile, offers high plug-play capability and in the future will be equipped with communication modules.
- Drafting of recommendations for ancillary services and network codes

The proposed strategy was tested on six ESB trial sites and the results were validated. The network codes related to the implementation of AVM were prepared in WP3.

More information is available in Deliverables D3.3, D3.4, D3.5, D3.6, D3.7, D3.8 and D3.9, which are provided on the web page www.re-serve.eu

2.4 Pan-European real time simulation infrastructure and live 5G testing platform

The vision of the Energy Union requires a scientific framework of support to validate solutions and concepts in a realistic manner before implementation. The concept implemented was to create a network of laboratories that, using real time simulation, which can support all the stakeholders in defining the next step in the evolution of the grid infrastructure. Such a lab system could support both market regulation and network code definition.

Commercial off the shelf (COTS) real-time simulators do not offer solutions for interconnecting simulation sites across the internet to share computational power. At the same time, the network size that can be simulated in a detailed real-time simulation is easily one magnitude smaller than what is possible in non-real-time simulations.

To address the interconnection problem, components were developed to build a pan-European real-time infrastructure: A gateway that connects simulation sites with minimal latency across the internet and a web interface that lets users monitor and control the simulators connected to this network. This solution was already employed in a large transatlantic real-time simulation demonstration called Real-Time Super Lab. In this experiment 8 laboratories participated: RWTH, POLITO and six laboratories in the US.

In May 2019, two researchers from RWTH conducted further interconnection tests during a 3 week-long Transnational Access (TA) Researcher Exchange (REX). The TA has been sponsored

by the European Horizon 2020 Research Infrastructure Project “ERIGrid” and was conducted in collaboration with two ERIGrid project partners TU Delft (Netherlands) and DTU (Denmark). During this TA, the tools developed have been tested, further improved and shared with ERIGrid partners.

Another problem with interfacing simulation sites is that simulation results from different COTS simulators are not always the same. It is difficult to analyse these differences because their implementations are not disclosed. For this reason, RESERVE isproviding a minimal simulation kernel designed for geographically distributed co-simulation that can be used in each laboratory and is verifiable because it is developed as open source.

Main achievements

The laboratory interface, called VILLASframework, for the pan-European co-simulation has been mostly implemented in the first reporting period. It includes:

- VILLASnode, which is a gateway to interconnect laboratories
- VILLASweb, which allows visualizing data exchanged between simulation sites in real-time
- Pintura, which visualizes and IEC61970 CIM based grid data and allows for editing the component parameters

In the second reporting period, the focus was on integrating these components with each other. Now, it is possible to visualize the grid topology generated by Pintura inside VILLASweb together with real-time measurements.

A third component named *VILLASdata* has been added to VILLASframework. It is responsible for offline storage and analysis of simulation results using a combination of relational (PostgreSQL) and NoSQL (Apache Cassandra) databases. For the addition of this new component, the performance of the existing VILLASweb code has been improved.

DPsim, the RESERVE real-time solver, is integrated with VILLASweb besides the integration with VILLASnode that was completed in the first reporting period. The integration with VILLASweb allows to send basic control commands to DPsim from the web interface and facilitates the use of DPsim in the context of a co-simulation monitored by VILLASweb.

After evaluating which frequency and voltage control concepts developed by the partners could be deployed to a DCS as described in the first periodic report, we prepared the components for the tests to be done in the trials accordingly.

The Ericsson communication network facilities have been integrated into the real-time simulation infrastructure of RWTH and were used to characterize different wireless techniques and scenarios in benchmark tests. This allows the emulation of these wireless connections for future experiments even if the communication network facilities are not available anymore.

More information is available in Deliverables D4.3 and D4.6 which are provided on the web page www.re-serve.eu.

2.5 Trials for validation of research results

Frequency Control Technique Laboratory Trial

The aim of the work done in the second half of the project was to continue collecting high reporting rate synchronized measurements from the Romanian power system buses during severe perturbation with fast dynamics, then to draw the appropriate conclusions. Additionally, the results of the off-line and real-time simulations, together with the achievements presented in WP5, are intended to demonstrate the effectiveness of the proposed solutions for frequency control in future low-inertia power systems.

Voltage Control Technique Field Trials

The objective of the Voltage Technique Field Trials is to validate in real world conditions the control techniques and ICT architectures developed within the RESERVE project. The trials utilise

a mixture of both mature and cutting edge inverter based generation and storage technologies which are key to the realisation of a 100% renewable electricity system.

Validation of pan-European Infrastructure

The objectives are to show how the pan-European infrastructure can be employed to demonstrate new concepts and what are the advantages of the real-time solver specifically developed in RESERVE.

The pan-European infrastructure was used in the RT-Superlab and other collaborations demonstration. Furthermore, we have presented the functionality of selected control techniques developed in WP2 and WP3 in real-time simulations on the developed infrastructure.

The real-time solver was validated with regards to performance using different grid topologies, a realistic grid inspired by the Romanian system and the benchmark network that was also used for the development of frequency control concepts.

Validation of ICT Concepts using 5G

RESERVE has defined ICT concepts using 5G mobile networks. The concepts and requirements placed on the ICT by new power systems are validated by running tests. As part of test cases for performance measurement tests were defined in order to validate the requirements.

Main achievements

Frequency Control Technique Laboratory Trial

Additional sets of data were collected by Transelectrica from the PMUs installed in the Romanian power system buses during critical events that occurred in Romania or outside Romania. The high granularity data provided by the PMU allowed us to capture the fast dynamics experienced during the events and to compare these data with external data.

The Dobrogea region of the Romanian power system was implemented in Simulink. Frequency containment control, Frequency restoration control, VPP control, together with wind and BESS dynamics models were included in the model. Various simulations have been done on-line and in real time.

Voltage Control Technique Field Trials

Permission was requested from authorities to deploy the field trials; technologies were procured and customised and sites commissioned live on the network. Voltage control techniques developed within RESERVE were customised for each trial site and performance monitored and adapted as necessary.

A range of the ICT concepts developed were implemented in the control and communication architectures deployed in the Field trials.

The end to end system was validated thus showcasing the robustness and potential for scalability of each elements of the solution as well as the solution as a whole. Which was further confirmed with system's ability to facilitate 3rd party aggregators devices and communication methods and would allow for rapid growth in the event of these new actors in the energy sector becoming larger and larger in presence.

Validation of pan-European Infrastructure

Voltage control techniques were successfully validated under realistic conditions with dynamic models and in a real-time scenario.

The components of the pan-European simulation infrastructure were tested and improved in another collaboration focussed on geographically distributed real-time simulation, in this case undertaken in cooperation with TU Delft.

The DPsim real-time solver developed in RESERVE was validated using a grid inspired by the Romanian grid and synthesized grid data. Due to optimisation of the code and operating environment, it was possible to run simulations with computation times per step in the magnitude of 10 to 100µs which is in the range expected from commercial-off-the-shelf computing hardware.

Validation of ICT Concepts using 5G

During the second reporting period tests were conducted on 5G-prototype (NR) system and enterprise 5G-ready radio systems. The results achieved by running the tests on these two test systems are compared with the results achieved on 5G-ready test system in first reporting period. The results have shown that the requirements defined by the RESERVE can be achieved by 5G mobile network. Through our series of tests, we have demonstrated that 5G network fulfil the stringent requirements of energy scenarios for ultra-reliable and low latency communication protocols. The edge cloud concept was demonstrated, highlighting its contribution to reducing latency and increasing the reliability of communications.

More information is available in Deliverable D5.2, D5.3, D5.5, D5.7 and D5.9 which are provided on the web page www.re-serve.eu

2.6 Regulatory, legal issues, business models and CSR

Starting from the technical challenges regarding the voltage and frequency control for maintaining the stability of the energy system in the scenario "up to 100% RES", the activity focused on estimating the impact on the regulatory framework, standardisation issues, business models and CSR.

Following the analysis of the technical proposals on voltage and frequency control, and an extensive activity of consultations with the representatives of the institutions and organisations in the field of policies and regulation, we achieved a set of harmonised network codes and defined a new structure of ancillary services.

The final list of proposals to modify the regulatory framework, transmitted to the relevant European authorities and organisations (such as ENTSO.E, ACER, CEER, DG Energy, etc.) with roles on influencing and triggering the implementation process, includes the following:

- One Network Code proposal dedicated to storage
- 11 final updates of the existing Network Codes
- 7 final proposals for new ancillary services
- 4 final proposals for updating the existing ancillary services

After a comprehensive stakeholder analysis, an analysis of the market changes is done. Under consideration of the pillars of sustainability and Corporate Social Responsibility, new and existing business models are evaluated. Furthermore, RESERVE's new and changed network codes are evaluated on sustainability and Corporate Social Responsibility. In a next step, recommendations are made to policy makers, enterprises and other stakeholder groups. The recommendations suggest inter alia a broad debate on topics suggested by RESERVE's consortium.

The main achievements

- An analysis of the main political and economic and social milestones that allowed us to better assess and propose a new set of key regulatory principles referred to as "options", to be considered when determining the appropriate governance framework for the future electricity transmission networks (beyond 2040)
- The extension and intensification of consultations with stakeholders such as TSOs, DSOs, the European Commission, national and European regulatory organizations, including ENTSOE, which allowed for an extension and better substantiation of the final RESERVE proposal list. Into the same context, we organized the second RESERVE dedicated workshop on the regulatory framework in Brussels, with a wide international participation from all categories of organizations and stakeholders to support our proposals.

- The second iteration and complete definition of the final set of proposals, as part of the deliverables D6.2 and D6.4, including the following: a new transmission network code, 7 new ancillary services, 4 changes within the definition of existing ancillary services, and 11 updates of the existing network codes.
- Main milestones set-up for the development and implementation of the plan to adopt the proposals internationally, including through consultation with representatives of the European Commission, ENTSOE, ACER, CEER and other relevant European organizations and institutions in the field of energy regulation.
- Disseminating and exploiting the project results by constantly participating to the EU BRIDGE initiative meetings and several international meetings and events (a detailed information on the attended events are included in the WP7 report)
- Based on the RESERVE results, we have formulated and submitted a series of recommendations to policy and regulation authorities and organisations (such as ENTSO.E, ACER, CEER, DG Energy, etc.) with roles on influencing and triggering the implementation process of our proposals, including changes in the network codes and a new structure of ancillary services to policy makers.
- Favorable reaction and involvement of EC DG Energy and ENTSO.E in the implementation process of Network Codes updates proposed in the RESERVE project. At the closing event of the RESERVE project organized in the European Parliament, the representatives of EC DG Energy and ENTSO.E officially declared that the RESERVE project is a reference in the context of higher RES penetration, and the proposals advanced by RESERVE are taken over by ENTSO.E experts for analysis and further implementation.

More information is available in Deliverables D6.2, D6.3, D6.4, D6.6, and D6.7, which are provided on the web page www.re-serve.eu

2.7 RESERVE Recommendations

RESERVE has developed recommendations to sector actors. The first recommendation is on the RESERVE network codes and ancillary services. The second one proposes a public debate on five proposals in order to kick off a discussion about the framework for the pathway to 100% RES.

2.7.1 Recommendations to Sector Actors

# I	**ENTSO-E and system operators should consider adopting RESERVE's updated network codes and new ancillary services structure**

RESERVE has developed proposals for new and updated network codes and ancillary services, which are needed to support the transition to up to 100% RES. They are based on RESERVE's research that has been conducted in the fields of frequency control, power system inertia and voltage control and have been validated in field trials deployed on the Irish grid by the DSO ESB Networks and through simulations based on network data from the Romanian TSO TRANSELECTRICA. RESERVE is involved in an ongoing dialogue with ENTSO-E and EDSO regarding the RESERVE proposals. The modified and new network codes and ancillary services proposed by RESERVE are needed in order to implement a stable power system with a low level of available mechanical inertia. They are intended as the starting points for the development of new standards focused on ensuring the security and restorability of the grid. An extensive list of the RESERVE proposals for updated and new network codes and ancillary services can be found in Deliverables 6.3 and 6.4].

# II	**A public debate on how to achieve up to 100% is needed – RESERVE offers six concrete proposals to kick-off the discussion**

During the RESERVE project, partners have held regular discussions on the economic, regulatory and societal changes needed to accompany the successful implementation of the RESERVE technical results in order to enable society to move towards 100% RES. Debates in the field of energy, in particular electricity, are often led by experts but they concern every single private individual. Therefore, it is important that politicians take part in the debate in their role as

representatives of the people. We have identified two groups of sector actors who should be in the focus as leaders of a public debate:

- energy system operators, enterprises and prosumers, and
- policy makers, authorities and regulators.

2.7.2 Suggested Proposals for Energy System Operators, Enterprises and Prosumers

System Operators face major changes in grid structure and grid management due to decentralized and mostly mechanical inertia-free generation. RESERVE suggests a public debate focused on the following proposals:

1)	Energy system operators should consider smart solutions in their investment strategies

The results of RESERVE propose smart solutions for controlling the grid. Furthermore, RESERVE has developed a programmable inverter which can be used as a wideband grid impedance measurement device. System operators, enterprises (such as Ancillary Service Providers) and prosumers need to consider investing in such advanced equipment.

Current regulatory regimes lack support for investments in services and in measurement systems. Supporting such investments would be a potential action which would promote the transition towards 100% RES. The TOTEX approach, proposed by the EU Winter Package [4], is a first step in this direction.

2)	Due to the volatility of RES, a new energy pricing system is needed to encourage new behaviour and investments

Currently, private customers and most companies are charged for every kWh of energy consumed. To cover peaks and troughs in renewable electricity generation, storage options are needed for maintaining grid stability. Consumers and enterprises have to be incentivised to use electricity during periods of excess generation and to provide additional storage capacity. To achieve this incentivisation, suitable innovative energy pricing schemes must be put in place. For example, a share of the financial savings achieved through changed consumption behaviour could be allocated to consumers and enterprises.

3)	Energy system operators should investigate the use of 5G features when planning their transition to up to 100 % RES based generation

Future grid operation requires the ability to perform distributed control of the RES, which are spread out over the distribution grid. Measurements must be gathered from the RES and control actions communicated to them. This requires a communications system that encompasses grid control centres, substations and the distributed RES themselves. RESERVE has placed a particular focus on investigating how mobile 5G technologies can provide the communications capabilities required for 100% RES penetration. In particular, 5G's high resilience and low communications latency make it a suitable technology for distributed control applications.

2.7.3 Suggested Proposals for Policy Makers, Authorities and Regulators

Policy makers, authorities and regulators must address the harmonisation of the European energy system and introduce legislation to support an energy transition towards 100% RES. RESERVE suggests a public debate focused on the following proposals:

4)	Further open balancing markets to enhance the participation of owners of RES and storage systems

RESERVE proposes lowering the entry barriers to participation in balancing markets in order to increase the capacity offered for balancing. In Germany, a recent step in this direction was taken with the lowering of the minimum power generating capacity of participating systems in the balancing markets from 5 to 1 Megawatts, enabling many smaller power generators to participate in balancing markets for the first time.

5)	Deploy specific targets for the development of the available storage capacity and provide corresponding incentives for storage investments

Increasing the share of power generation from RES needs to be accompanied by a corresponding increase in the capacity of storage facilities in order to maintain grid stability. Depending on regional variations in electricity generation, appropriate targets for storage capacity need to be established. Depending on the perspective, it is expected — in the case of Germany — a demand for between 83 TWh [5] or even 147 TWh [6] of storage capacity by 2050. The timeframe of these targets should reflect RES integration plans up to the final target of achieving 100% RES by 2050. RESERVE suggests the establishment of an intermediate target for 2030.

Incentives have to support the expansion of storage capacities. A higher amount of decentralized power storage capacity can increase local self-consumption which discharges the distribution grid [7]. According to the German regulations for renewable energy, storage capacity provided to the grid should receive attractive remuneration, even for decentralized and small-scale storage capacity. If the price of storage continues to decrease, incentives could be adjusted in the following years.

6)	Introduce legislation which reflects the true cost of energy, considering social and environmental costs

If the costs of pollution and measures required to address the climate change are considered as components of the cost of energy, then conventional power is already costlier than is generally appreciated. In this context, the full cost of energy is not reflected in current electricity prices. For example, the costs of the climate change are not covered by today's electricity prices. Were the full costs of energy to be included in the electricity price, as suggested in recently discussed CO_2 tax proposals, the cost of electricity would rise dramatically. The German Environment Agency estimates about 180 Euro per ton of CO_2 to be today's market price if all environmental costs were to be considered [8]. Switching from fossil fuel electricity generation to renewable energy sources would reduce the total cost of energy through reducing the environmental damage caused by the burning of fossil fuels.

2.8 Generating Impact with RESERVE

The overarching objective of the work implemented during the whole project time was to maximise the scientific, industrial and societal impact of the project by creating awareness of the technologies and the innovation activities, as well as collecting the guiding feedback received from the most relevant stakeholders in order to incorporate the recommendations in the strategic orientation of the project.

Initially, the marketing objectives and the special targets for the RESERVE project, derived from the strategic goals, were worked out, and consequently the most appropriate style and design of the communication and dissemination material were created and continuously adapted in order to maximise the impact on the most relevant target groups of the project.

Numerous actions were undertaken during the whole project time in order to channel the most relevant results and conclusions about the ongoing work. The focus has been especially on the

definition of a new -or updated- set of harmonized network codes and ancillary services as well as on the identification of the most promising project exploitable results, which resulted in the draft of an exploitation plan. These activities include for example networking events with TSOs, DSOs and SDOs with the purpose of creating a group of experts with whom to exchange on our results and exploitation ideas. Strategic discussions based on the inputs received from the technical work packages (WP1-WP5) were supported in WP7 by the regulatory framework defined within WP6.

In parallel, during the whole duration of the project, all RESERVE partners have been very active in communicating the results obtained in conferences and workshops, and in promoting the project in both scientific and industrial communities by participating to high level conferences and innovation events and exhibitions.

The main achievements

First of all, new communication and dissemination material were prepared and presented at the attended events in the second half of the project, such as a new banner, 3 technical posters and a final brochure resuming the main project topics and achievements. New videos of the field trials in Ireland and of the demonstrations in the RWTH Aachen laboratories were also shot. Various articles about the RESERVE project appeared in national online news sites and newspapers in Ireland and Romania, as well as in EU communication media such as the INEA Brochure, the BRIDGE Newsletter and on the Success Stories section of the EC Website. The project website and the social media were regularly updated with the most relevant news.

The work started since the beginning of the project to create awareness of the ongoing work, especially with focus to the definition of a new set of ancillary services and harmonised network codes, continued in the second period. The main project achievements were shared during formal and informal consultations with representatives of relevant categories (TSOs, DSOs, SDOs, manufacturers …), and feedbacks and inputs received by the relevant stakeholders and by the advisory board members, as well as from representatives of European institutions, were collected and integrated in the ongoing exploitation plans. The most relevant events that have been organized in this context were the 2nd RESERVE advisory board meeting (Brussels, 25 January 2019), a stakeholder consultation workshop on the project results (Brussels, 21-22 November 2018), and various bilateral meetings with ACER and ANRE, as well as with member of the ENTSOE, EDSO, EURELECTRIC, EVEA, CEN/CENELEC and with DG Energy representatives.

In the second half of the project RESERVE has continued disseminating the project concept and the results of the technical work through the organization and participation with talks and exhibition stands in numerous targeted events such as the EUW2018, the Innogrid+ 2018/2019, and the EUSEW 2018/2019. The results of the projects were presented at 65 high level scientific and industrial conferences and produced already 18 articles published in peer-reviewed scientific journals and 1 book (see Chapter 1.5.2 for the complete list). Two more books are currently under editing process and are expected to be published soon. Furthermore, three open source software were released (DPSIM, VILLAs Framework, MQTT Broker) and a fourth one will be released soon (AVM).

Apart from the continuous communication and dissemination activities described so far, two important events were organised by WP7 in the second half of the project. The first was the Exploitation Strategy Seminar (ESS) that took place in Bucharest on the10th of October 2018. The ESS is a service offered under project formal request by the EC, and had the objective to brainstorm and discuss on the exploitation opportunities of the project, as well as on risks and potential obstacles and enhance the team awareness on the importance of connecting with customers and better communicating the project results. The other important achievement of WP7 was the very successful organisation of the training course at the RWTH Aachen University: „Challenges and solutions in Future Power networks" which will be soon available free of charge on a dedicated YouTube channel.

More information is available in Deliverables D7.2 and D7.3 which are provided on the web page www.re-serve.eu

3. Conclusions

The strategic objective of the RESERVE project is:

To enable up to 100% penetration of renewables by developing innovative approaches to system level automation based on innovative ancillary service provision with a close to market level of maturity, supported with validation of the concepts and policies using a pan- European real-time simulation Infrastructure, anchoring the approach with the main sector actors in Europe and beyond."

After 36 months of operation, RESERVE has achieved the project operational goals, exceeding them in many respects, building on the early successes of the project to go beyond the original plan to produce extra results, such as the development of a prototype programmable inverter and the definition of recommendations for action based on the projects' technical results.

The political and regulatory climate has changed during the project lifetime and the changing environment has made it easier to promote the uptake of the project results to our target audiences, particularly in the energy sector in which efforts to address climate change are increasingly in focus. The level of importance in the energy sector attributed to researching how to achieve the project strategic goal of enabling up to 100% RES generation, without the inertia of hydroelectric power, has grown significantly and the interest in the project results is very high resulting in the publication of 3 books based on the project work and invitations for project members to present results in further events beyond the end of the project. The prospects for the uptake and exploitation of project results in commercial contexts look bright. The project partners end the project further collaborations in running projects and with plans and to continue to work together in the future in research, innovation and commercial contexts, building on the many successes of the RESERVE project.

4. List of Abbreviations

B2B	Business to Business
BMS	Building management system
CAPEX	CAPital EXpenditure
CENELEC	European Committee for Electro technical Standardization
CEP	Complex Event Processing
COTS	Commercial off-the-shelf
CPMS	Charge Point Management System
CSA	Cloud Security Alliance
EMS	Decentralised energy management system
DER	Distributed Energy Resources
DMS	Distribution Management System
DMTF	Distributed Management Taskforce
DSE	Domain Specific Enabler
EAC	Exploitation Activities Coordinator
ERP	Enterprise Resource Planning
ESB	Electricity Supply Board
ESCO	Energy Service Companies
ESO	European Standardisation Organisations
ETP	European Technology Platform
ETSI	European Telecommunications Standards Institute
GE	Generic Enabler
HEMS	Home Energy Management System
HV	High Voltage
I2ND	Interfaces to the Network and Devices
ICT	Information and Communication Technology
IEC	International Electro-technical Commission
IoT	Internet of Things
KPI	Key Performance Indicator
LV	Low Voltage
M2M	Machine to Machine
MPLS	Multiprotocol Label Switching

MV	Medium Voltage
NaN	Neighbourhood Area Network
NIST	National Institute of Standards and Technology
O&M	Operations and maintenance
OPEX	OPerational EXpenditure
PM	Project Manager
PMT	Project Management Team
PPP	Public Private Partnership
QEG	Quality Evaluation Group
S3C	Service Capacity; Capability; Connectivity
SCADA	Supervisory Control and Data Acquisition
SDH	Synchronous Digital Hierarchy
SDN	Software defined Networks
SDOs	Standards Development Organisations
SET	Strategic Energy Technology
SET	Strategic Energy Technology
SG-CG	Smart Grid Coordination Group
SGSG	Smart Grid Stakeholders Group
SME	Small & Medium Enterprise
SoA	State of the Art
SON	Self Organizing Network
SS	Secondary Substation
TL	Task Leader
TM	Technical Manager
VPP	Virtual Power Plant
WP	Work Package
WPL	Work Package Leader