THEME [ENERGY.2012.7.1.1] Integration of Variable Distributed Resources in Distribution Networks

IGREENGrid

(Deliverable 1.6)

SiNGULAR

Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration

(Deliverable 11.2)

sustainable

(Deliverable 9.8)

Short report on exchanged experiences on demonstrations and validation of the proposed solutions

Common Deliverable

Authors

Authors	Organization	Email
Gerardo Osório	UBI (SiNGULAR)	gjosilva@gmail.com
João Catalão	UBI (SiNGULAR)	catalao@ubi.pt
Pedro Godinho Matos	EDPD (SuSTAINABLE)	Pedro.godinhomatos@edp.pt
David Rubio	IBERDROLA (IGREENGrid)	drmi@iberdrola.es
Nuno Silva	EFACEC (SuSTAINABLE)	nuno.silva@efacec.com
Jovica Milanovic	Man. Univ. (SuSTAINABLE)	jovica.milanovic@manchester.ac.uk
Kai Strunz	TU Berlin (SuSTAINABLE)	kai.strunz@tu-berlin.de
Ricardo Bessa	INESCTEC (SuSTAINABLE)	rbessa@inesctec.pt
André Madureira	INESCTEC (SuSTAINABLE)	andre.g.madureira@inesctec.pt
Pablo Frias	IIT (SuSTAINABLE)	pablo.Frias@iit.comillas.edu
Despina Koraki	TU Berlin (SuSTAINABLE)	despoina.koraki@tu-berlin.de
André Neves	EDPD (SuSTAINABLE)	andre.neves@edp.pt
Gianfranco Chicco	POLITO (SiNGULAR)	gianfranco.chicco@polito.it
Cláudio Monteiro	SMARTWATT (SiNGULAR)	cdm@fe.up.pt
Anastasios Bakirtzis	AUTh (SiNGULAR)	bakiana@eng.auth.gr
Vassilis Nikolopoulos	INTELEN (SiNGULAR)	v.nikolopoulos@intelen.com
Efthalia Skoufa	ALSTOM (SiNGULAR)	efthalia.skoufa@power.alstom.com
Javier Contreras	UCLM (SiNGULAR)	Javier.Contreras@uclm.es
Daniel Henriquez	ITC (SiNGULAR)	dhenriquez@itccanarias.org
Benoit Bletterie	AIT (IGREENGrid)	Benoit.Bletterie@ait.ac.at
Marco Rossi	RSE (IGREENGrid)	marco.rossi@rse-web.it
Nikos Hatziargyriou	ICCS (IGREENGrid)	nh@power.ece.ntua.gr

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Executive summary

This deliverable, which is common to the three projects, explains the collaboration made between SiNGULAR, SuSTAINABLE and IGREENGrid projects near the end of their lifetime, corresponding to a short report on exchanged experiences on demonstrations and validation of the proposed solutions. The deliverable focuses specially on 6 topics: energy storage, forecasting, generation curtailment, demand side management, voltage control, and scalability & replicability.

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1 Projects Overview

1.1 SiNGULAR

The main objective of the SiNGULAR Project is to develop tools for the optimal planning distributed energy sources in insular grids as well as to create innovative tools for improving the operation of island power systems under high RES penetration. The planning and operation of island power systems is more complex than those of continental power systems, given the grid stability problems caused by the massive integration of non-dispatchable and dispersed energy sources. These tools have been developed in different areas: RES forecasting, power flow analysis, energy storage management, scheduling algorithms, market issues and DSM strategies. All of them are key tools for the optimal operation of island electrical systems under high RES penetration scenarios, and will contribute to overcome existing technical, regulatory and market barriers to the massive integration of RES in insular systems from technical, regulatory and market point of view. In all cases, the stochastic nature of RES and its operation is a key common factor, and the uncertainty has to be managed by the insular grid operation.

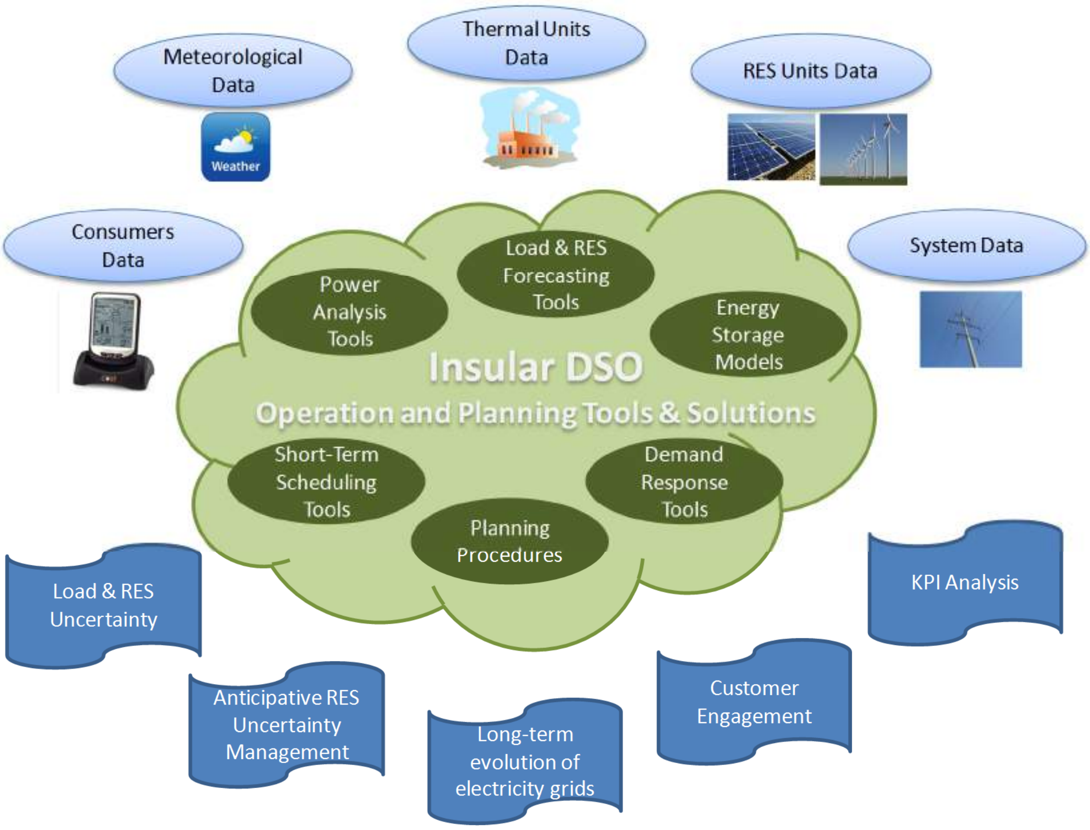


Figure 1 (SiNGULAR Approach)

The final result expected is to demonstrate that the algorithms and tools developed in

SiNGULAR to improve RES integration. These algorithms and tools will be tested and validated in various pilot sites, and under different meteorological conditions, allowing for testing the robustness and general performance of these solutions under real conditions with respect to what can be done in conventional laboratory setups. Their application at the different proposed sites will allow comparisons of data gathered during the systems operation in different islands.

Some of these pilot sites like S. Miguel (Azores), Crete (Greece) and Braila (Romania) will test in real or near-real operation thanks to the direct participation of grid operators as project partners in the SiNGULAR consortium: EDA, HEDNO and ELECTRICA.

1.2 SuSTAINABLE

The SuSTAINABLE project will develop and demonstrate a new operation paradigm, leveraging information from smart meters and short-term localized predictions to manage distribution systems in a more efficient and cost-effective way, enabling a large-scale deployment of variable distributed resources. The SuSTAINABLE concept is based on the cloud principle, where the Distribution System Operator (DSO):

I. collects information from smart metering infrastructure and other distributed sensors, and communications from external partners, market operators, and maintenance staff;

II. processes the information using tools such as distribution state-estimation, prediction tools, data mining, risk management and decision-making applications;

III. communicates settings to power quality mitigation devices, protection relays and actuators, distribution components and distributed flexible resources;

IV. assesses its market strategy as a provider of ancillary and balancing services.

The SuSTAINABLE concept also involves an active management of distributed flexible resources by DSOs. A multi-objective decision-making scheme will be designed to keep network voltage inside operational constraints, to minimize DG energy spillage related to network constraints, to minimize operational expenditures related to high reliability and continuity of service for loads and generators, to minimize aging of automatic tap changers subjected to sudden variations of power flows, and to maximize the balancing and ancillary services to be provided to TSOs when necessary. It will also focus on flexible protection schemes, to avoid failures in selectivity and reliability of the protection plan in low-impedance earthed neutral MV networks related to DG integration. Finally, the market strategy to be defined by the SuSTAINABLE concept encompasses aspects related to flexibility pricing for distribution network users and distribution system operators´ strategies with respect to balancing and ancillary services markets.

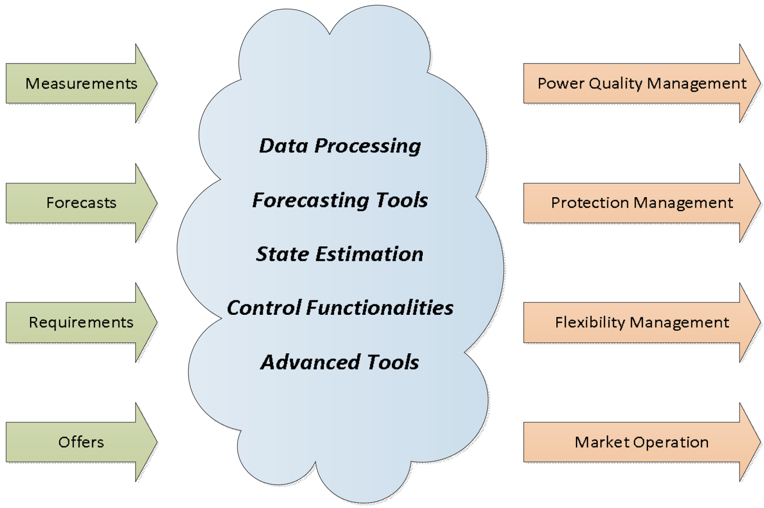


Figure 2 (SuSTAINABLE Approach)

1.3 IGREENGrid

In the IGREENGrid project, six world-class DRES integration Demo Projects in low and medium voltage grids are being developed in the European Union. These projects are led by some of the most relevant DSO members of the EEGI. Based on sharing the outputs of these experiences and evaluating their results using the IGREENGrid KPIs defined on the project (according to the EEGI guidelines) and the results of the scalability and replicability analysis, a set of recommendations will be produced in order to identify the most promising solutions for an appropriate integration of small and medium size variable renewable resources in distribution grids. The Project focuses on increasing the hosting capacity for DRES in power grids without compromising the reliability or jeopardizing the quality of power.

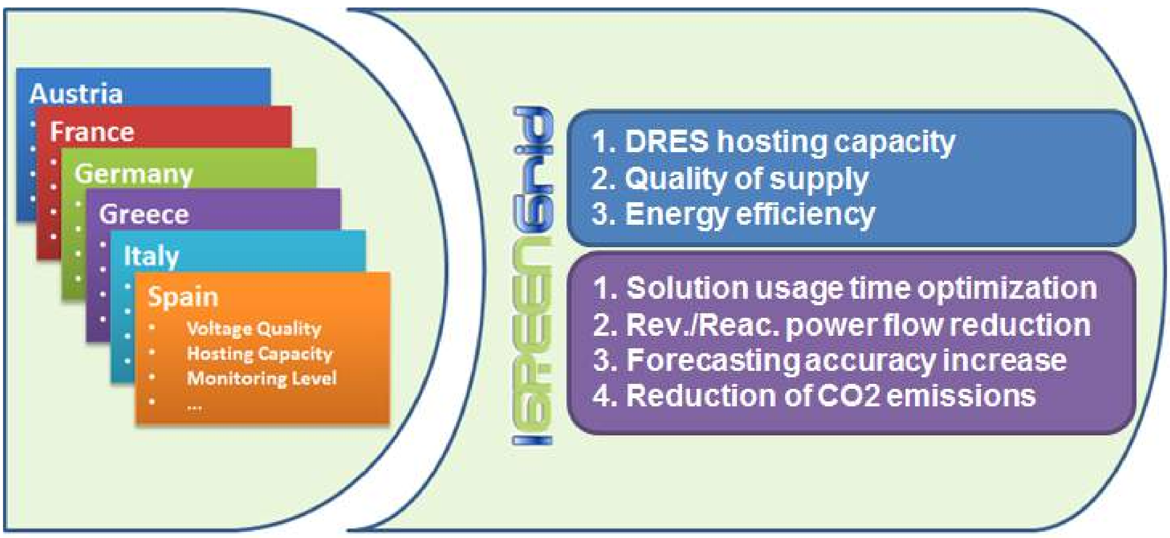


Figure 3 (IGREENGrid KPIs)

The main final result will be a set of guidelines, consisting in a portfolio of accurate methodologies and tools for an appropriate integration of small and medium size variable renewable resources in distribution grids. In particular, different climatic, cultural and technical frameworks (focused on European networks) will be considered. Furthermore, the expected outputs will be related to the results of the projects, and will consist of sharing knowledge and promoting best practices and initiatives for the integration of DRES. The different solutions will be brought from the individual demo projects results and then validated thanks to models/simulation/testing in the rest of network environments in order to assess the replicability and scalability at EU level. The technical, regulatory and economical aspects will be carefully taken into account.

2 Energy Storage

This section describes the benefits from storage applications, identification of promising and innovative applications and some conclusions of energy storage.

2.1 Introduction

In brief, the benefits of energy storage are:

- Storage is a key technology for the development of smart grids with high share of renewables.
- A large-scale roll-out of storage has not yet emerged, even though there is available a large portfolio of storage technologies.
- In this chapter, innovative concepts and applications for energy storage are discussed, as they were developed within IGREENGrid, SiNGULAR and SuSTAINABLE.
- This can give new impulses for storage usage and its affiliated value.

2.2 Benefits from Storage Application

Grid	Renewable Generation	Customer
Improve reliability	Reduction of curtailment	Improve reliability
Improve power quality	Reduction of variability / capacity firming	Improve power quality
Provision of ancillary services	Cover forecast uncertainty	Energy management according to time-of-use tariffs
Voltage control		Improve self-sufficiency
Congestion management		
Investment deferral		
Limitation of upstream power flow		
Black start		
Islanding		

Table 1 (Benefits from storage applications)

2.3 Identification of Promising Applications

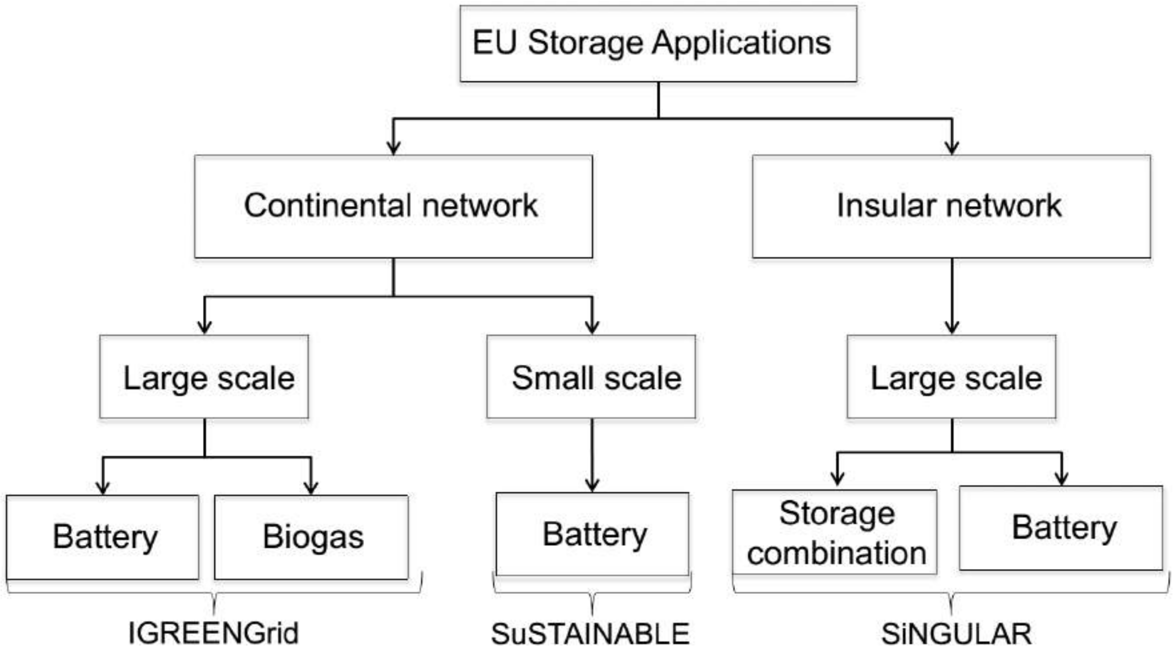


Figure 4 (Identification of promising application schema)

2.4 Innovative Applications

2.4.1 IGREENGrid German Case

Problem Addressed

- Mitigation of DG intermittency to match generation and demand.
- Mitigation of network congestions.

Innovation

- Biogas storage is used.
- Multiple service functions are applied.

Figure 5 (Biogas storage power plant)

Technology

- Accumulation of biogas and conversion in electrical energy.
- One CHP (190 kW) is directly fed by the digester.
- Second CHP (220 kW) is fed from biogas storage tank with capacity 3.2 MWh.
- Efficiency: 98%

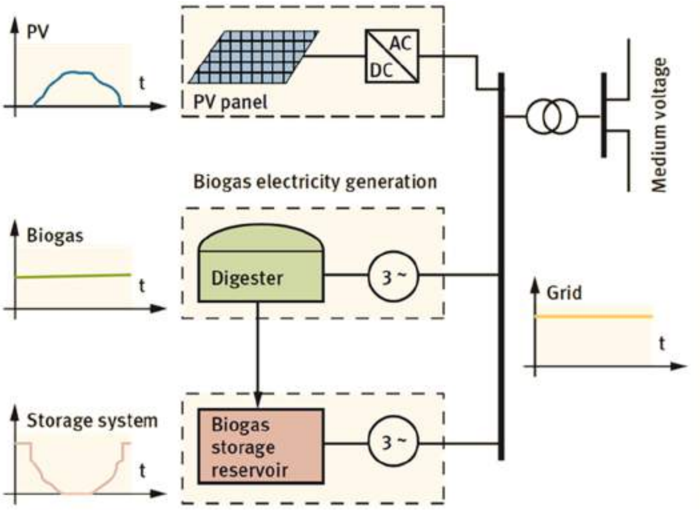


Figure 6 (General behaviour of Biogas power plant considering a medium voltage grid)

Value and Results

- Good performance in voltage control.
- Deferral of network reinforcement.
- Cost effectiveness due to simple architecture and limited ICT requirements.

2.4.2 IGREENGrid Italian Case

Value Addressed

- Power flow and voltage control.
- Black start and resynchronization.

Innovation

- Implementation of storage for multiple network services.

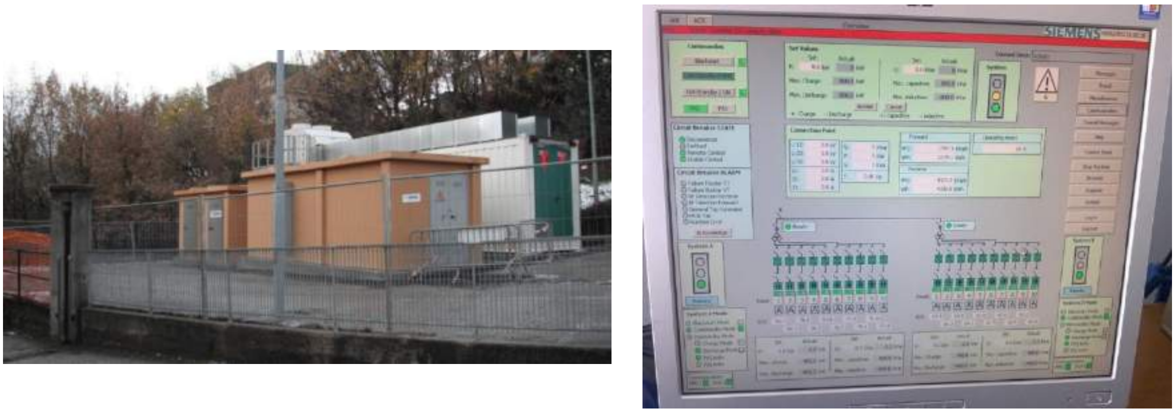


Figure 7 (Energy storage module [left] and its software controller [right])

Technology

Storage plant with capacity 500 kWh, maximum power of 1 MVA, $\eta = 0.85$. It is composed by:

- 20 Li-ion battery racks, each containing 14 Li-ion batteries in series.
- 20 three-phase inverters, 2 three winding three-phase transformers.

Figure 8 (General schema of MV storage usage)

Value and Results

- Practical experience gained in exploiting storage for network services. Lessons learned from pilot test:
    - Selection of storage efficiency, capacity, rated power, and selection of storage technology.
    - Dimensioning black start capabilities.
    - Management of communication protocols and ICT interfaces.

2.4.3 IGREENGrid French Case

Problem Addressed

- Services to TSO: frequency control, congestion relief.
- Services to DSO: capacity support, local voltage control, reactive power support, contingency support, optimization of TSO fees.
- Services to DG: ancillary service support, smoothing of fluctuations, reduction of curtailments, generation or load peak shifting.
- Services to Storage Operator: energy management based on market.

Innovation

- Multi-service operation is possible with simple storage only. Ability to connect to different feeders depending on operation. Battery management system development.

Technology

- 1.3 MWh Li-ion battery connected to MV network with a 2 MVA power conversion system.

Value and Results

- Validation is on-going.
- The considered storage shows a good technical performance.
- Experience gained in storage integration and standardization process.
- The cost-benefit analysis for use of storage for distribution network operation needs careful consideration1.3 MWh Li-ion battery connected to MV network with a 2 MVA power conversion system.

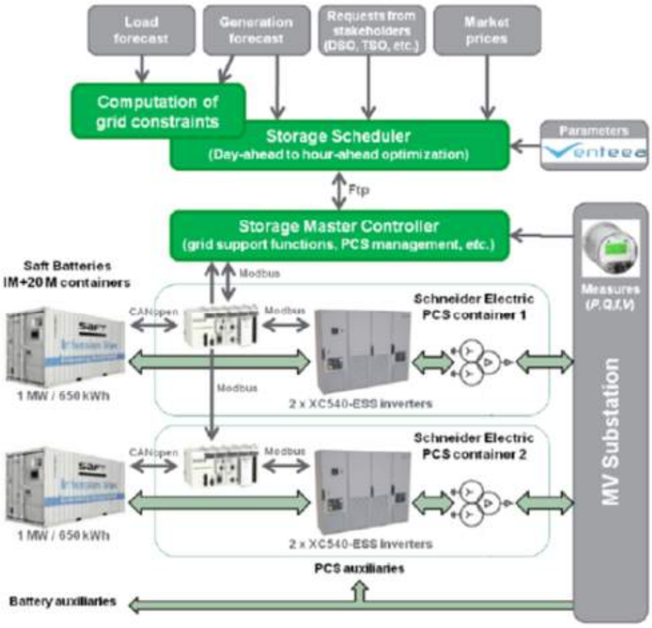


Figure 9 (Storage technology schema used in French case)

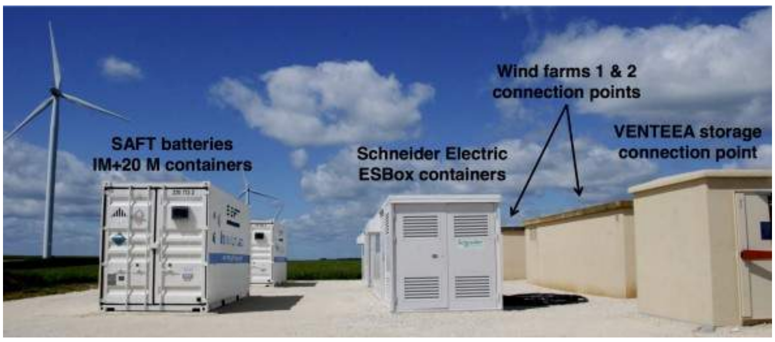


Figure 10 (Multiple technologies used *in loco* in French Case)

2.4.4 SuSTAINABLE Évora Case

Problem Addressed

Storage devices were used for the application of voltage control strategies in an LV network with microgeneration and loads.

Innovation

Storage devices were used as a priority control asset in implementing:

- Centralized voltage control algorithm and local voltage control.

Technology

64 lead-acid batteries with 12 V 12 Ah with a total nominal capacity of 4.6 kWh

Figure 11 (Smart storage inverters and interface with smart meters [left] and batteries [right])

Value and Results

Centralized control algorithm sent set-points to smart inverters of the batteries to inject/absorb power in response to voltage violations

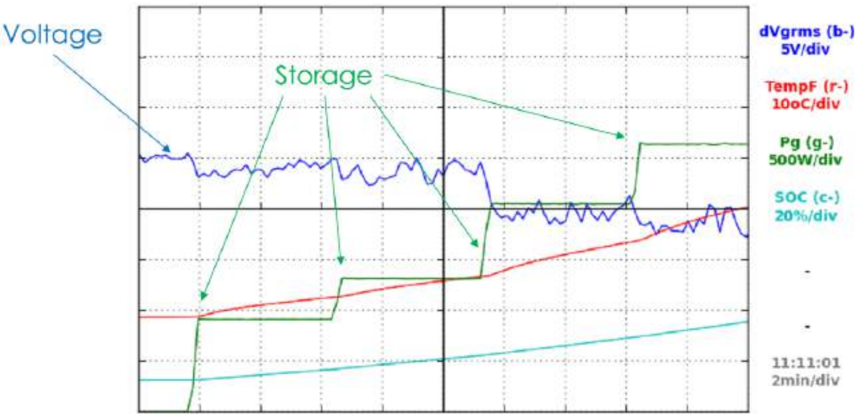


Figure 12 (Voltage, storage, temperature and state-of-charge behaviour of batteries)

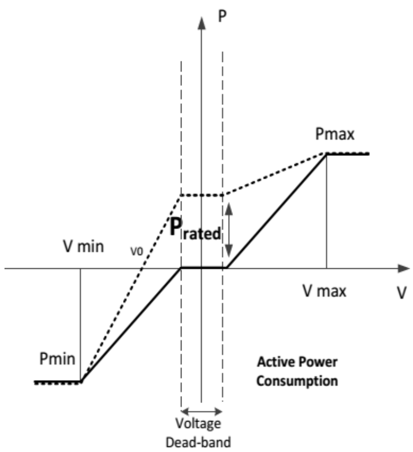


Figure 13 (Local droop control in storage inverters)

- Local control strategies (droops) embedded in the smart inverter of the batteries as a response to local, fast acting voltage variations.
- Increased integration of energy from RES that would otherwise be curtailed due to voltage problems.

2.4.5 SiNGULAR Crete Case

Problem Addressed

- Frequency regulation.

Innovation

- Combination of a battery with a super-capacitor or flywheel to provide frequency control.

Technology (Simulation)

- 10 MW of energy storage (ES): Li-ion, NiMH, NiCd, Lead Acid batteries.
- 10 MW of power storage (PS): super-capacitor or flywheel.
- The size in MW of the storage system was chosen to be 10MW, which represents 26% of the estimated operational reserves for Crete.
- A 10MW storage system is able to provide the same primary reserve capacity with a 133.3MW conventional power plant.

Value and Results (Simulation)

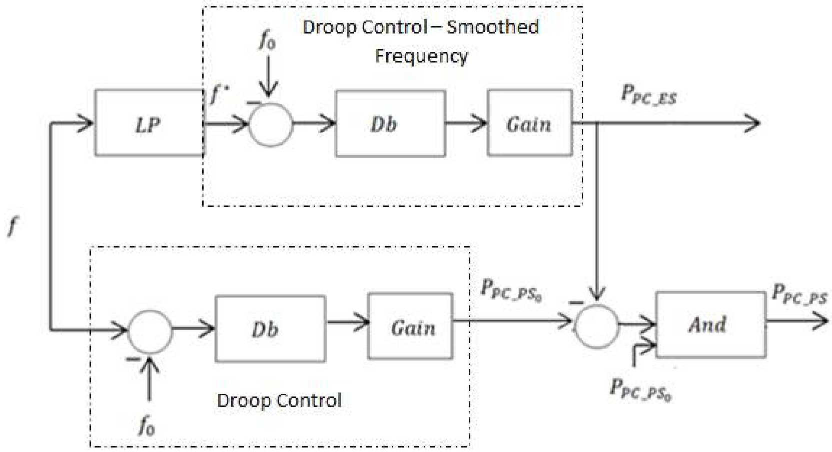


Figure 14 (Control droop frequency diagram)

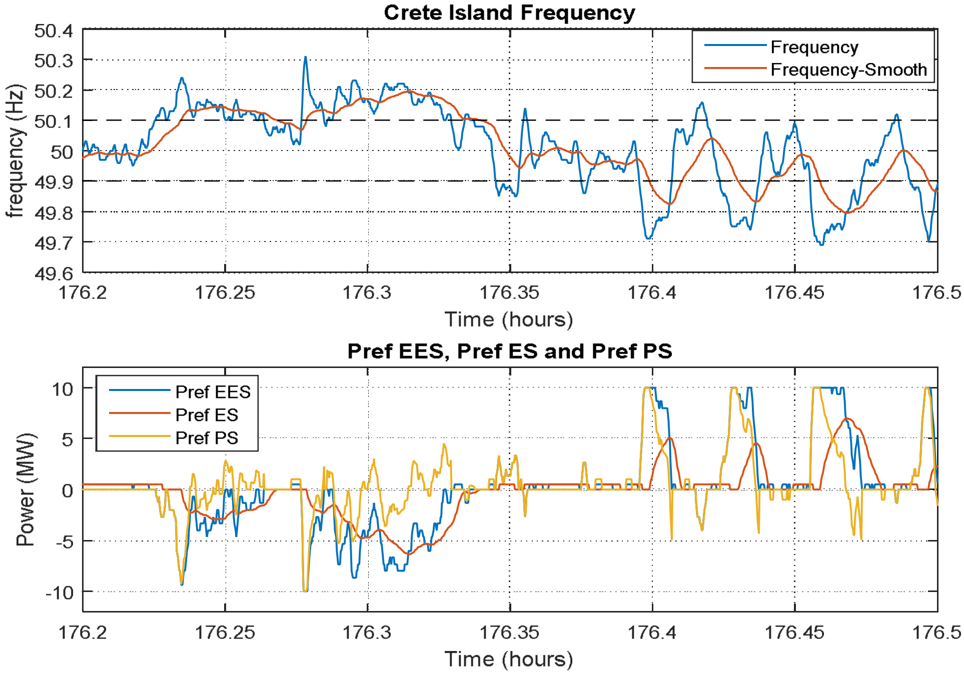


Figure 15 (Frequency [up] and Power from EES, ES, PS system [down] results)

- Power storage can react faster in frequency oscillations.
- Cost is reduced when combining energy storage with flywheel.
- Average 30% reduction in number of cycles for the battery.
- Average 45% life gain for battery with hybrid system.
- Average 63% mileage increase.

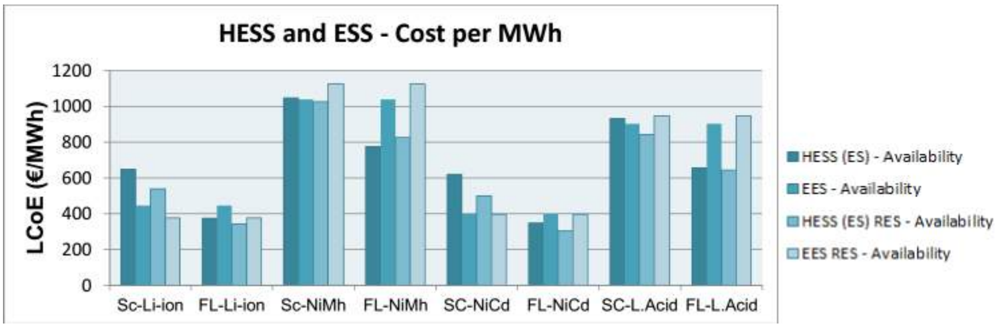


Figure 16 (Cost per MWh of each technology analysed)

Problem Addressed

- Bulk energy storage.
- Minimise high RES curtailments.

Innovation

- Main objective was to maximise the lifetime of the battery, the battery is charging only when generation exceeds demand by more than 4%. The required energy capacity that needs to be installed was calculated versus the required percentage of RES.

Technology

Mathematical model for a number of technologies:

- Li-ion, NiMH, NiCd and lead acid to provide ~ 5 MWh.

Value and Results

- To reduce number of charging cycles: charge if generation exceeds by 4% demand.
- Optimised curve for CAPEX: storage needs to be installed for RES penetration larger than 40%. For RES penetration larger than 40% value of cost of energy (CoE) more favourable for system with storage

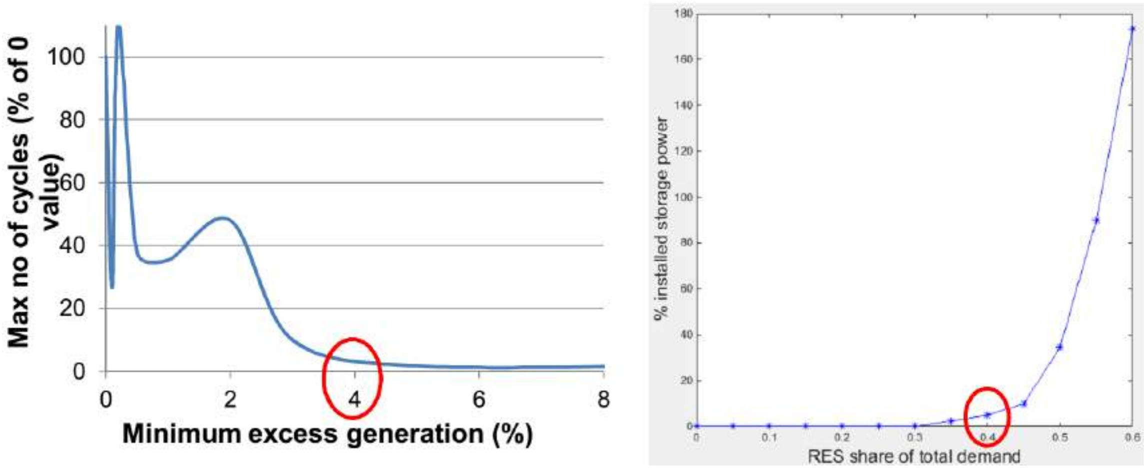


Figure 17 (Maximum number of cycles [left] and RES share of total demand [right] results)

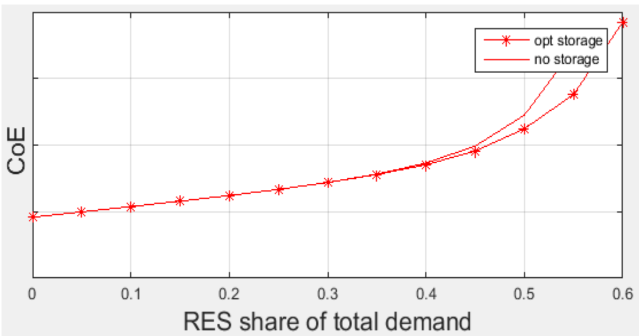


Figure 18 (Value of cost of energy considering energy storage)

2.5 Conclusions

- The three projects have introduced a large number of innovative and illustrative applications of storage.
- Storage was shown to be a solver for congestion, voltage control and renewable generation intermittency.
- Some applications have a cost-benefit relation that makes them already attractive.
- Others could soon emerge as early adopters.
- The three projects have played a good role in illustrating the value of storage in distribution networks.

3 Forecasting

3.1 Why Use Forecast?

- High penetration of distributed resources, with high variability.
- For distribution networks, relative small consumption with irregular behaviour.
- Providing forecast information is equivalent to provide time for decision.
- The forecast reduces the need of storage, reduces the need of reserve and increases the usage of renewable capacity.
- Forecast is the cheapest way of control and the most profitable investment.
- New power system control parading:
    - Predictive power system operation.

3.2 Which Forecast Applications?

- Generation management (Scheduling).
- Storage management.
- Predictive network operation management.
- Predictive mitigation of extreme event contingencies (reliability).
- Predictive price signal generation, for real time tariffs.
- Predictive demand side management and demand response operation.

- Planning is deferent and better when system operates with forecast.
- Better distributer resources usage and intelligent operation.

3.3 Probabilistic Forecast

- Why the 3 projects insist in this approach?
  - Forecast is uncertainty by definition.
  - Most of the decision problems are risk based, we are more interested in the extreme situation with low probability than in the expected values.
- Why probabilistic forecast is not used yet?
  - Because is difficult to model and expensive.
  - Because most of the users don't know how to use it.
  - Or simply, because they do not even use forecast yet.

3.4 Time Framework

- Forecast with hourly resolution.
- Forecast for 7 days horizon (168h)
- Forecast refreshment 4 times per day

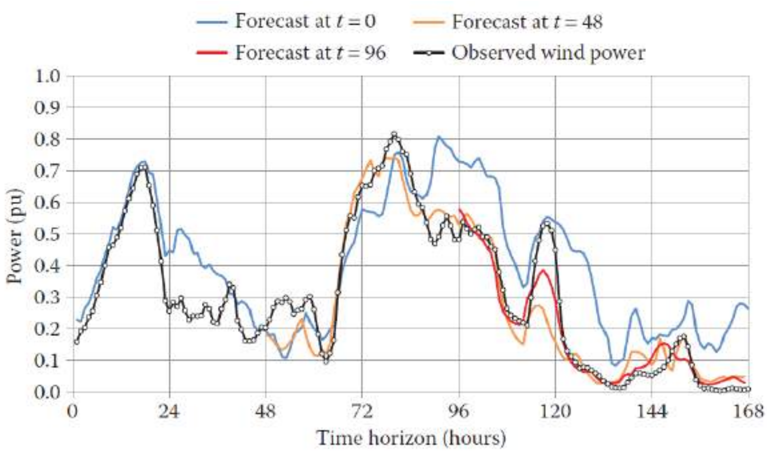


Figure 19 (Different forecast results along 168 hours ahead)

3.5 Characteristics of Forecast

	iGREENGrid	SINGULAR	SUSTAINABLE
Load Forecast (System Level)	Not relevant	YES	Not relevant
Load Forecast (Distribution Level)	YES	YES (some pilots)	YES
Load Forecast (Consumer Level)	YES (Node level)	NO	Not relevant
Wind Forecast (System Level)	YES	YES	NO
Wind Forecast (Wind farm Level)	YES	YES (Some pilots)	NO
PV Forecast (System Level)	YES	YES	YES
PV Forecast (PV plant Level)	YES	YES (some pilots)	YES
PV Forecast (Consumer Level)	YES (Node level)	NO	YES
Hydro Power (System Level)	NO	YES	NO
Hydro Power (Hydro plant Level)	NO	NO	NO
Electricity Price/Cost forecast	NO	YES (cost, Azores)	NO
Provide probabilistic Forecast or quantiles ?	YES	YES	YES
Use meteorological forecast ?	YES	YES	YES
Use online SCADA information ?	YES	YES (some pilots)	YES (from smart meters)
Graphic interface is available ?	YES	YES	YES
Is a Web/Desktop system ?	YES	YES (Web)	YES (Web)
Forecast systems is in operation ?	YES	YES (All)	YES (28 MV/LV sub.)
New forecast systems are in use by DSO ?	YES	YES (some pilots)	YES
There are previous forecast systems ?	NO	NO (only in Crete)	NO

Table 2 (Different point-of-view features of forecast between projects)

3.6 Resume of Added Value of Projects

IGREENGrid

- Load and PV density forecast based using RBFNN with estimation of the RBFs widths using a multi-objective genetic algorithm. The PV forecasting tool creates predicted densities of solar power using the bootstrap method. The tool is applied to each of the seven PV plants of HEDNO's pilot case at Sperchiada.
    - Not public accessed to the tools.

SiNGULAR

- Aggregate all kind of forecast applications in a forecast web service platform. Provide probabilistic forecast. Forecast for system level, for small systems.
    - http://smartwatt.net/SingularWeb/

-

SuSTAINABLE

- Load and PV generation forecast applied at distribution level. Probabilistic PV forecast including spatial distributed information. Load forecast with disaggregation characteristics appropriated for demand response usage. Applied and used by EDP distribution network.
    - Not public accessed to the tools.

3.7 Interfaces with Users

Figure 20 (IGREENGrid forecast output example)

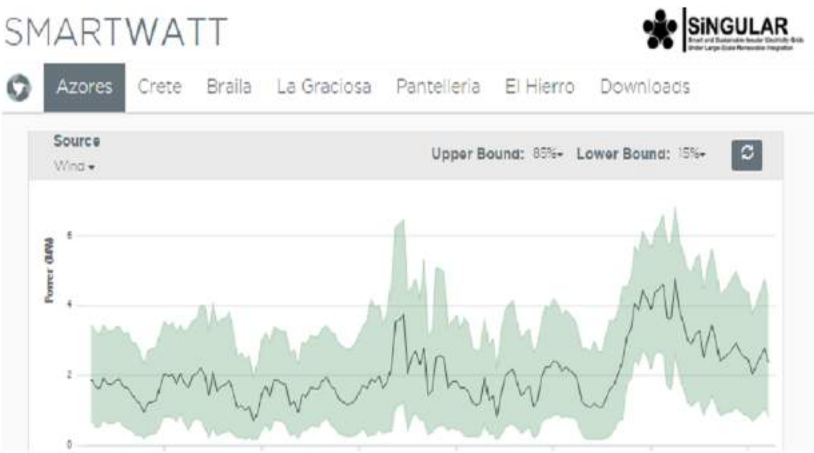


Figure 21 (SiNGULAR forecast output example)

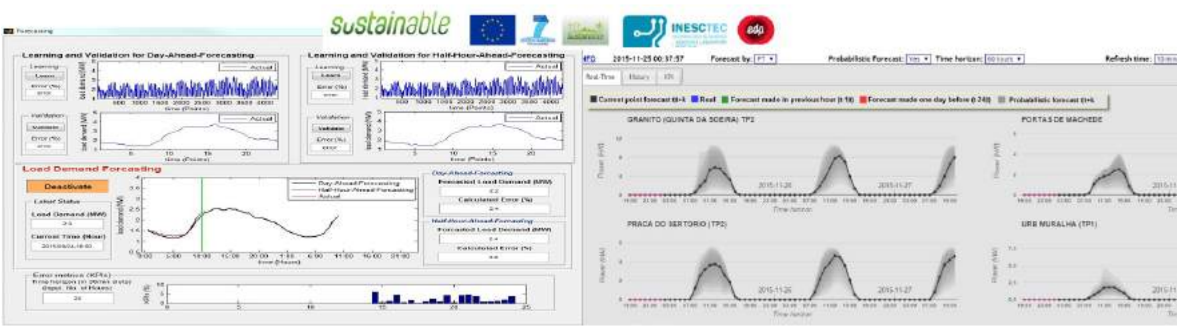


Figure 22 (SuSTAINABLE forecast output example)

3.8 Usage of Forecast

- In insular systems, only the big islands (Crete) use forecast:
    - Consumption and wind are the most important, but also PV and hydro for islands with these renewables resources.
    - Very important for generation scheduling and storage management.
- In continental grid is not usual to have forecast at distribution level:
    - Consumption, solar and wind are the most important.
- At consumer level is not usual to have forecast:
    - Consumption and PV are the most relevant

3.9 Value of Forecast

- For insular systems, using forecast for scheduling and storage management can save 1 to 10 €/MWh.
- For distribution systems, predictive operation based on consumption, wind and PV forecast improve quality of service and avoid RES curtailment.
- For consumer level, consumption forecast, PV forecast and price forecast are important for manage demand respond. Savings are related with the reduction of cost o net load deviation (10 €/MWh).

3.10 Evaluating Forecast

- Difficult to evaluate, and difficult to find benchmark for the same location and same period of evaluation:
    - Global benchmark platforms are needed
- Evaluating uncertainties depends on the kind of usage of this information:
    - Frequency or distance functions
    - Quantiles or probability functions
- The required quality of forecast depend on the kind of usage:
    - Consumer level don't require the same quality as system scheduling
    - Quality of forecast for LV consumption is much difficult than LV or HV

3.11 Suggestions for Future, Promoting Usage of Forecast

- Create common benchmark platforms to compare forecast services.
- Facilitate access and reduce cost of global NWP forecast.
- Convince DSO to participate in the process, providing data and providing online SCADA connection.
- Develop predictive tools for power system optimization that make use of forecasts.
- Create premium or penalty mechanisms indexed to forecast performance.

4 Generation Curtailment

4.1 Introduction

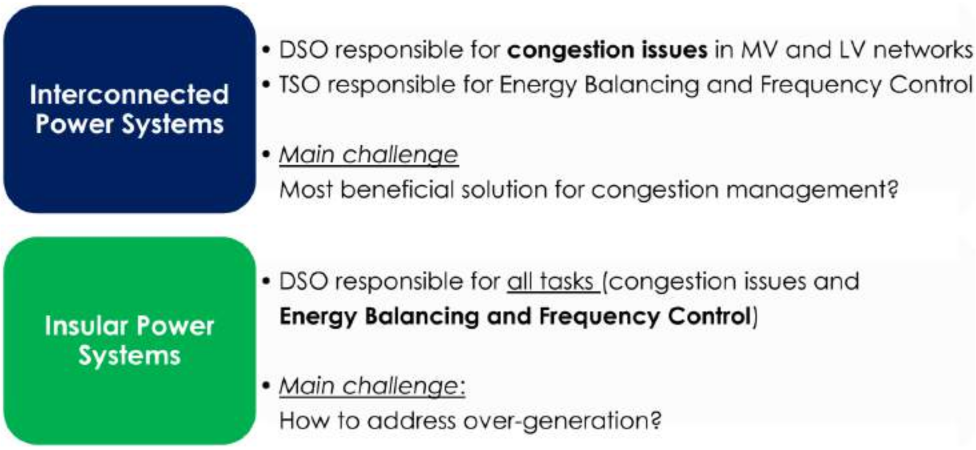


Figure 23 (Questions to overcome about distributed generation (DG) curtailment)

4.2 DG curtailment – Situation in some EU countries

The interconnected networks → Curtailment for distribution grid management: Countries are subjected to different regulatory frameworks concerning curtailment.

Non-interconnected networks → Curtailment for system security: DG curtailment is normally subjected to dedicated regulation which is similar to the one adopted for interconnected systems in case of system security actions.

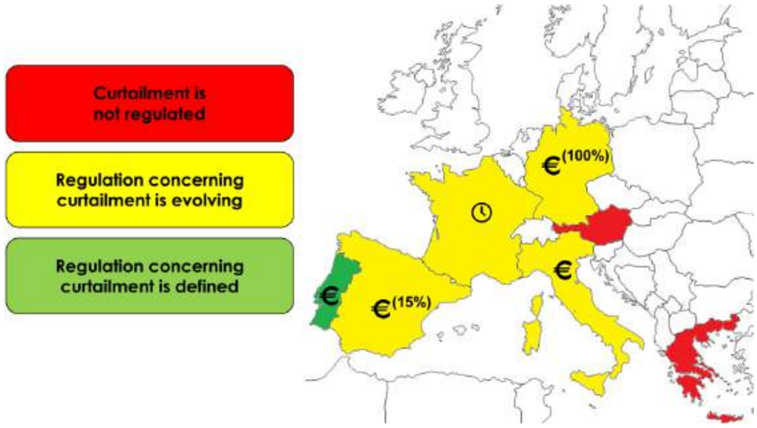


Figure 24 (curtailment status in some EU countries)

Figure 25 (curtailment status in some EU Islands)

4.3 DSO – DG Curtailment Cases

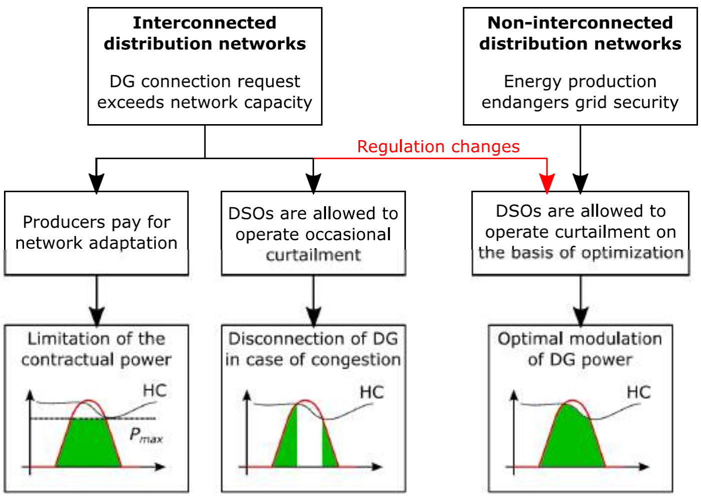


Figure 26 (DG curtailment cases considering regulation changes)

4.4 DG Curtailment in Non-Interconnected Systems

Non-interconnected networks are operated by means of optimization algorithms, able to trigger DG curtailment in case of necessity. From SINGULAR experience short-term operations can be managed by means of two different approaches.

- Advanced Probabilistic Unit Commitment and Economic Dispatch Model (Risk-based Approach);
- Mixed-Integer Linear Programming-based Scheduling Model (MILP-based Approach).

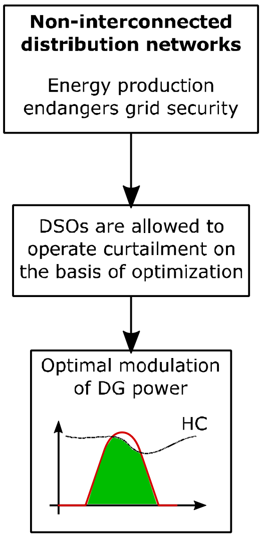


Figure 27 (DG curtailment in non-interconnected systems)

4.4.1 Short-Term Optimization – Risk-Based Approach

Minimization of the network operation costs on the basis on risk analysis (stochastic approach).

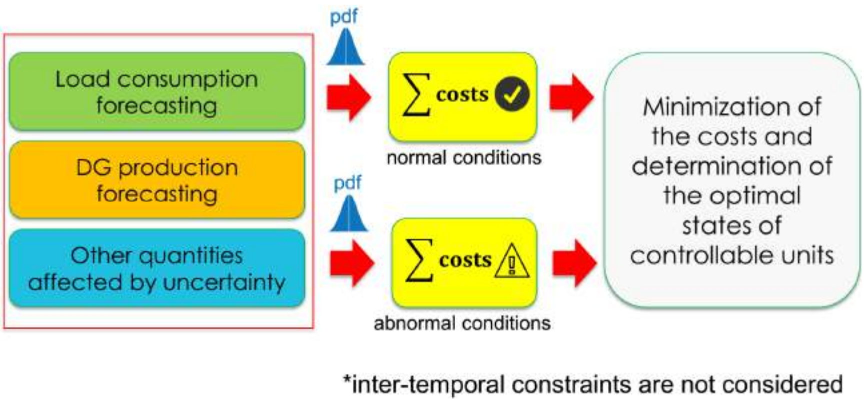


Figure 28 (Risk-based approach optimization)

4.4.2 Short-Term Optimization – Mixed Integer Linear Programming Approach

Minimization of the total operating costs over the scheduling horizon.

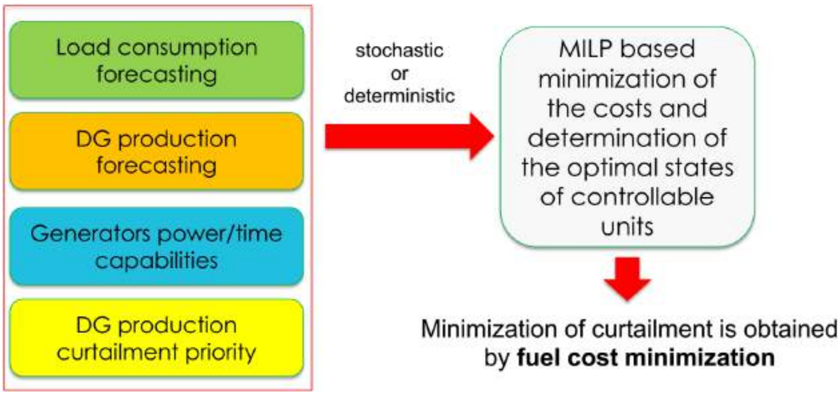


Figure 29 (Mixed integer linear programming approach)

4.4.3 Short-Term Optimization Results in Case of Curtailment

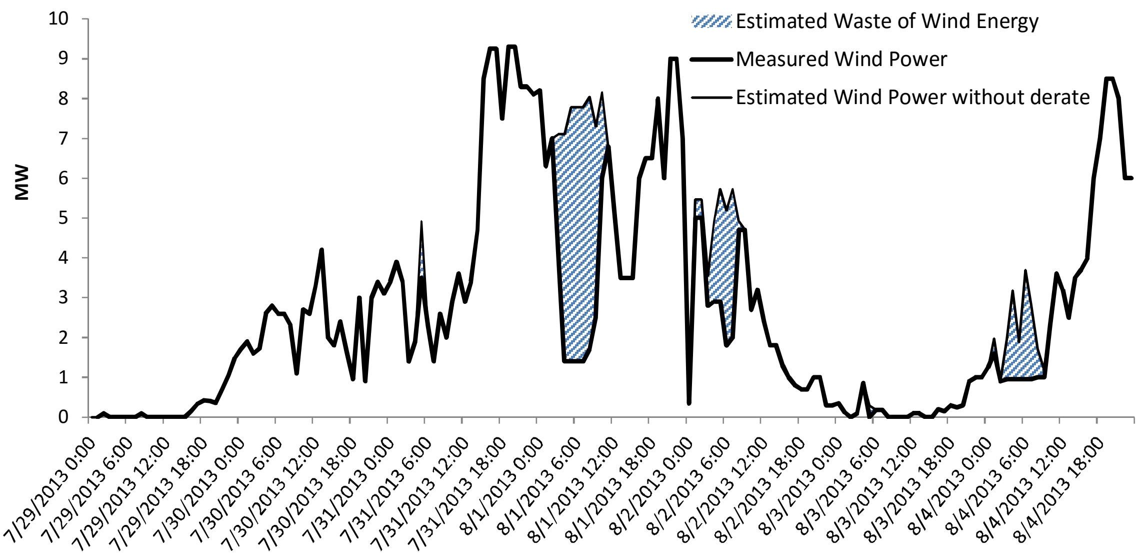


Figure 30 (Short-term optimization results considering curtailment)

4.5 DG Curtailment in Interconnected Systems

4.5.1 Limitation of the Contractual Power

In some European countries, connection fees include network adaptation cost when reinforcement/updates are necessary.

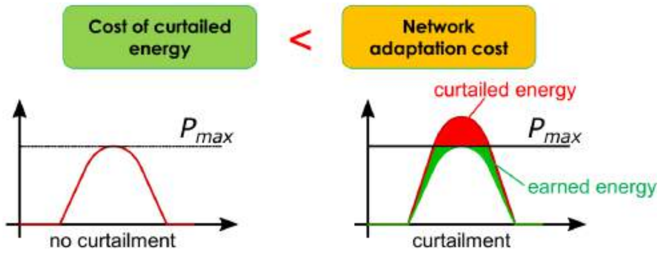


Figure 31 (Limitation of contractual power example)

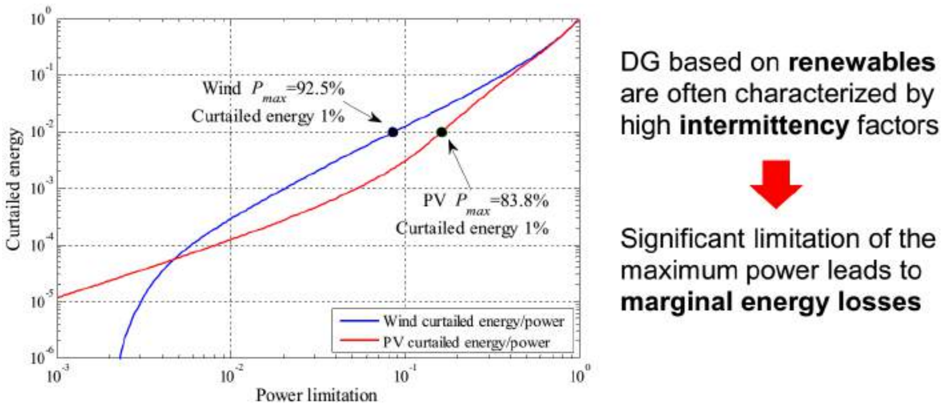


Figure 32 (Power limitation due to curtailed energy)

4.5.2 Disconnection of DG

In most of the European countries, disconnection of DG is operated in order to overtake emergency situations. In few cases, this disconnection can be requested by DSOs for the management of occasional distribution network congestions

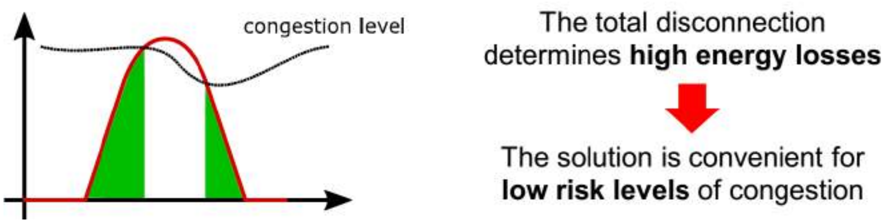


Figure 33 (disconnection of DG considering congestion level example)

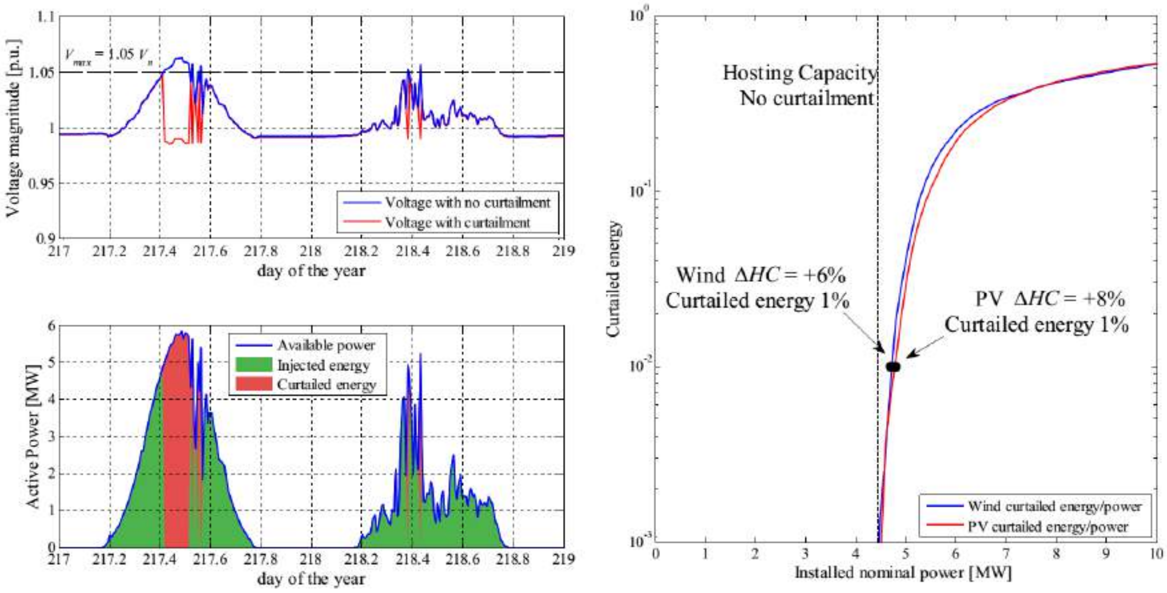


Figure 34 (disconnection/curtailed energy in DG system)

4.5.3 Disconnection of DG: IGREENGrid Greek Demo – Spercheiada Distribution Network

Different DG local controllers have been simulated in order to investigate their benefits in terms of renewables integration.

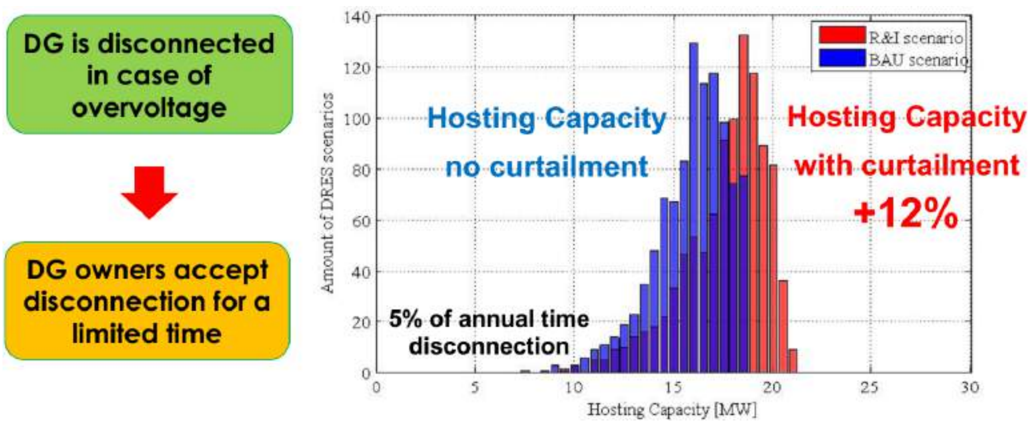


Figure 35 (Difference results of hosting capacity with/without curtailment)

4.5.4 Optimal DG Curtailment

One of the most discussed regulation update is about the integration of curtailment in distribution network operations. The results show that simulations and real-field tests demonstrate that DG curtailment is a cost-effective strategy for renewables integration.

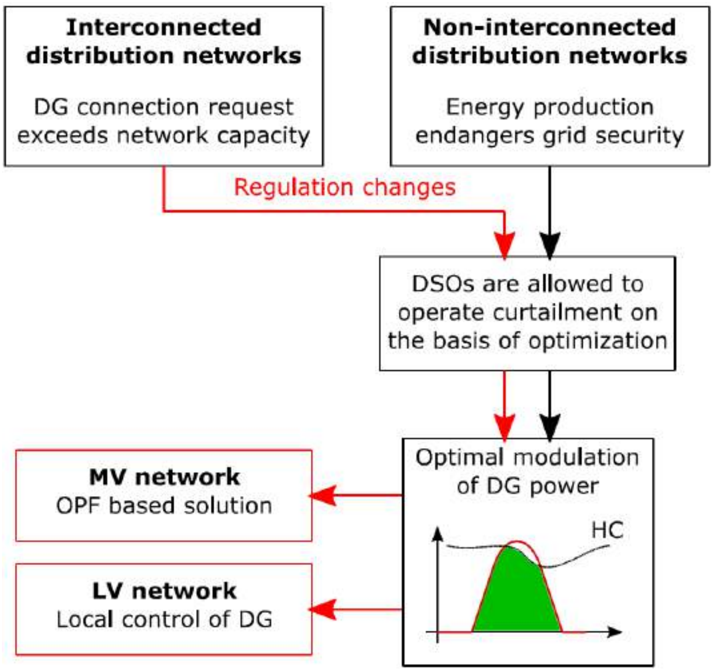


Figure 36 (Optimal curtailment strategy)

4.5.5 Optimal DG Curtailment – MV Network

In brief, MV distribution networks are characterized Figure 37

Figure 37 (Optimal DG curtailment considering MV network)

Centralized controllers can be based on an optimization function (OPF) in which curtailment is included with a given priority, i.e., normally: curtailment = last resource

Figure 38 (Optimal DG curtailment cost-function consideration)

4.5.6 Optimal DG Curtailment – MV Network: IGREENGrid Austrian Demo – Lungau Distribution network

Optimal Power Flow (OPF) control is operated on controllable network assets, including active power control (curtailment). The OPF optimizes the voltage and current profiles of the network by acting as shown in Figure 40.

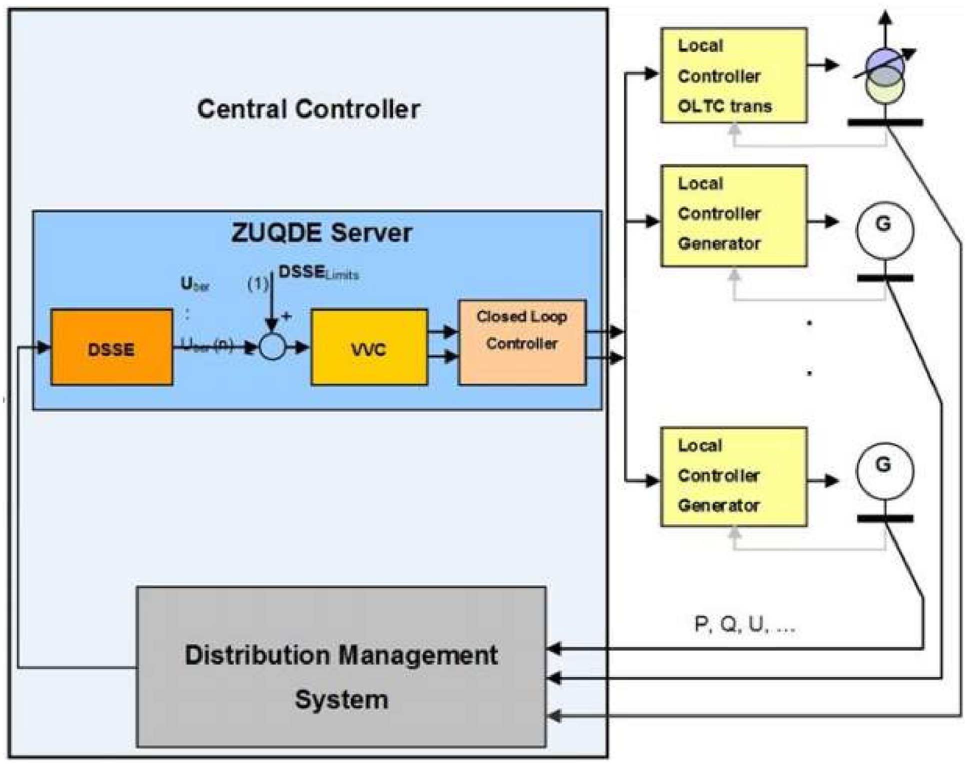


Figure 39 (Lungau Distribution network central controller diagram)

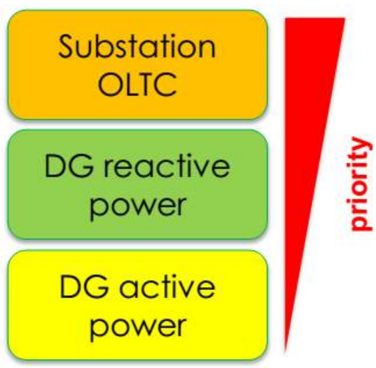


Figure 40 (The OPF action levels on the network)

4.5.7 Optimal DG Curtailment – LV Network

LV distribution networks are characterized as shown in Figure 41. Furthermore, Local controllers can be tuned in order to limit the power injection in case of local congestions, i.e., overvoltage as stated in Figure 42.

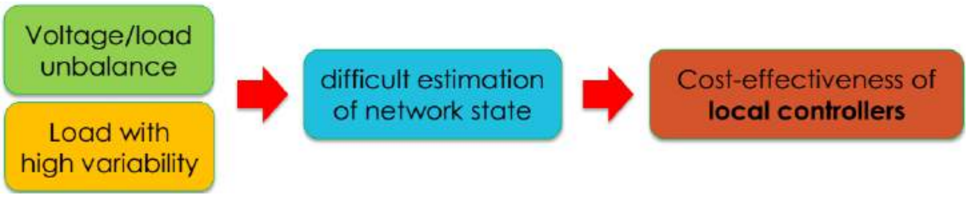


Figure 41 (Optimal DG curtailment considering LV network)

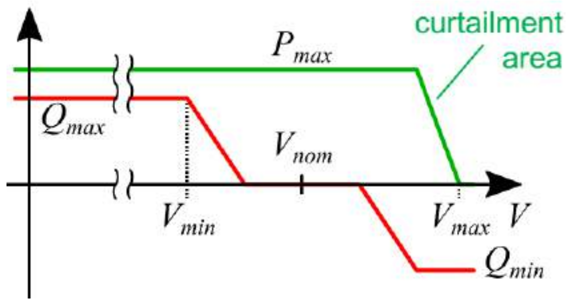


Figure 42 (Limitation of power injection in case of local congestions example)

4.5.8 Optimal DG Curtailment – Local Controller

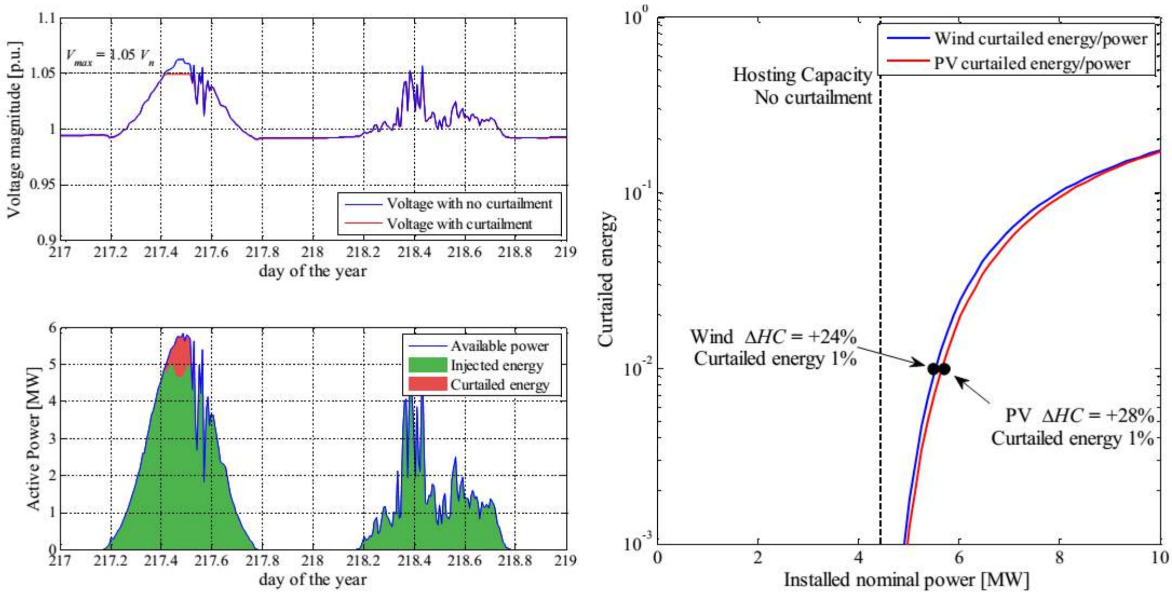


Figure 43 (Optimal DG curtailment example considering a local controller)

4.5.9 Optimal DG Curtailment – LV Network: SuSTAINABLE Portuguese Demo – Évora Distribution Network

PV power plants have been equipped with controllable inverters able to accept active power set-points. On the basis of the monitored voltage values, the controller acts on PV inverters and storage units' profiles.

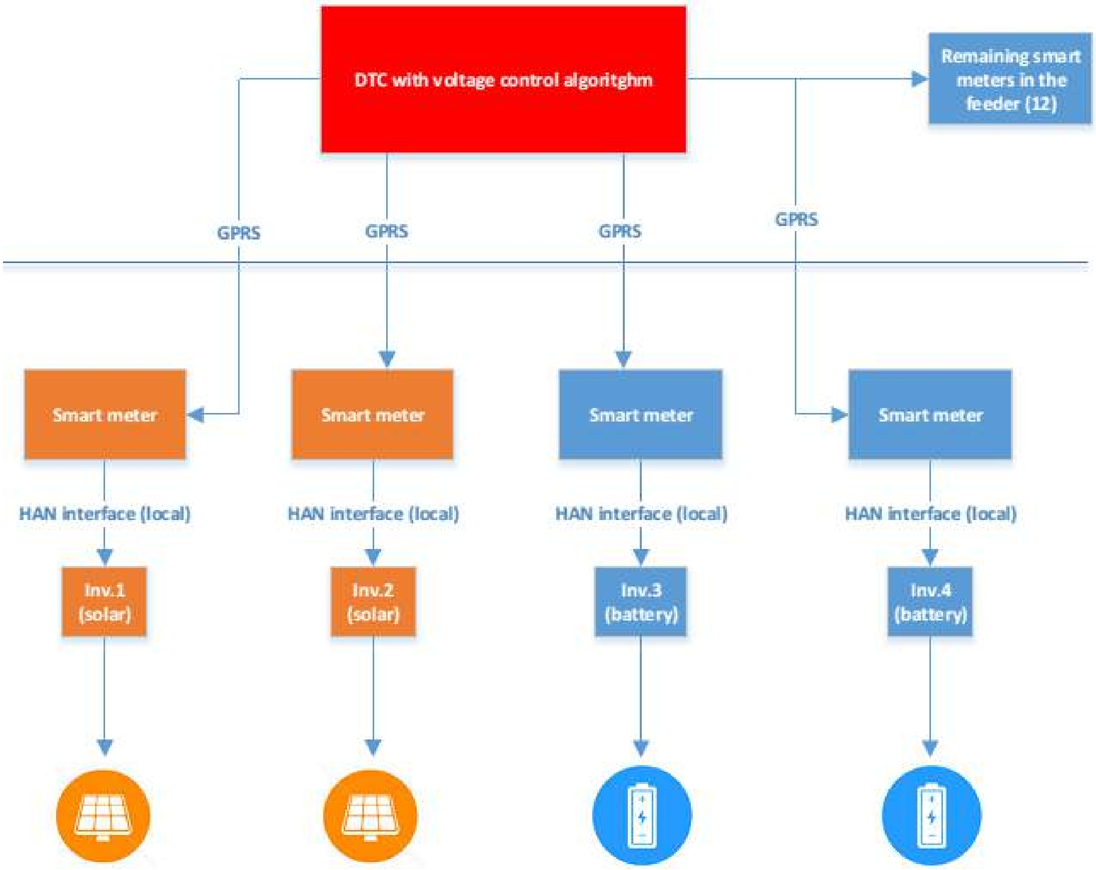


Figure 44 (SuSTAINABLE Portuguese Demo – DG network example)

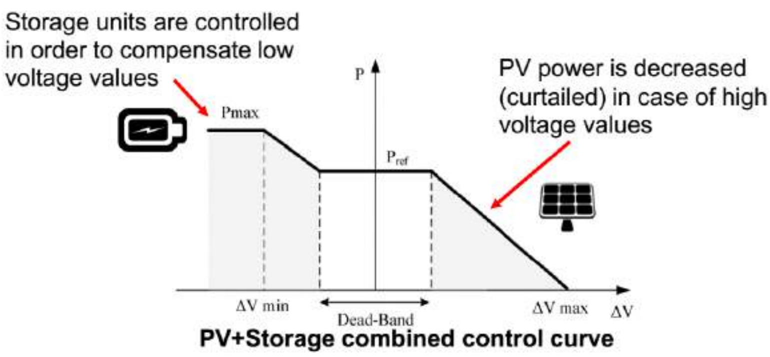


Figure 45 (PV and storage power curve)

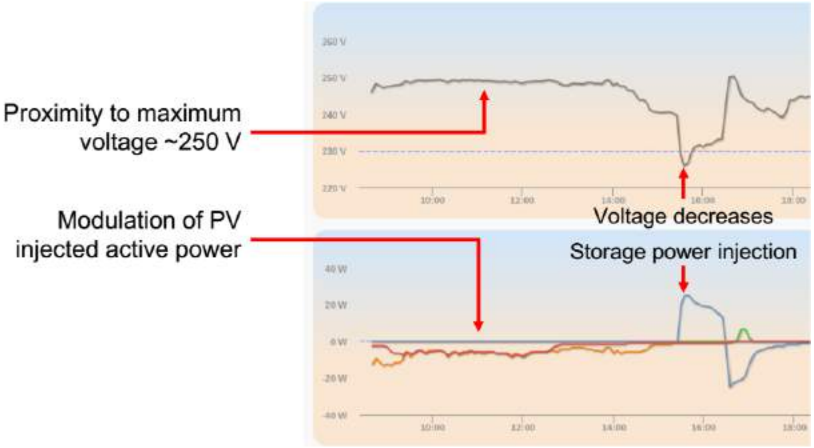


Figure 46 (Influence of storage and correction of voltage value)

4.6 Conclusions

4.6.1 Non-Interconnected Networks

- Island networks are deeply monitored and the flexibilities are selected by means of optimization functions tuned in order to:
  - Obtain an acceptable stability level of the grid at the lowest cost.
  - Minimize curtailment of non-programmable renewable DG.
- On the basis of SiNGULAR experience, curtailment can be further limited by exploiting:
  - High time resolution load and generation forecasting tools.
  - Stochastic scheduling able to be frequently updated.
  - Demand response, storage and electric vehicles.

4.6.2 Interconnected networks

- The main problem of interconnected networks with large DG diffusion is grid congestion (voltage and current).
- Increase of DG penetration requires cost-effective strategies for network adaptation.
- Simulations and real-field tests have demonstrated the efficacy of DG active power control (curtailment):
  - High performance in terms of voltage regulation thanks to high R/X ratios typical of distribution networks.
  - Limited impact on the total production thanks to intermittent nature of renewable based generators.

5 Demand Side Management

5.1 DR Market Analysis

- Various DR maturity levels in every EU country.
- Local analysis has to take into account local regulations.
- Utilities or DSOs will lead ion de-regulated markets?

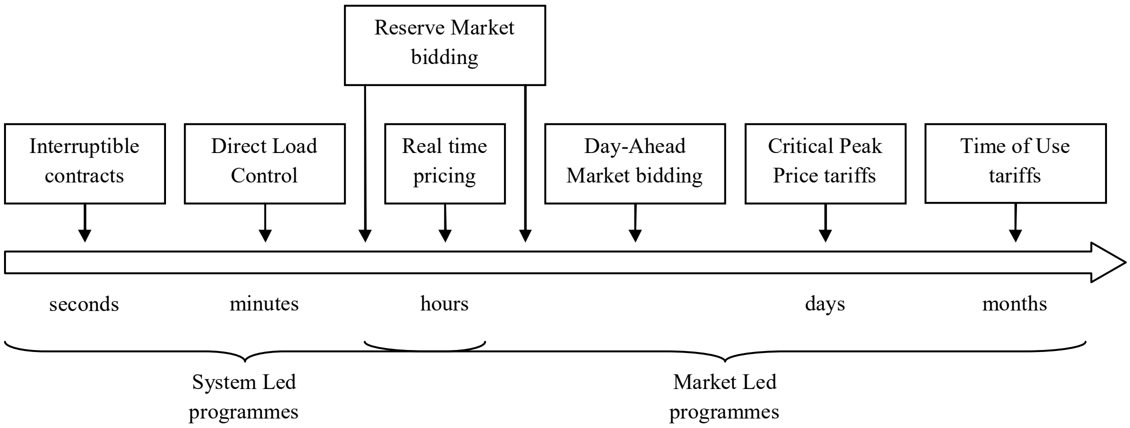


Figure 47 (DR market general structure)

5.2 Technical Approach of DR

- MV vs LV DR approaches on the technical side for balancing.
- Focused on the Voltage control for MV & LV.

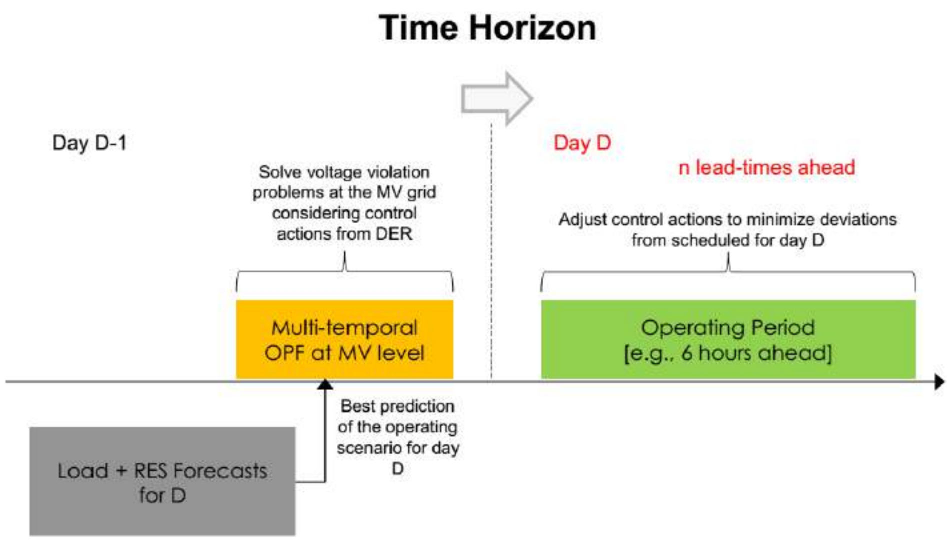


Figure 48 (Time horizon schema of DR approach)

5.3 DR in the Generation and Production Expansion Plans

- Using DR to balance and manage RES integration.
- Planning is crucial for future distributed techs, i.e., storage, microgrids, …
- Planning maths and models have been used. DR is inside the planning equation to model elastic loads and help protections. So far, planning is very “price-oriented”.

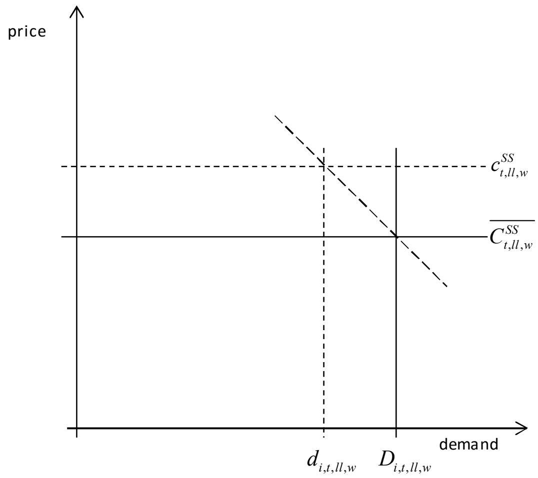


Figure 49 (price vs. demand curve example)

5.4 Behavioral DR: A Big Trend Involving Humans

- Communication is driven by engagement levels.
- Shift human behaviours’ to crop peaks and save energy.

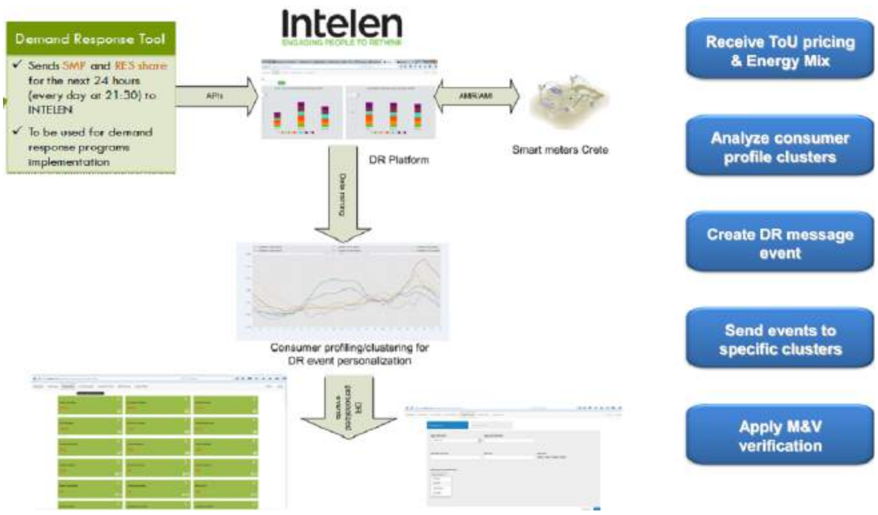


Figure 50 (Different steps and outputs of INTELENs’ approach)

DR Events

DR Event	Time of Event	Duration	Scope	Status	Outcome
1	20:00-21:00	1 hour	Reduction	DR was successful	-2.88%
2	19:00-20:00	1 hour	Reduction	DR was not successful	0.37%
3	20:00-22:00	2 hours	Reduction	DR was successful	-3.89%
4	21:00-00:00	3 hours	Reduction	DR was not successful	10.88%
5	12:00-17:00	5 hours	Reduction	DR was not successful	15.45%
6	00:00-02:00	2 hours	Increase	DR was successful	70.47%
7	14:00-18:00	4 hours	Increase	DR was successful	3.37%
8	20:00-22:00	2 hours	Reduction	DR was not successful	7.90%
9	21:00-22:00	1 hour	Reduction	DR was successful	-0.67%
10	19:00-22:00	3 hours	Reduction	DR was not successful	25.14%

Table 3 (Different DR events considered in human interaction)

Data driven DR Strategy

- Surveys and direct customer feedback tune the behavioural model.

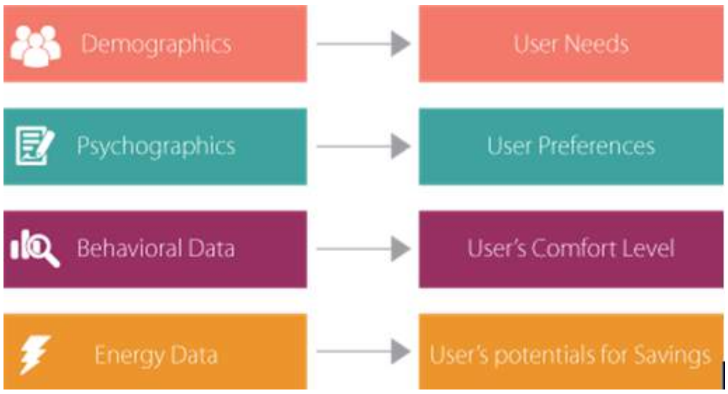


Figure 51 (Behavioural model strategy)

Data driven: DR Utility case study

Figure 52 (DR utility in different steps considered by INTELEN)

Data driven: Utility Strategy

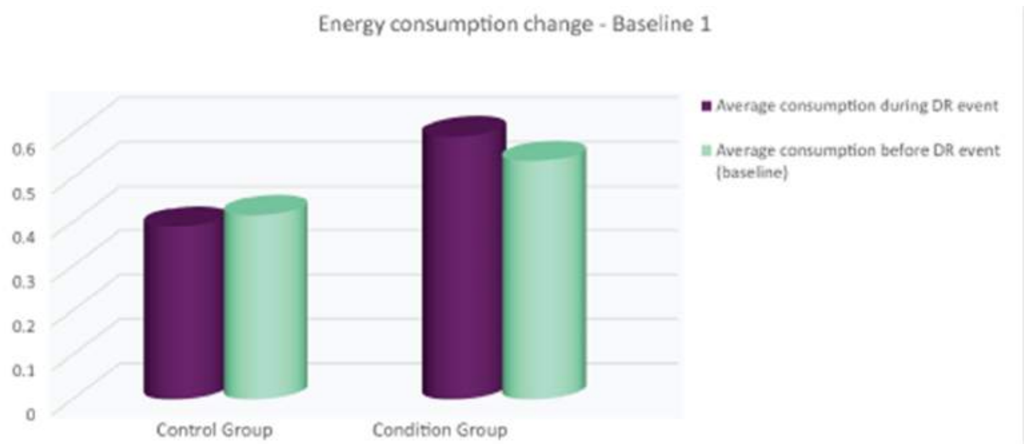


Figure 53 (Energy consumption change – case 1)

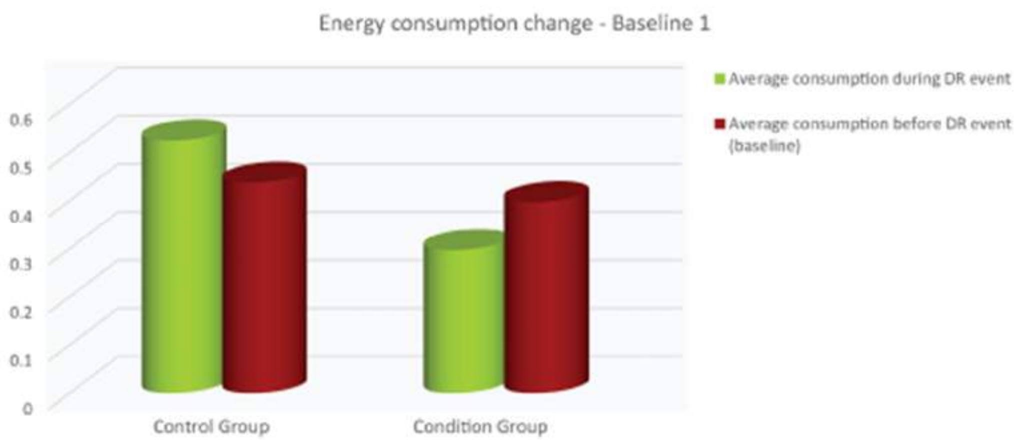
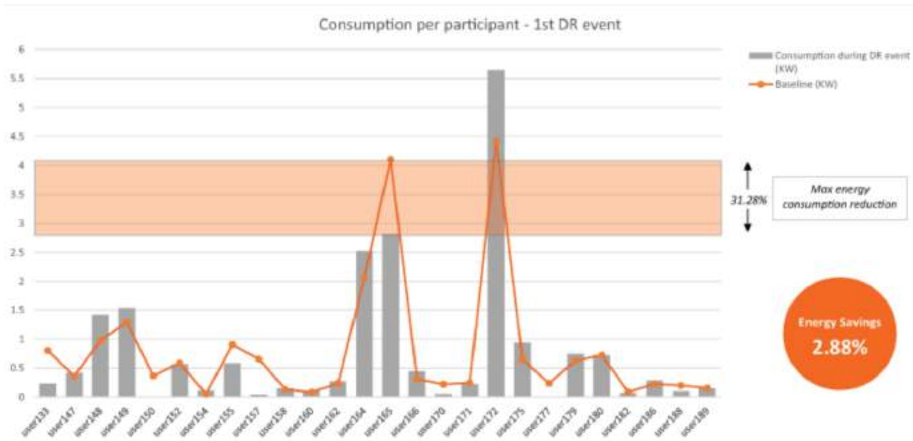


Figure 54 (Energy consumption change – case 2)



Cluster	Size	Center (KW)	Achieved the goal	Energy Savings
1 - Low consumption	14	0.208	7	18.78%
2 - Medium consumption	10	0.928	5	-0.11%
3 - High consumption	2	4.265	1	0.72%

Figure 55 (Consumption per participant results example along time)

- Identify Pareto 20-80 rule inside the data sets

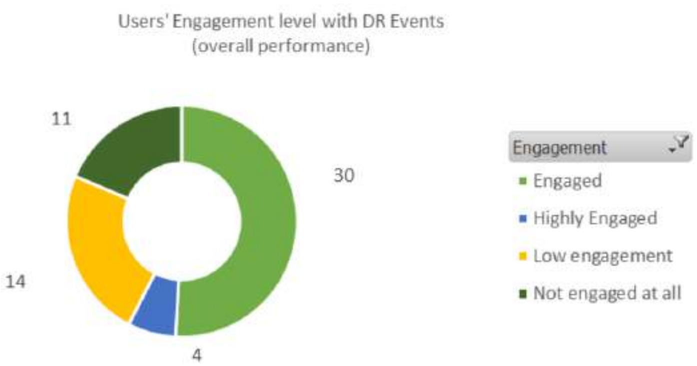


Figure 56 (Users' engagement performance with DR events)

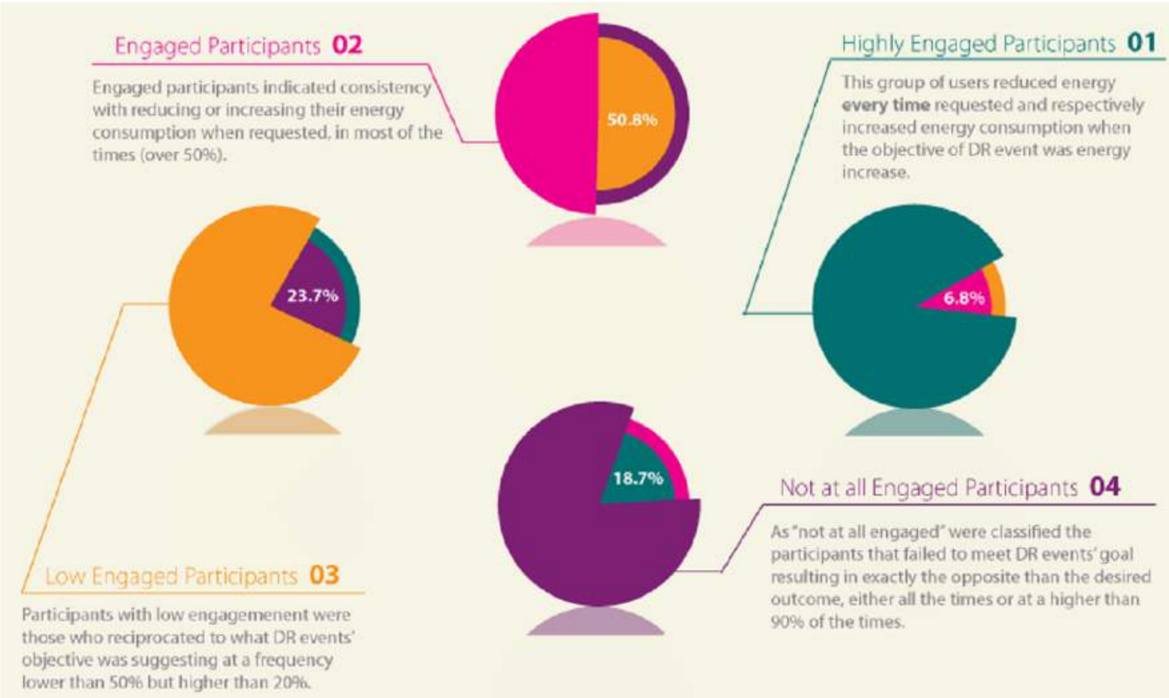


Figure 57 (Statistical engagement results from users in DR events)

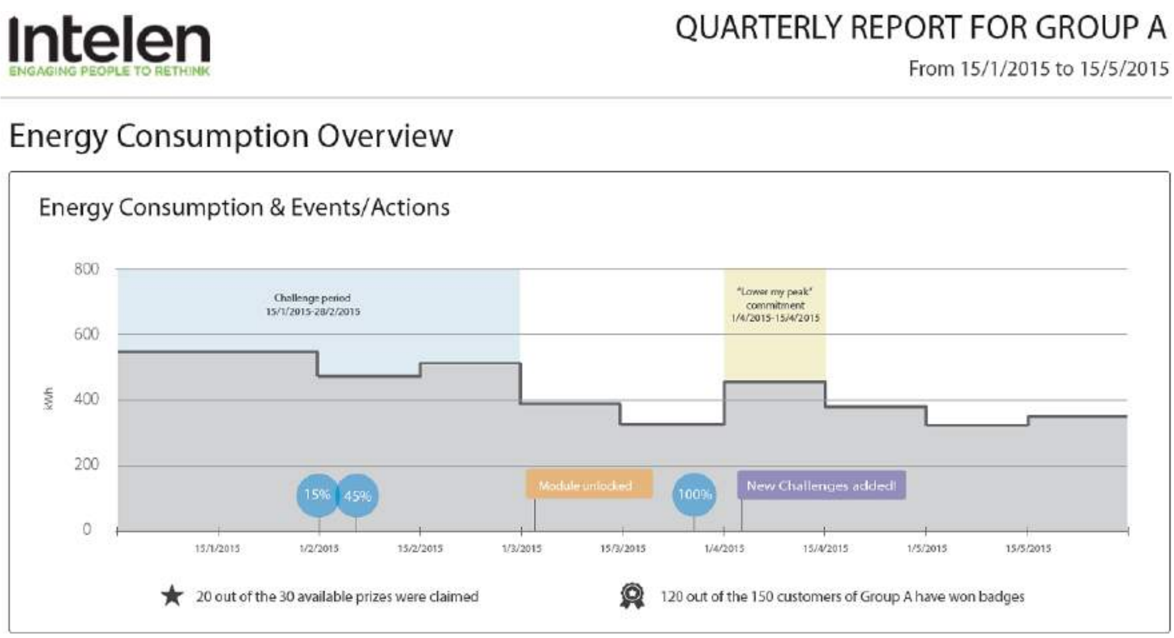


Figure 58 (Energy consumption overview example)

5.5 The Future of DR

- Prosumer-based DR systems & Hybrid houses.
- Behavioural DR will grow big in the next 5 years.
- DR will also produce sustained energy efficiency.
- Storage will change the way we do dispatched DR.
- DR will be a business tool for prosumers to earn money.
- Micro-storage on the appliance level is disruptive.
- Micro-grids will evolve more having Prosumer in the centre.
- Centralized DR will be combined with distributed DR & control.

6 Voltage Control

6.1 Introduction

Voltage control is one of the key aspects that have been affected by the increasing diffusion in the electrical networks of Distributed Energy Resources (DER) encompassing Distributed Generation (DG), Demand Response (DR) and Distributed Storage (DS). The occurrence of voltage rise due to the power injected in the grid by the local DG, especially in rural areas, has caused the insufficiency of the mostly centralized voltage control paradigm in operation for decades, when shunt capacitors were the main local source of reactive power support in distribution networks. Different control structures can be found:

- Centralized control: classical strategy used in traditional systems with passive loads where the voltage at the starting point of the network is increased in order to bring all the node voltages above the minimum voltage limit.
- Decentralized (or local) control: each network node is controlled using local voltage control resources, either included in the generation unit or in the converter or as additional equipment.
- Coordinated (or distributed) control: centralized and local controllers interconnected through a communication system that makes available the information on the relevant variables at the system nodes and where such information can be managed in different ways and at different hierarchical levels.

Voltage control variables can be discrete (e.g., transformer taps, capacitor banks) or continuous (for most of the variables) and may be categorized into:

- Time-dependent, corresponding to changes activated on-line during network operation such as tap positions for HV/MV substation transformers with OLTC, controllable capacitor banks and remote-controllable voltage control settings of local generators and converters.
- Time-independent, such as tap changer set-points for transformers without OLTC, fixed capacitors/reactors, and non-remote-controllable voltage set points of other equipment.

6.2 Voltage Control Architectures

Centralized Control according to the Virtual Power Plant (VPP) concept in SuSTAINABLE:

- Enables the VPP to optimally co-ordinate the resources best suited to address voltage issues (including generation/absorption of reactive power with converters, modification of the active power output of generators and the application of demand side management)

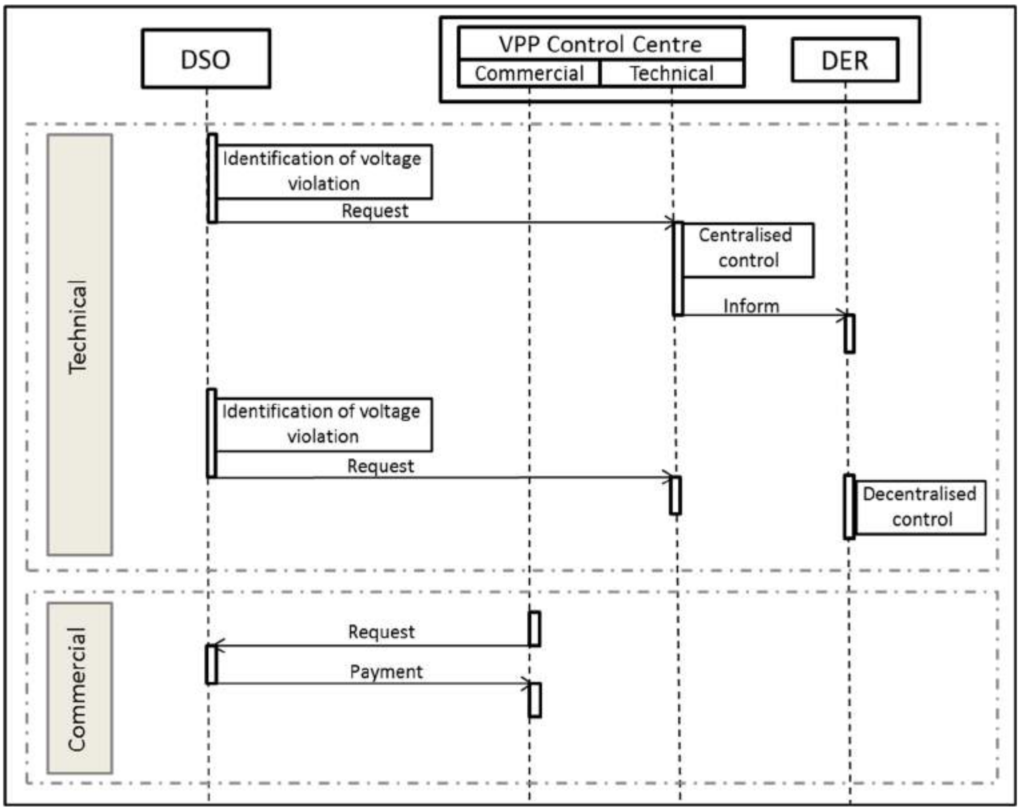


Figure 59 (Voltage control architecture timeline in SuSTAINABLE)

Distributed Control in IGREENGrid:

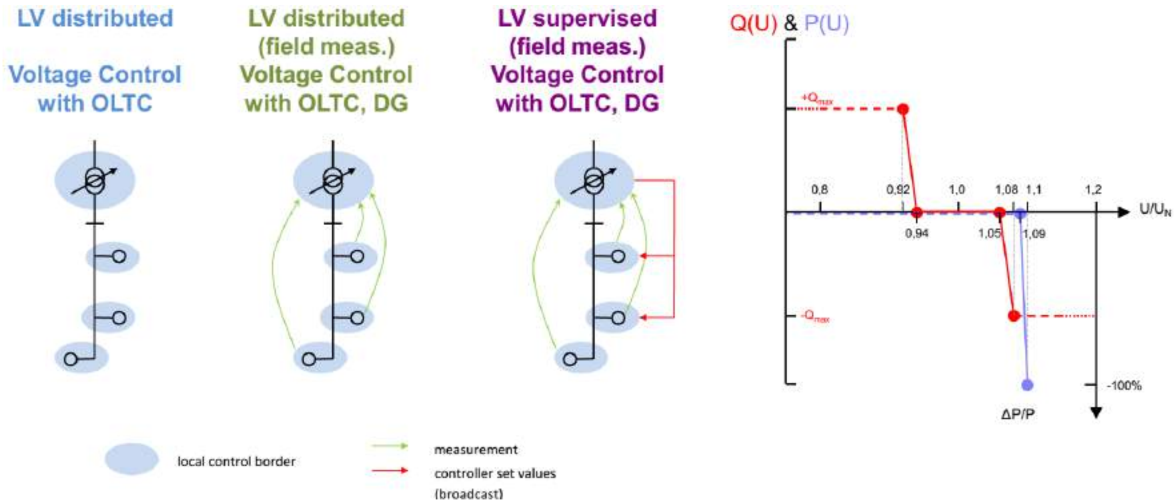


Figure 60 (Distributed voltage control architecture in IGREENGrid)

Coordinated Control in SuSTAINABLE:

- Exploits two control levels at the MV (Multi-Temporal OPF) and LV (Centralized Voltage Control) in coordination with local voltage control strategies (Droops).

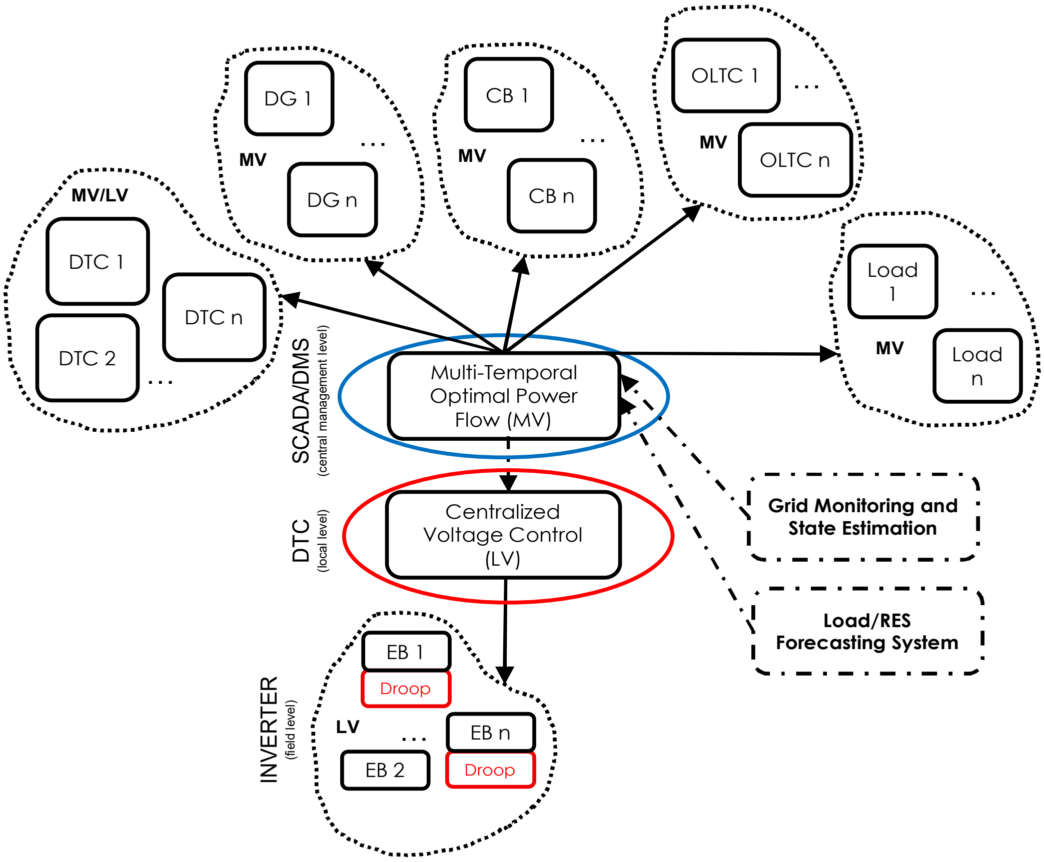


Figure 61 (Distributed voltage control architecture in SuSTAINABLE)

6.3 Voltage Control at the MV Level

Different approaches for voltage control at the MV level have been proposed.

Proposed approach for the voltage control at the MV level in SuSTAINABLE:

- D-1 Analysis: the multi-temporal OPF will produce a set of control actions for the next day by MV network node (DTC) with the objective of maximizing the integration of energy from variable RES subject to a set of technical constraints.
- N-Lead-times Ahead Analysis: the multi-temporal OPF developed for the day-ahead analysis will be used in order to adjust the control actions identified with the objective of minimizing the deviations in a sliding window of 6 lead-times ahead.

As example, Figure 48 shows more details about proposed approach.

Coordinated voltage control improves the voltage profile over the entire network, where daily voltage variations at several nodes along the MV feeder are depicted for the baseline and the proposed control scenarios → An essentially flat voltage profile is obtained, practically for any reasonable RES penetration level.

Probabilistic Approach for Voltage Control at the MV Level in IGREENGrid (HEDNO site):

- Stochastic RES Forecasting and Probabilistic Load Flow are used to assess the effect of P-V control strategies, as a means to increase the RES hosting capacity without violating voltage limits for the whole operating period.

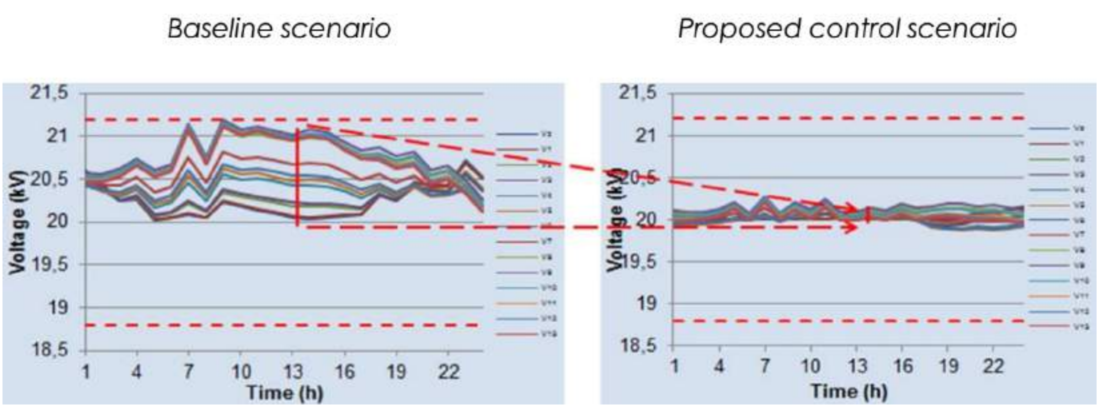


Figure 62 (Example of baseline scenario vs. proposed control voltage approach in SuSTAINABLE)

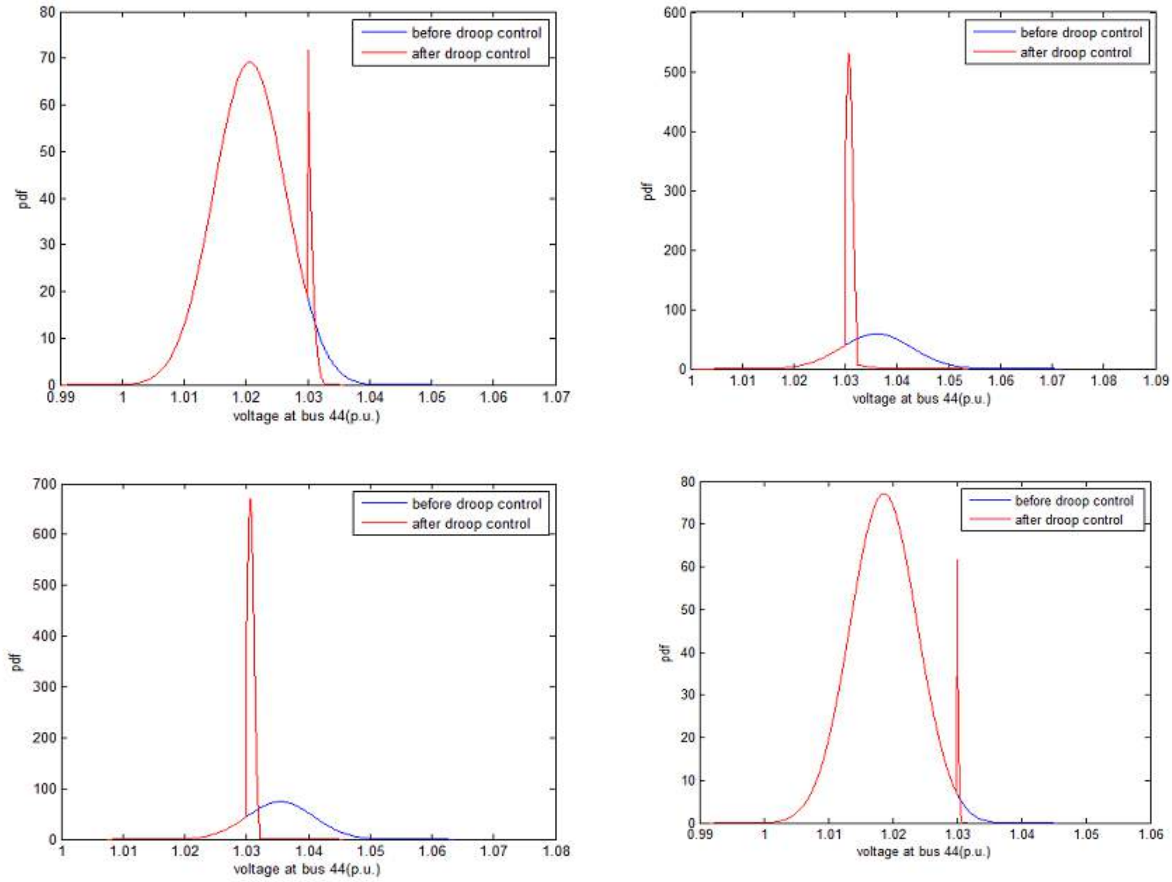


Figure 63 (Voltage PDFs at most remote bus per season 12.00pm with and without droop control with 180% PV installed capacity in IGREENGrid)

6.4 Voltage Control at the LV Level

Voltage control at the LV level has also been addressed and demonstrated in SuSTAINABLE.

Overview of the LV Grid Control in SuSTAINABLE:

- The proposed methodology is based on a set of rules that uses the grid's DER according to a merit order in order to maximize the integration of energy from RES.
- Two different scenarios are considered depending on the level of grid information:
    - Full knowledge of the LV grid: Topology and access to smart metering devices and possibility of executing a "smart" power flow.
    - Limited knowledge of the LV grid: Unknown topology; access only to smart meter readings and geographic coordinates.

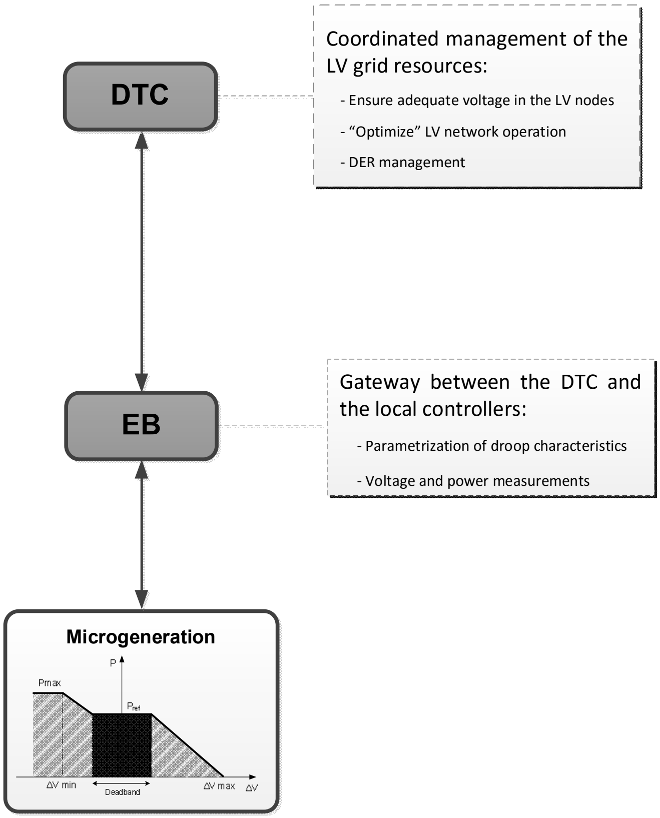


Figure 64 (Overview of the LV grid control by SuSTAINABLE)

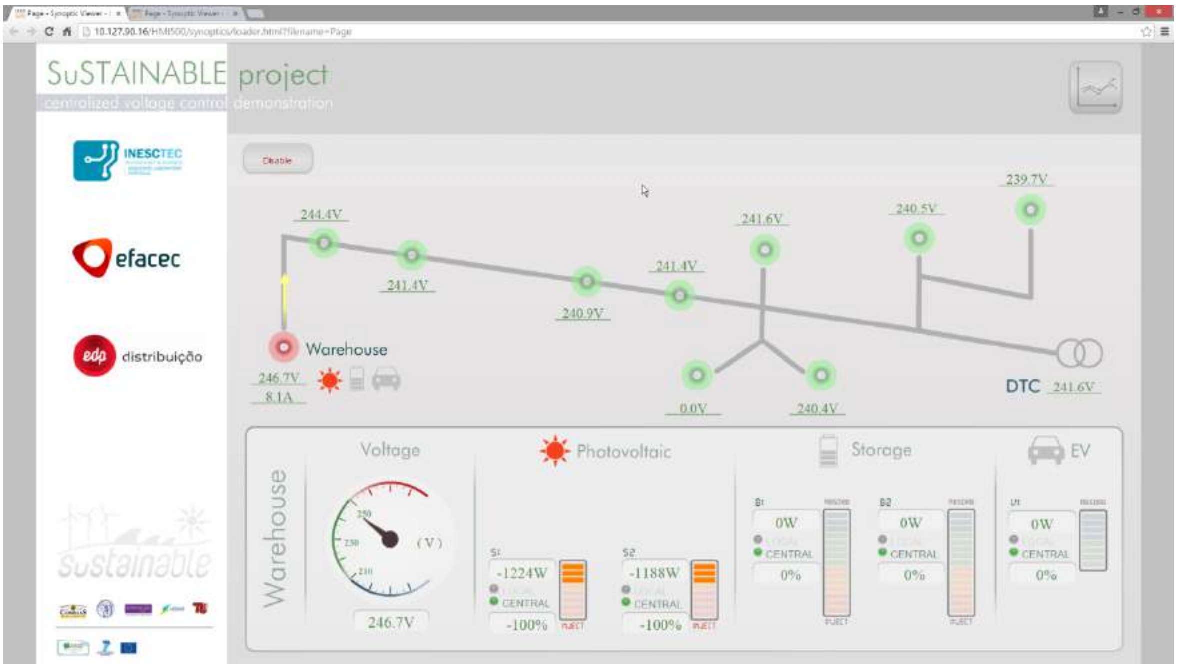


Figure 65 (Demonstration of the centralized control in SuSTAINABLE (EDP's InovGrid site): part 1)

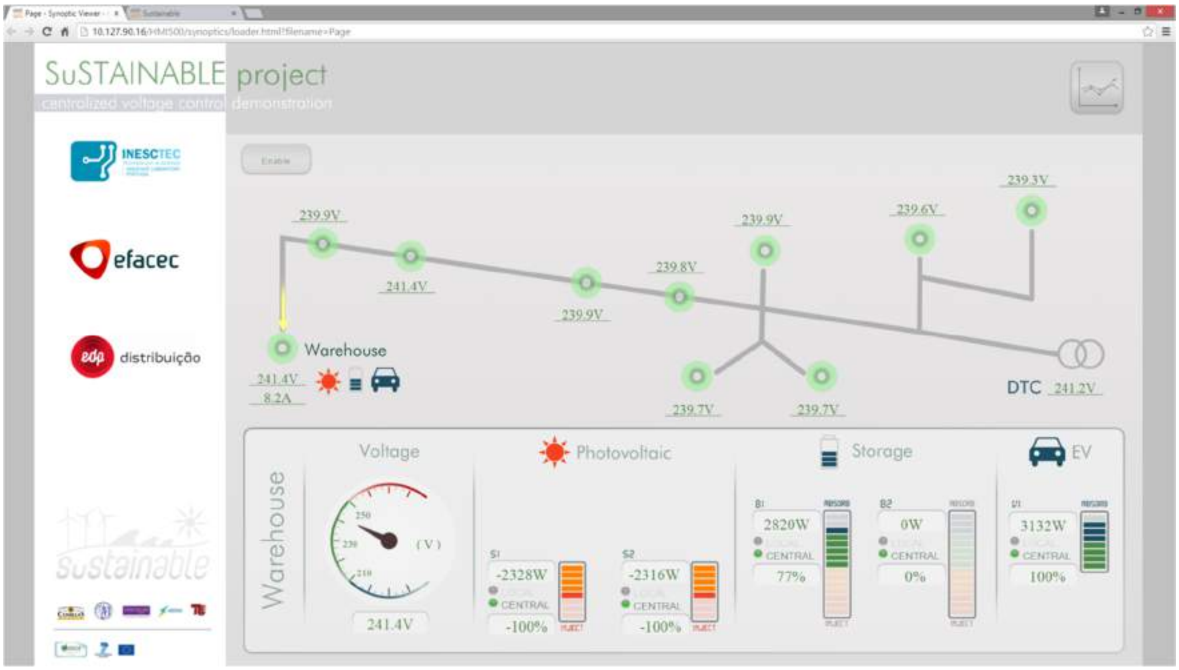


Figure 66 (Demonstration of the centralized control in SuSTAINABLE (EDP's InovGrid site): part 2)

Figure 67 (Demonstration of the centralized control in SuSTAINABLE (EDP's InovGrid site): part 3)

6.5 Voltage Control in Isolated Systems

Voltage control in isolated systems has been addressed in SiNGULAR:

- Advanced control of inverter-interfaced generation behaving as a Virtual Synchronous Generator (VSG).
- Detailed voltage control loop with modeling of:
  - Inverter capability.
  - Non-ideality of the inverter (losses).
  - Dedicated inverter protection scheme to allow appropriate fault ride-through capability.
- Simulation with three successive steps of reference voltage in normal conditions:
  - First two steps: good transient performance.
  - Third step: reference value not reached because of hitting the inverter capability limit.

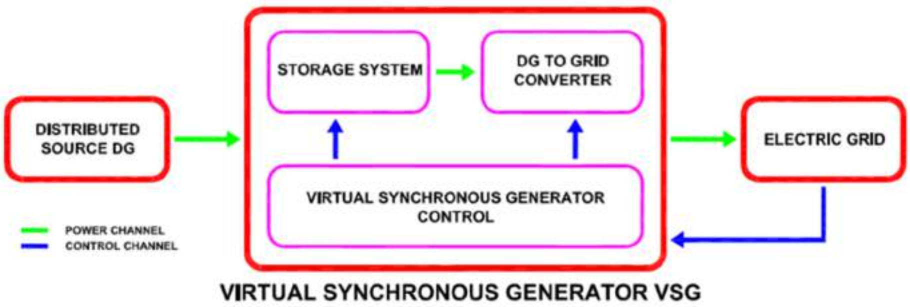


Figure 68 (Virtual synchronous generator schema in SiNGULAR)

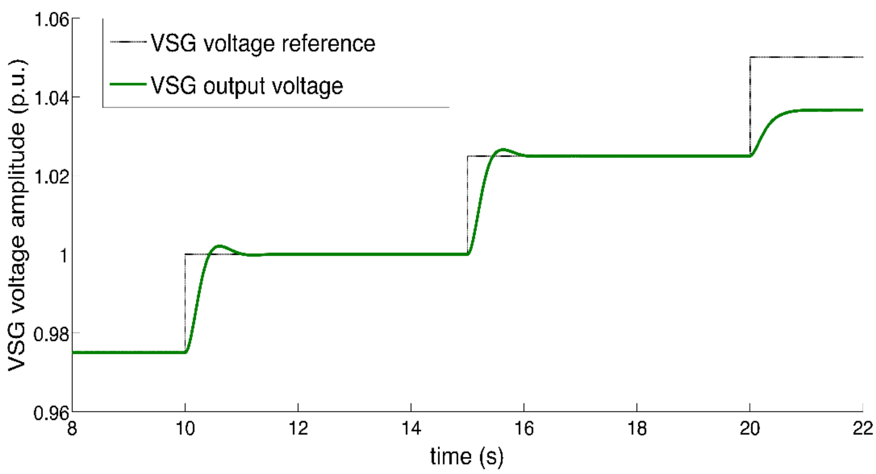
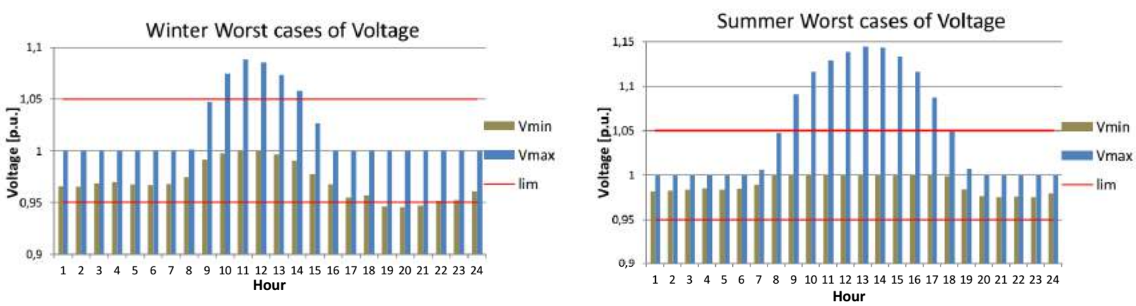


Figure 69 (Virtual synchronous generator output example results in SiNGULAR)

6.6 Regulatory Issues

6.6.1 Cost-Benefit Assessment – Benefits of Voltage Control in Quality of Supply

In SuSTAINABLE a methodology has been developed for identifying the potential benefits and costs deriving from the use of the MV voltage control tool presented in 6.3:



Winter benefits

	Value (€)
Benefits voltage profile (1 day)	103.8
Benefits energy losses (1 day)	32.5
Total benefits (1 day)	**136.3**
Number of days	40
Total benefits (winter)	**4,089.1**

15 years CBA

	Value (€)
Total benefits year 1	17,568.1
Deployment costs year 1	43,818.0
Net benefit year 1	**-26,249.9**
Costs discount rate	0.05
Cumulative Net Benefit	**120,714.7**

Summer benefits

	Value (€)
Benefits voltage profile (1 day)	285.6
Benefits energy losses (1 day)	17.3
Total benefits (1 day)	**302.9**
Number of days	40
Total benefits (summer)	**12,116.1**

Figure 70 (Results CBA MV Évora Feeder in SuSTAINABLE)

6.6.2 Replicability and Scalability

In IGREENGrid, several approaches have been considered in order to investigate the scalability and replicability of smart grids solutions:

1. Perform detailed simulations on a reduced set of reference networks (set of real networks identified by clustering techniques to be representative of all networks) and draw general conclusions.
2. Perform less detailed simulations (actually more statistics) on a comprehensive set of networks and draw general conclusions.
3. Perform detailed simulations on synthetic networks and draw general conclusions

As an example, the critical length (defined as the feeder length for which both the voltage and the loading limits are reached) for types of cables and lines was assessed, as shown in Figure 71.

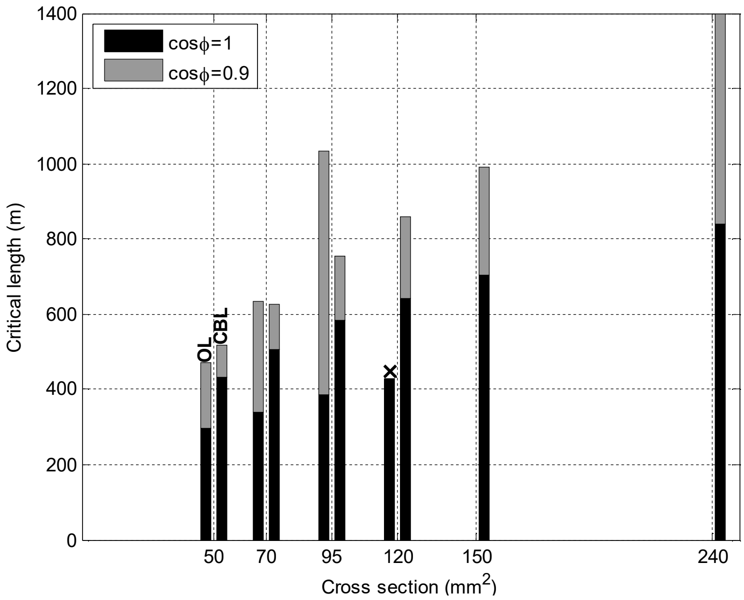


Figure 71 (critical length example in IGREENGrid)

6.7 Final Remarks

Voltage control emerges as a priority for further developments in the three projects.

Concerning voltage control at the MV level it was seen that this is a common focus taking advantage of the several DER available.

Moreover, local voltage control based on droop control (with variants) is also addressed for interfacing DER to the network.

Also, a detailed cost-benefit analysis is important to provide the framework for the voltage control strategies identified.

Finally, scalability and replicability issues need to be addressed based on the results obtained from the application of the methodologies (from simulation, but especially from demonstration).

6.8 Open Questions

1. Is there such thing as an ideal voltage control architecture/approach for smart grids (centralized, decentralized or coordinated) or does it depend on each specific situation?
2. What are the specific challenges and requirements that voltage control faces in islanded smart grid systems and how can they are tackled?
3. What changes to regulation and grid code are required and /or incentives to other stakeholders to be enrolled in the process?
4. Do we need a common approach between EU countries for this issue in order to enable the development and deployment of technological solutions (uniformization of procedures, standardization activities)?
5. How can we increase customer participation and provide means for using DER especially at the domestic level (revise legal framework, provide incentives e.g. monetary)?

7 Scalability & Replicability

7.1 Objectives and Challenges of the Scalability and Replicability (S&R) Analysis

- Case study → big picture
  - Solution A
    - Works in networks 1,7,13,15,…
    - It is competitive in networks 1,13, …
    - …
- Dimension of the problem:
  - Type of networks.
  - DRES scenarios.
  - Smart grids solutions.
  - Number of computations.

7.2 Further Challenges of the S&R Analysis

- Benchmark different SG concepts according to relevant criteria (KPIs for HC, voltage quality, energy efficiency, costs…)
- Common approach / frame / assumptions to compare the performance of solutions
- Estimate the costs components for the solutions – quantitative cost analysis (CAPEX, OPEX)

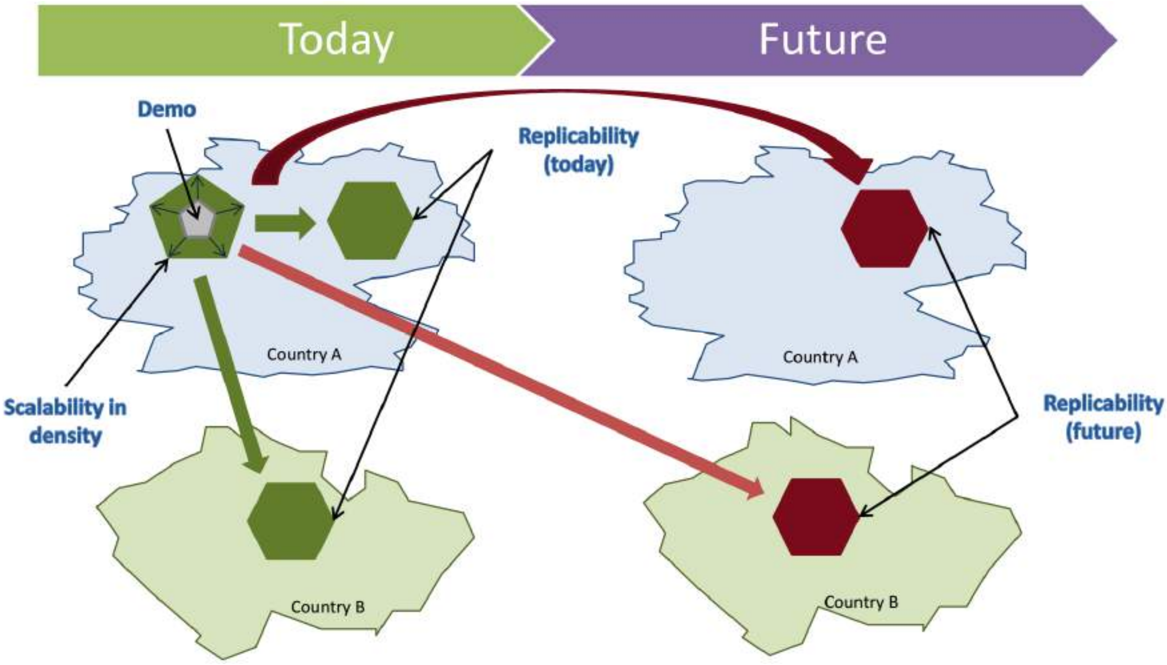


Figure 72 (Scalability and replicability analysis example)

- Two approaches in IGREENGrid:
    - Qualitative assessment of the S&R potential (→ selection of the most promising solutions).
    - Qualitative assessment of the S&R (→ technical and economic evaluation of the most promising solutions).

7.3 Qualitative SRA

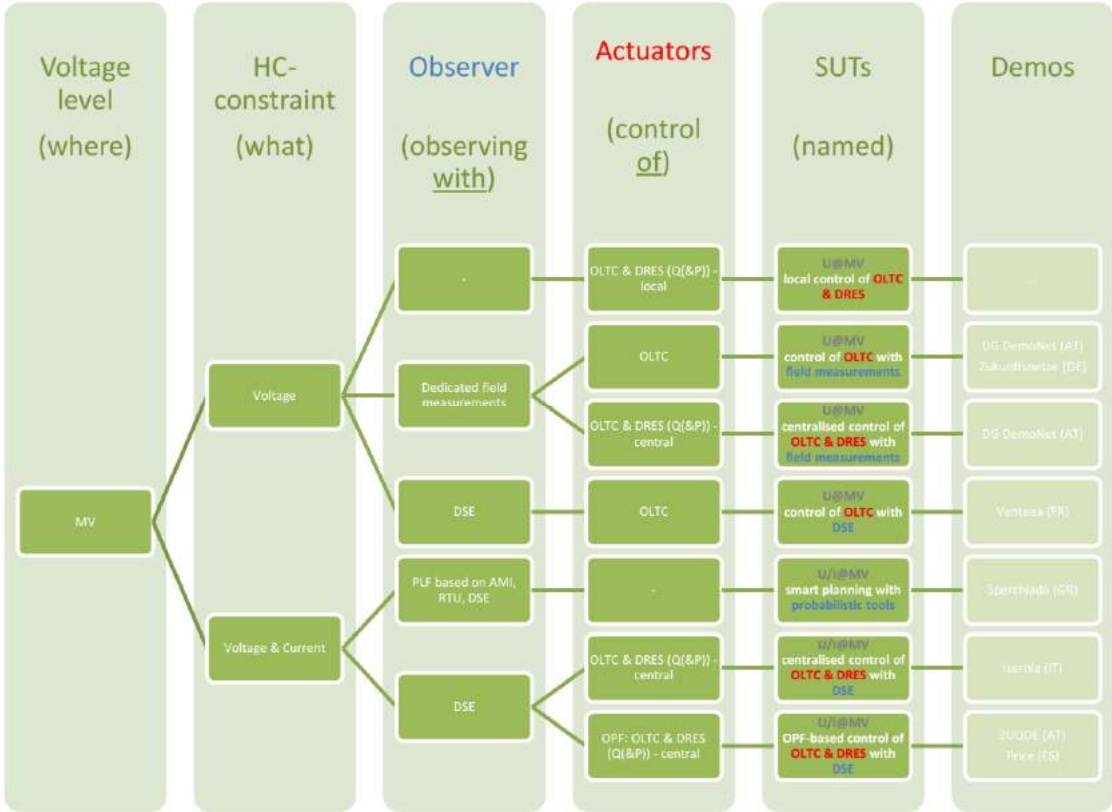


Figure 73 (Classification of solution in qualitative SRA)

7.3.1 Results of the Qualitative Evaluation: Example of LV Voltage Control

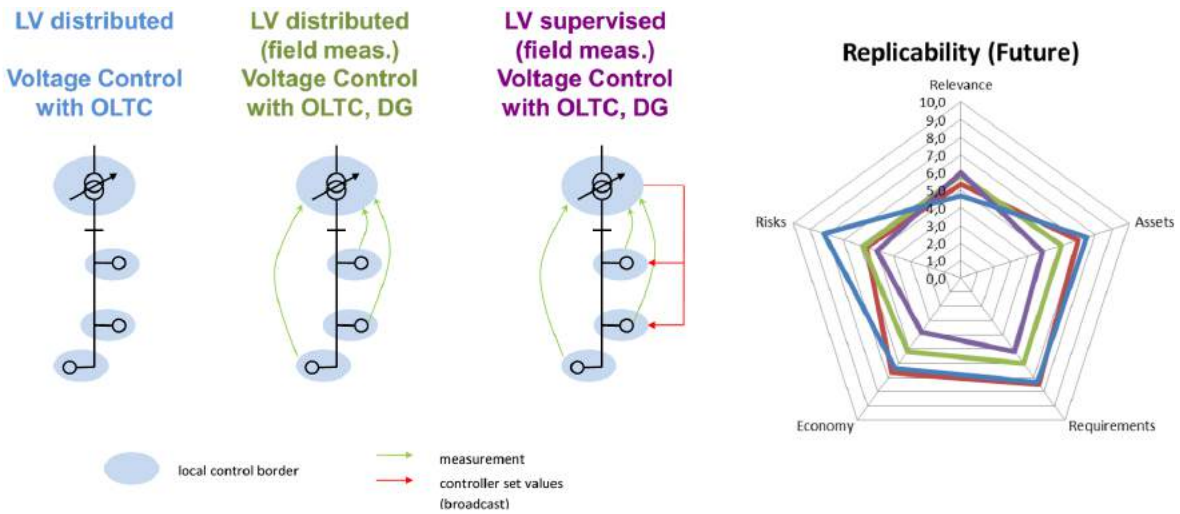


Figure 74 (Results of the qualitative LV control)

7.4 Quantitative SRA

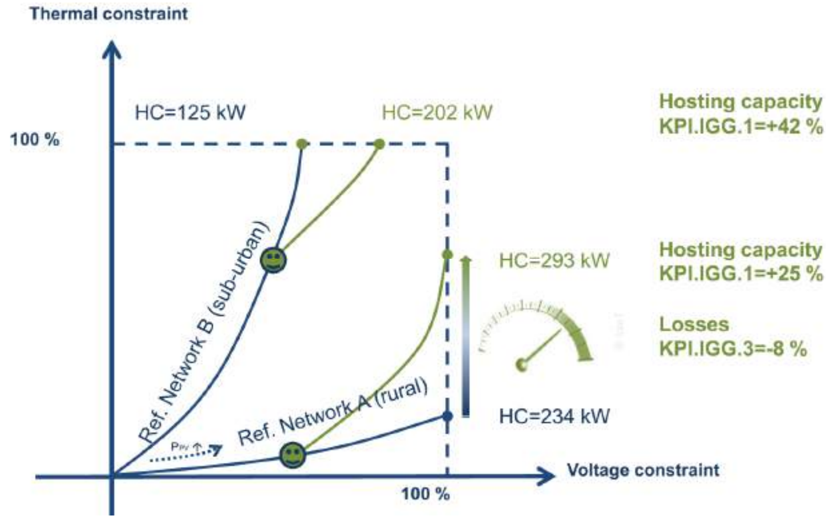


Figure 75 (Increase of the hosting capacity: textbook illustration)

7.4.1 Technological Evaluation of SG Solutions: Methodology

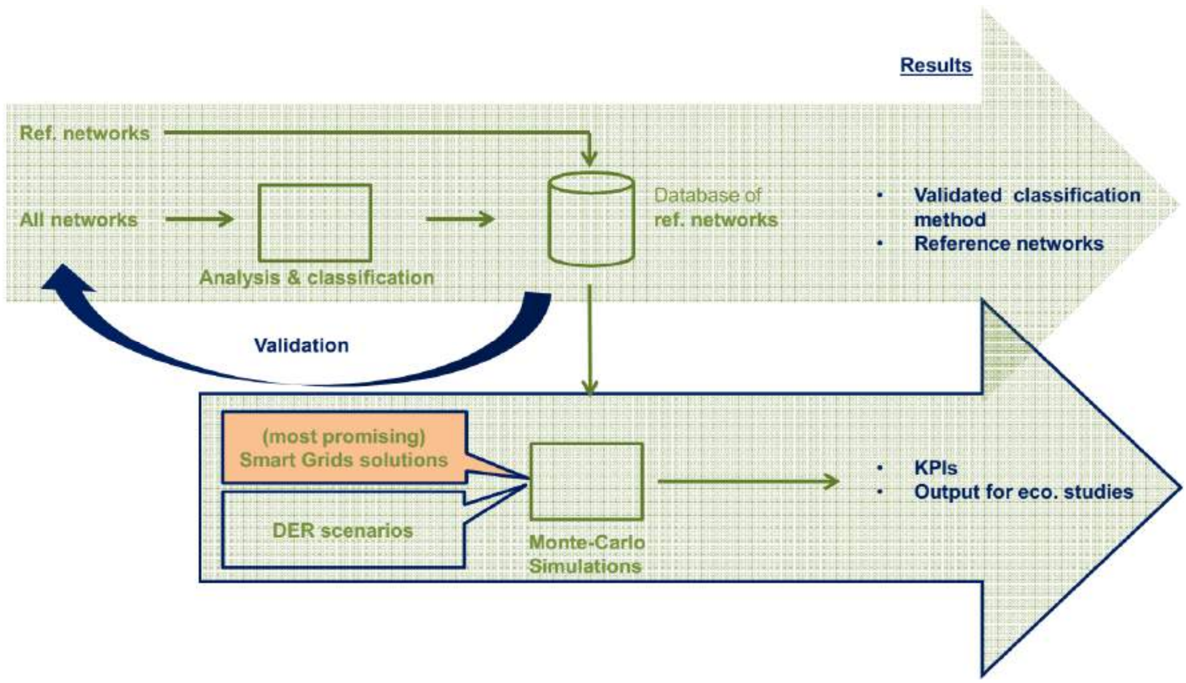


Figure 76 (Illustrative example of the technological evaluation methodology)

Q1: Which networks to use?

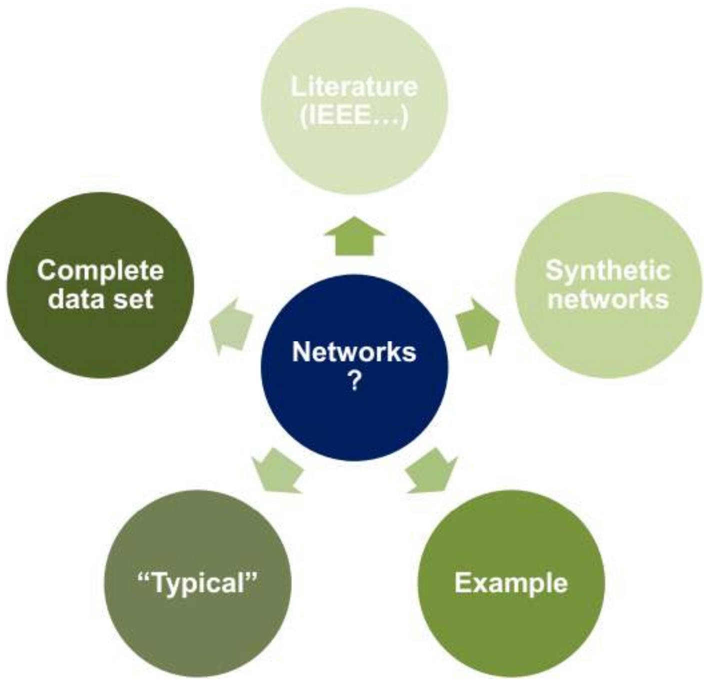


Figure 77 (Illustrative example of the network to be chosen)

Q2: Which DRES scenario to consider?

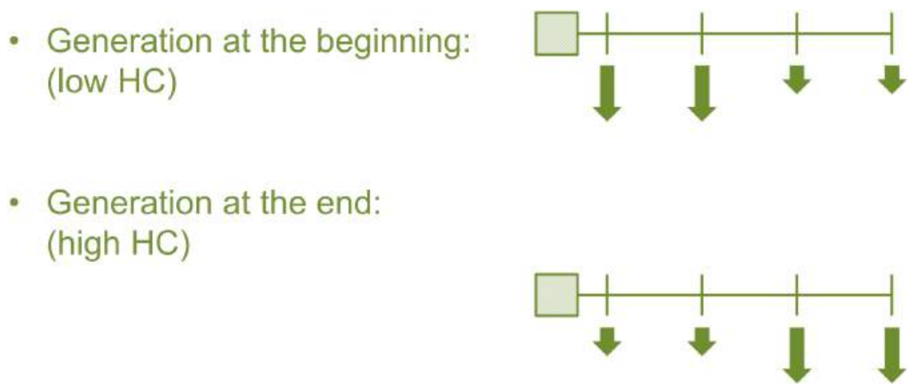


Figure 78 (Illustrative example of possible scenarios to be used)

Data basis at a glance

- More than 15 smart grids solutions (MV&LV) and 8 DSOs'.
- Data from GIS/NIS/SCADA; Wind & PV data per country
- From 6 DSOs:
    - 28 MV networks and 24 LV networks
- From 2 DSOs:
    - More than 25.000 LV feeders and more than 13.000 LV feeders

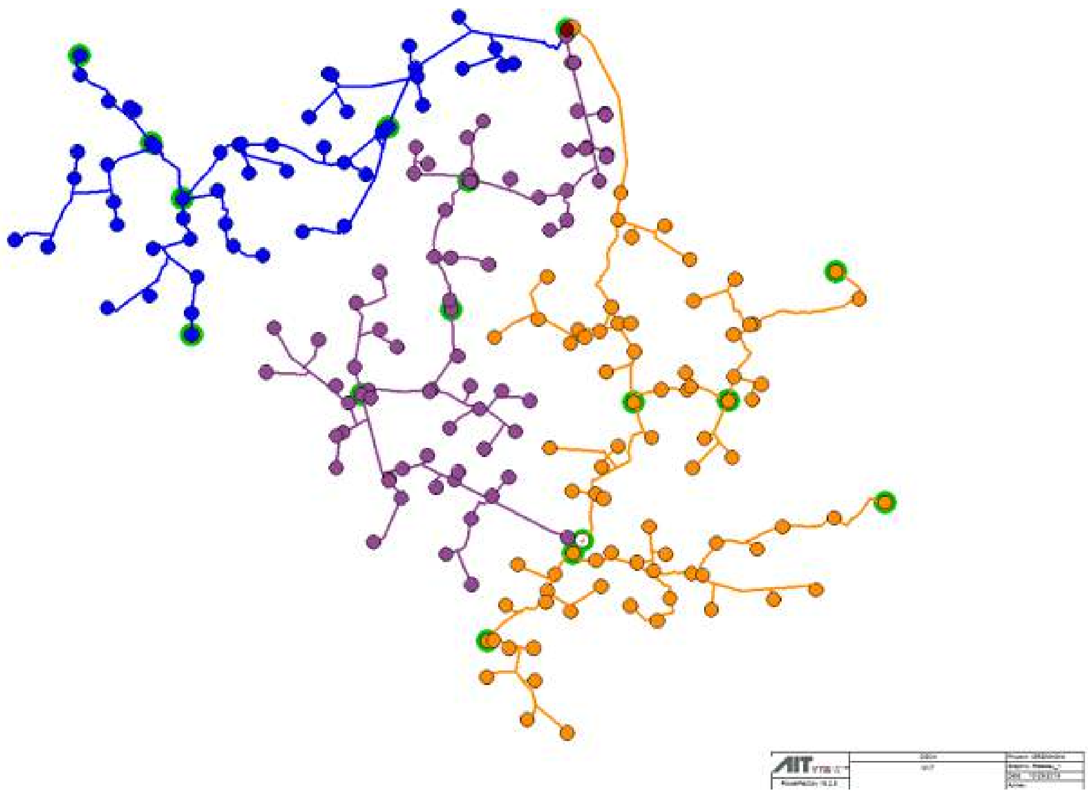
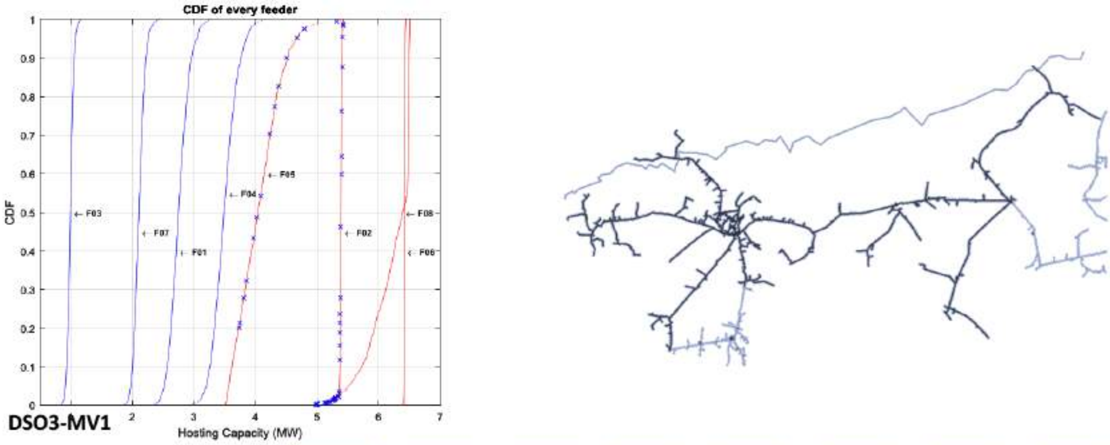


Figure 79 (MV and LV network under study and its geographical location)

Feeder screening (1 of 52 ref. networks)



	F1	F2	F3	F4	F5	F6	F7	F8
Standard Information								
Length (km)	11.9	6.2	38.5	14.2	4.6	5.8	15.1	10.5
Number of loads	24	18	87	43	8	19	50	24
Step 1								
Type of constraint	U	IU	U	U	IU	I	U	I
Voltage constrained (%)	100	4	100	100	1.4	0	100	0
Current constrained (%)	0	[illegible]	0	0	[illegible]	100	0	100
HC50 (MW)	2.75	5.38	0.99	3.49	4.04	6.42	2.11	6.38

Figure 80 (CDF hosting capacity and feeders' standard information)

Feeder screening (More than 48.000 LV feeders)

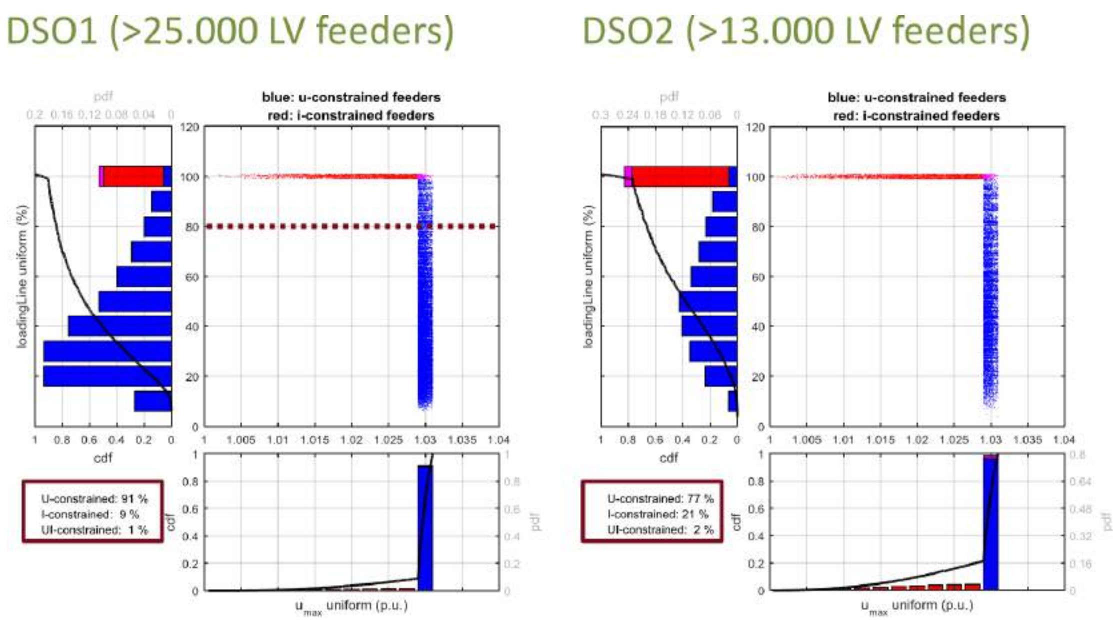


Figure 81 (Feeder screening comparison between DSO1 and DSO2)

Potential of reactive power control in LV networks

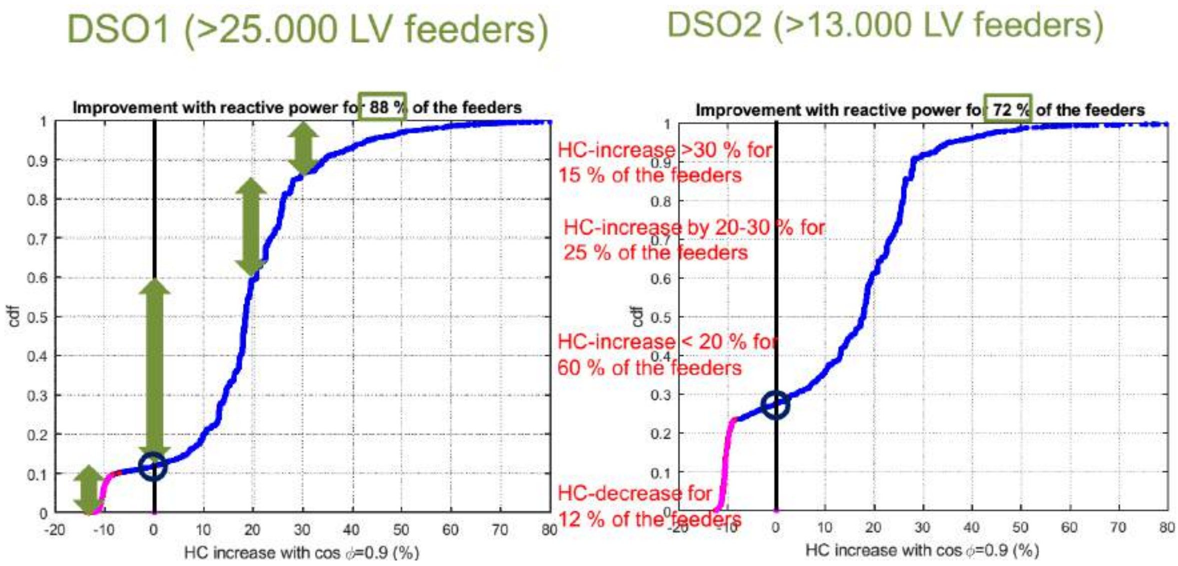


Figure 82 (Potential reactive power control in LV networks comparison between DSO1 and DSO2)

7.5 Conclusion on the S&R Analysis

- Generic results supported by comprehensive simulations.
- Example of results:
  - Q-control → HC increase by *x* % for most of the networks;
  - OLTC@distribution transformers → HC increase for *y* % of networks
- SRA-results relevant for different stakeholders (guideline):
  - DSOs (deployment and investment prioritisation
  - Industry (product development) and Policy

7.6 Approach

- For each of the 9 SuSTAINABLE Functionalities (SFs), the barriers to their scalability and replicability were identified.
- The potential impact of the barriers to hinder deployment was assessed.
- Mitigation strategies for these barriers were developed.
- Four scenarios were developed with differing conditions.

- The different need for each SF and the timescale for mitigation of barriers to each SF were determined for each scenario.
- Based on need and the ability to deploy, timelines for SF deployment have been developed.

7.7 Description of Scenarios

- Scenario 1: Portugal
    - Substantial wind deployment
    - Low PV deployment expected to accelerate rapidly
- Scenario 2: Greek island
    - Insular network
    - High seasonal and intra-day load variability
- Scenario 3: UK
    - Low DER penetration that is expected to increase
    - Market-driven DER integration
- Scenario 4: Germany
    - High PV and wind with expectance to increase
    - Distribution congestion due to DER already existing

7.8 Suggested Actions to Support Smart Grid Deployment

- Key Mitigation actions and timescales for each scenario are shown.
- Short term is considered as 0-3 years, medium term 3-7 years and long term 7-12 years.

	Timescale for Mitigation			
Mitigation Action	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Pilot Tests	Short			
Revision of Regulation, Policy and/or Market Structure	Short/Medium	Short/Medium	Short/Medium	Short/Medium
Smart Meter Roll-out	Medium	Short/Medium	Short/Medium	Short/Medium
Participant Engagement through New Agents or Education Campaigns	Medium	Medium	Short	Short/Medium
Enhanced DER Converter Automation	Medium/Long	Medium	Short/Medium	Short/Medium
Real Time Communications Deployment	Medium	Medium	Medium	Medium
Storage Cost Reduction	Medium/Long			

Table 4 (Suggested actions scenarios to support smart grid deployment)

7.9 SiNGULAR contributions in Scalability and Replicability

- In SiNGULAR there are not specific tasks on Scalability and Replicability.
- However, SiNGULAR has activities on test and validation of the tools developed in several insular power systems: different sizes and generation mixes.

Pilot Sites	Peak Load [MW]	Voltage Levels [kV]	Generation Mix
Crete Greece	650	150/20/15/.4	Thermal (Steam, ICE, CCGT) /Wind/PV
São Miguel Azores	75	60/30/10/.4	Thermal (ICE) /Geothermal/Hydro/Wind
Great Island of Braila Romania	15	110/20/.4	Mainland Romania + Wind
Pantelleria Italy	7	10.5/.4	Thermal (ICE)/PV/(Wave)
La Graciosa Canary Islands	0.8	20/.4	Thermal (ICE)/(Wind)/(PV)
El Hierro Canary Islands	6.2	20/.4	Thermal (ICE)/Wind/Hydro-Pumped storage

Pilot islands	Tools validated
Crete (Greece)	Forecasting Scheduling Power Analysis Demand Response
Sao Miguel (Azores/Portugal)	Forecasting Scheduling Power Analysis Planning
Braila/Scanteiesti (Romania)	Forecasting Power Analysis
Pantelleria (Italy)	Forecasting Power Analysis
La Graciosa (Canary Islands/Spain)	Forecasting Storage Management Planning
El Hierro (Canary Islands/Spain)	Forecasting

Figure 83 (Different features and tool applied on islanded systems considered by SiNGULAR)

- Forecasting tool has been tested in all islands. The validation demonstrates that this tool is scalable and replicable: models training is needed.
- Planning and Power Analysis algorithms have been tested in several islands: grid data and RES resources are necessary (between other info) as inputs/configuration to run de the tools developed. Both are completely scalable and replicable after the previous configuration.
- Two distinct approaches have been developed for Scheduling: (i) an advanced probabilistic unit commitment based on risk analysis [S. Miguel] and (ii) a second approach based on Mixed-Integer Linear Programming (MILP) [Crete]:
    - Risk-based approach is replicable in small islands with a limited number of fast conventional generation units.
    - MILP-based approach is more suitable for large islands, where both slow and fast conventional generating units operate.
    - Both can be applied to different power systems with moderate effort (mainly interface to the Insular power system SCADA).
- Summarizing: tools are scalable and replicable but adjustment to the specific local conditions is needed.

La Graciosa (smallest island)

	$MAPE_{Average}$	$MAPE_{MAx}$	Variance (MW)	Bias
Forecast Model	$Average_{D\_D+6}$	$Average_{D\_D+6}$	$Average_{D\_D+6}$	$Average_{D\_D+6}$
Consumption	8,75%	4,23%	0,00	-0,01
Theorethical PV	41,38%	8,10%	0,03	-0,01

Crete (largest island)

	$MAPE_{Average}$	$MAPE_{MAx}$	Variance (MW)	Bias
Forecast Model	$Average_{D\_D+6}$	$Average_{D\_D+6}$	$Average_{D\_D+6}$	$Average_{D\_D+6}$
Wind	41,37%	20,02%	769,14	-14,52
PV	28,25%	6,22%	75,49	-2,80
Consumption	7,57%	4,42%	1156,76	11,64
Agregation	17,04%	8,39%	2385,88	44,84

Figure 84 (Comparison results reported by SiNGULAR forecast tool considering different Island systems)