Modelling, operation, and control of virtual power plants

Tutorial

F. Milano, B. Marinescu, Á. Ortega

Agenda

- 3 presentations
  - A Taxonomy of Virtual Power Plants
  - Dynamic VPP Realization for Multi-time Scales Integration
  - Optimal Bidding of Renewable-based VPPs in Energy and Ancillary Service Markets
- 1.5 hours

Part 1

A Taxonomy of Virtual Power Plants

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Federico Milano received from the University of Genoa, Italy, the ME and PhD in Electrical Eng. in 1999 and 2003, respectively. From 2001 to 2002 he was with the University of Waterloo, Canada, as a Visiting Scholar. From 2003 to 2013, he was with the University of Castilla-La Mancha, Spain. In 2013, he joined the University College Dublin, Ireland, where he is currently a full professor. He has authored 8 books and more than 330 papers. He was elevated IEEE Fellow in 2016 for his contributions to power system modeling and simulation, IET Fellow in 2017, and IEEE PES Distinguished Lecturer in 2020. He is currently an editor in chief of the IET Generation, Transmission & Distribution, the chair of the Technical Program Committee of the PSCC 2024, a member of the CIGRE Irish National Committee, the chair of the IEEE Power System Stability Controls Subcommittee and a Senior Editor of the IEEE Transactions of Power Systems.

A Taxonomy of Virtual Power Plants

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University College Dublin

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Table of Contents

Prologue

VPP Definition

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Funding Schemes

The tutorial presents the contributions of two European projects, namely edgeFLEX (https://www.edgeflex-h2020.eu/) and POSYTYF (https://posytyf-h2020.eu/)

Summary

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- Overview of the structure, components and services that can be provided by VPPs.

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- Dynamic operation and control of the VPPs and introduces the novel concept of dynamic VPP.
- Operation of VPPs and their role in ancillary service electricity markets.

Table of Contents

Components

A VPP is most typically composed of four vital parts which are:

- Distributed energy resources (DERs)
- Energy storage systems (ESSs)
- Energy Management System (EMS) based on Information and Communication Technologies (ICT)
- Controllable loads.

VPPs vs. Microgrids

VPPs are **not** microgrids.

Microgrids usually have complete sensing and control of the grid among the controlled assets.

Yet, microgrids have several aspects in common with VPPs, one of them being the ability to provide frequency and voltage support.

Moreover, hierarchical controllers for frequency and voltage have been implemetned in both MGs and VPPs.

Distributed Energy Resources (DERs)

DERs are the main feature of VPPs, as they allow the scheduling of the VPP.

The control of power converters used with DERs plays a key role in the potential of VPPs in offering grid services.

The aggregation of DERs and their coordination is a crucial aspect for both the control and operation

For primary frequency and voltage control purposes, communication systems are necessary to provide coordination. The latency of the communication signals is one of the main issues to be solved.

Types of DERs

DERs as VPP components can be categorized according to the type of:

- Primary energy source
- Capacity of distributed generation (DG)
- Ownership of DG
- Operational nature of DG.

Primary Energy Source

Primary energy sources are divided into RES based like wind-based generators:

- photovoltaic arrays
- solar-thermal systems
- small hydro-plants

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Primary energy sources are divided into RES based like wind-based generators:

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and non-RES based like:

- Combined Heat and Power (CHP)
- biomass
- biogas
- diesel generators
- gas turbines
- fuel cells (FC).

DG Capacity

The Small-scale capacity DGs that must be connected to the VPP to increase access to the electricity market or they could be connected with controllable loads to form microgrids.

The medium-scale and large-scale capacity DGs that can independently take part in the electricity market.

However, they may opt for being connected to VPP to gain optimal steady revenue.

DG Ownership

Residential-owned, Commercial-owned, and Industrial-owned DGs, aka Domestic DGs (DDG), that are utilized for supplying all/part of its load.

Utility-owned DGs, aka Public DGs (PDG), that are used to support the main grid supply shortage.

Commercial company- owned DGs, aka Independent Power Producers DGs (IPPDG), that are to generate profits from selling power production to the network.

DG Operational Nature

When it comes to wind or PV systems as DG units, the output power is uncontrollable because it relies highly on a variable input resource.

To address this, such DGs must be equipped with battery storage to control the output power. This operational nature of DGs is called *stochastic nature*.

Other DG technologies such as FCs and micro-turbines have an operational dispatchable nature. They are able to alter their operation rapidly.

VPP should incorporate controllable loads, Energy Storage Elements (ESE), and dispatchable DGs to compensate for the vulnerability of the stochastic nature-DG type.

Energy Storage Systems (ESSs)

ESSs and energy management system (EMS) are a crucial aspect of the frequency control of non-synchronous devices and VPPs.

If properly controlled, energy storage can also be utilized to provide virtual inertia and fast frequency control.

ESSs have to be desgined with two goals: minimize cost and maximize services.

Clearly, minimum size (cost) designs might underperform in cases emergency frequency control is required.

Categories of ESSs

ESSs can be categorized according to their applications as either energy supply or power supply, as:

- **For energy supply**: Hydraulic Pumped Energy Storage (HPES), Compressed Air Energy Storage (CAES).
- **For power supply**: Flywheel Energy Storage (FWES), Super Conductor Magnetic Energy Storage (SMES), Super Capacitors.

Viability of ESS-based Frequency Control

A relevant question is whether the frequency response provided by ESSs has both technical and economic feasibility.

For example, a study[1] considered a 1.6 MW/0.4 MWh lithium-ion battery ESS that provides primary frequency regulation in the framework of a 100% renewable Danish energy market by 2050.

This study shows that the investment in the lithium-ion battery energy storage system can be profitable in the Danish market if it is committed to at least 10 years.

[1] M. Świerczyński, D. I. Stroe, R. Lærke, A. I. Stan, P. C. Kjær, R. Teodorescu, and S. K. Kær, *Field experience from Li-ion BESS delivering primary frequency regulation in the Danish energy market*, ECS Transactions, vol. 61, no. 37, p. 1, 2014.

Electric Vehicles

Among existing ESSs, electric vehicles (EVs) play a special role as they are expected to dramatically increase their capacity in the near future.

EVs can, in effect, be used as a VPP, in which EVs are utilized to support primary reserve in smart grids.

The control of EVs and their communication are of vital importance for the effective integration of EVs into VPPs.

Energy Management System (EMS)

The heart of a VPP is an EMS that coordinates the power flows from the generators, controllable loads, and storages.

Receiving information about the status of each element inside the VPP, forecasting RES primary sources and output power, loads forecasting and management, power flow coordination between the VPP elements, and also operation control of DGs, storage elements, and controllable loads are the most important duties of the EMS.

The main aims and objectives of the EMS are generation cost minimization, energy losses minimization, green-house gases minimization, profit maximization, voltage profile improvement, and power quality enhancement.

Controllable Loads – 1

Controllable loads can be classified into three types, as follows.

Type a: including residential loads such as fridges, washing machines, air conditioners, space cooling/heating, water heating, etc., which are interrupted or shifted by the load's utilities monitor. Such loads cannot inject power to the network at any time.

Controllable Loads – 2

Type b: including battery storage, Vehicle-to-Grid (V2G), the Combined Cooling Heating and Power (CCHP), etc. As opposed to type 1 of the controllable loads, these loads are able to inject power into the network. They can be charged from or discharged to the network. They have also more considerable flexibility to be scheduled and thus, they are tailored to network needs.

Type c: including microgrid, VPP, etc. Although microgrid and VPP have distributed generators, battery storage, renewable energy, etc., the loads take a great proportion in these systems.

Frameworks

From the perspective of the nature of the entity and their topology, VPPs are classified into Commercial Virtual Power Plant (CVPP) and Technical Virtual Power Plant (TVPP).

CVPPs operates just like a traditional generator, bidding in the electricity markets without considering the effect of its operation on the local grid.

TVPPs employ DERs to handle the local grid in terms of thermal and voltage congestions. The TVPPs are also able to provide ancillary services to help the security of the system.

Technical Virtual Power Plant (TVPP)

The primary responsibility of a TVPP is to dispatch properly the DERs and the ESSs to manage the energy flow inside the VPP cluster, and offer the ancillary services accordingly.

A TVPP receives information from the CVPP about the contractual DGs and the controllable loads.

Data that TVPP must consider are the maximum capacity and commitment of each DER unit, the prediction of production and consumption, the location of DER units and loads, the capacity and the locations of the energy storage systems, the available control strategy of the controllable loads at all times during the day as per the contractual obligations between the VPP and the loads.

Duties of TVPPs

- Managing the local system for DSO.
- Providing balancing, management of the network, and execution of ancillary services.
- Providing visibility of the DERs in the distribution grids to the TSO, thereby setting the stage for DG and demand to make contribution to the transmission system management activities.
- Monitoring the DER operation based on the requirements obtained by CVPP (system status information).
- Constantly monitoring the status for the retrieval of equipment historical loadings.

Commercial Virtual Power Plant (CVPP)

A CVPP carries out bilateral contracts with the DG units and the customers.

The data of these contracts is sent out to the TVPP to consider the amount of the contracted power all through the performance of technical research.

Duties of CVPPs

- Production schedule as per the predicted needs of consumers.
- Trading in the wholesale electricity market.
- Providing services to the system operator.
- Submitting characteristics, costs, and maintenance of DERs.
- Prediction of production and consumption as per weather forecasting and demand profiles.
- Outage demand management.
- Selling DER power in the electricity market.

Table of Contents

Frequency Regulation

This service brings back the frequency to the nominal operating level after any deviation occurrence due to the physical unbalance between generation and demand.

This is attainable by adjusting the active power reserves of the system through automatic and rapid responses.

The TSOs need to plan, in advance, to make sure that the correct levels of active power reserves are available in real-time, as well as that the TSOs must take remedial actions, when it comes to a shortage.

Active power reserves embrace generator units, storage, and sometimes demand response.

VPP Frequency Regulation

Ancillary services that can be provided by VPPs are:

- Inertia & inertial emulation
- Primary frequency control
- Load following
- Secondary & Tertiary frequency control
- Procurement/concerns for frequency reserve

Primary Frequency Control

This service has been recently renamed as *Frequency Containment Reserves (FCRs)*

FCR is the first control action to be activated, usually within 30s, in a decentralized fashion over the synchronous area.

Secondary Frequency Control

This service has been recently renamed as *Frequency Restoration Reserves (FRRs)*

FRR is the centralized automated control, enabled from the TSO in the time interval between 30s and 15min from the unbalance occurrence.

FRR can be categorized according to reserves with automatic activation (automatic Frequency Restoration Reserves, AFRR) and reserves with manual activation (manual Frequency Restoration Reserves, MFRR).

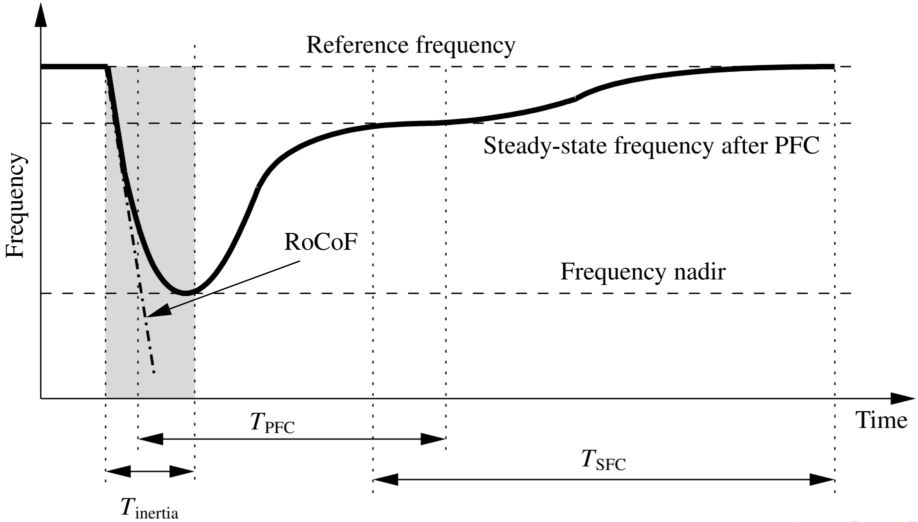
Tertiary Frequency Control

This service has been recently renamed as *Replacement Reserves (RRs)*

RR is a manual control.

Typical activation time for RRs is from 15min after the unbalance occurrence up to hours.

Time Scales of Frequency Control



Procurement/Concerns for Frequency Reserves

- *Compulsory Provision*: a class of generators is involved to provide specific reserves of ancillary services.
- *Bilateral Contract*: the TSO negotiates with each provider the quantity and price of the offered ancillary service. This permits the TSO to purchase only a specific ancillary services amount and to deal with sellers to minimize the overall expense.
- *Tendering and Spot Markets*: these refer to an ancillary service exchange process characterized by increased competition. Although the tendering market is usually composed of long-duration services, the spot market involves shorter and less standardized products.

Grid Strength

An important aspect of frequency regulation (not just by VPPs) is whether this service is offered in strong or weak grids.

This distinction affects how frequently this service is activated and whether higher reserves are required to implement it.

Strength is measured in terms of:

- Inertia
- Sensitivity to load changes

Strong Grids

These include a high number of rotating masses (conventional generators and motors) connected tend to be less affected by typical load-generation imbalances.

Frequency changes less sharply and in tighter deviations intervals.

VPPs connected to a strong grid will not be required to procure considerable reserves or activate them as much.

A VPPs might not be needed to be involved in primary frequency control, as other rotating generators may be assigned this role.

Weak Grids

Weak grids have few rotating machines (generators and motors) and some numbers of inverter-interfaced DG and storage systems.

Frequency deviations are more frequent and more severe and VPP assets might be expected to respond more frequently and in broader operating ranges causing added wear and tear.

Higher costs need to be accounted for when VPPs contribute to the frequency regulation of weaker grids.

The VPP assets need to be clearly accounted for in stability studies of such systems and more thoroughly.

Table of Contents

VPP Operation

The owner or operator of the VPP may be controlling the VPP assets either as an actual entity, like system operator control room personnel, or as a software framework, similar to distribution or energy management systems (DMS or EMS).

The VPP operator will need to abide by the level of the electric grid to which the size of the VPP and its assets are operating.

There mainly two operation levels:

- Distribution system level
- Transmission system level

Distribution Level

At the distribution level of power systems, VPPs are not expected to contribute directly to frequency regulation services as the aggregated power of their assets cannot easily justify the procurement of reserves and their release upon disturbances.

No standardized code/regulation explicitly required them to contribute to the frequency regulation until recently that a framework was discussed [IEEE 1547-2018].

Aggregators of assets or collectives of VPP operators may coordinate and bid their reserves for services to the market operator, provided proper regulatory framework exists.

Transmission Level

Most of the resources connected at the transmission level in power systems are expected to contribute with frequency regulation services to support the grid stability.

Except for renewables, all other generators have been typically designed with governors that respond to frequency deviations at either the primary or secondary level.

In terms of market involvement, generating assets at the transmission level submit bids for up and down reserves and the operator clears and assigns them.

VPP operators are expected to handle both the market and technical aspect of frequency regulation and the procurement of reserves in cases the VPP assets are connected at the transmission level of power systems.

Operation Methods

There are variety of operation methods for VPPs. Most relevant are:

- Numerical methods
- Heuristic methods
- Hybrid methods

For optimal operation of VPP in terms of power loss minimization, cost reduction, profit maximization, and environmental emission reduction, a wide variety of numerical and heuristic control methods are used.

Numerical Methods

The most widely used numerical methods are

- Linear Programming (LP) which is capable of addressing optimization problems in terms of optimal DER power and DG energy extraction;
- Nonlinear Programming (NLP) to determine the length of time of several DGs;
- Gradient Search,
- Sequential Quadratic Programming (SQP),
- Dynamic Programming (DP),
- Exhaustive Search for finding several purposes like optimal DG locations, optimal DG sizes, minimization of cost, and also reduction of loss.

Heuristic Methods

Due to the potential and proven capabilities of metaheuristic methods for solving optimization problems, a wide variety of metaheuristic algorithms have been presented.

Examples are: Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Fuzzy Logic Controller (FLC), Artificial Neural Network (ANN), Tabu Search (TS), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Harmony Search (HS), Cat Swarm Optimization, and Firefly algorithm (FA).

Examples of objective functions are optimal placement, size, and type of DG, power loss minimization, energy loss minimization, profit maximization, voltage profile improvement, maximization of DG penetrations, power quality improvement, reliability indices.

Hybrid Methods

Combination and hybrid heuristic algorithms have come to researchers' attention with the same purposes yet better performances.

Foe example, GA-PSO, FLC-ANN, PSO-FA, to name but a handful.

AI-based Machine Learning is the next level of these algorithms.

Table of Contents

Examples

For illustration, we consider two examples:

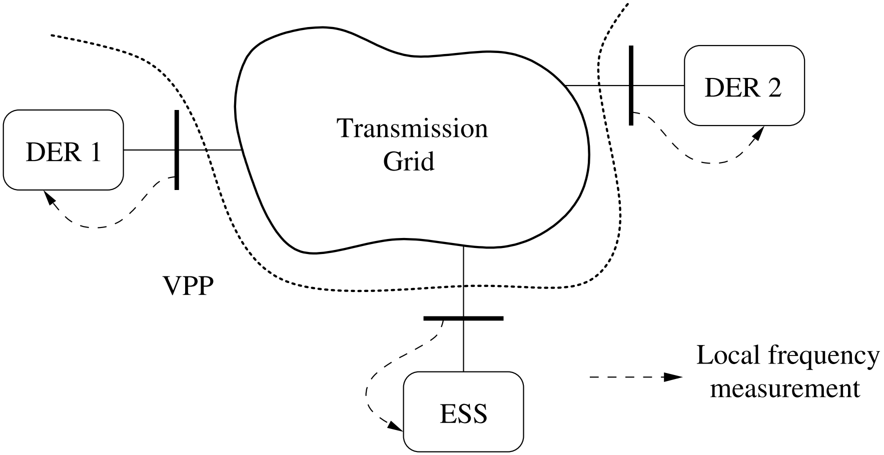
- Impact of topology on the effectiveness of VPP frequency control
- Secondary frequency control of VPPs

Impact of Topology on VPP Frequency Control

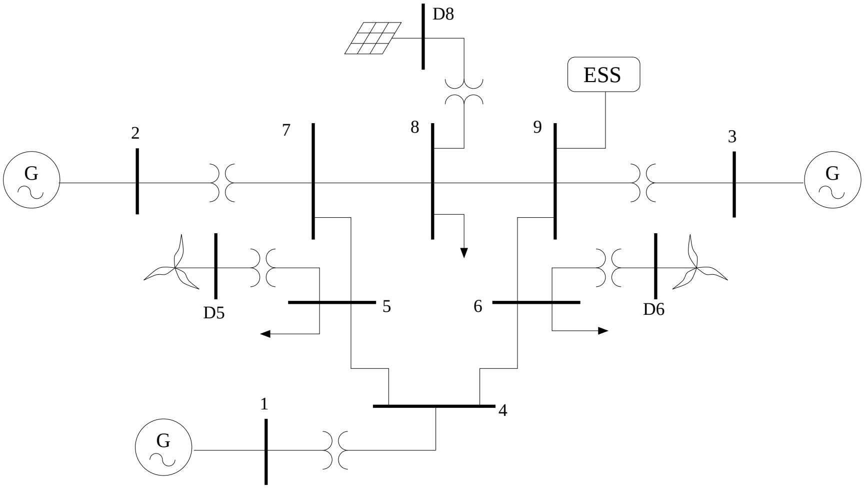
This example considers two different VPP topologies:

- Transmission system VPP (TS-VPP), where DERs and ESSs are connected directly to the high-voltage transmission system
- Distribution-system VPP (DS-VPP), for which the devices are connected with the transmission grid via a point of common coupling (PCC).

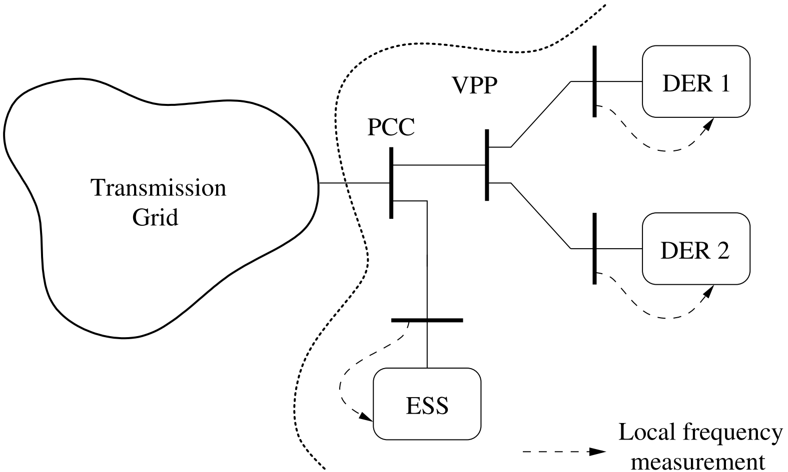
Transmission-System VPP Topology



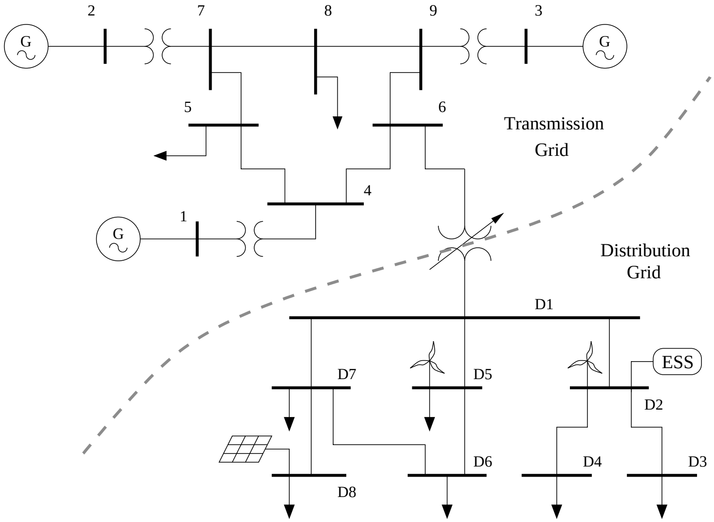
Transmission-System VPP Test System



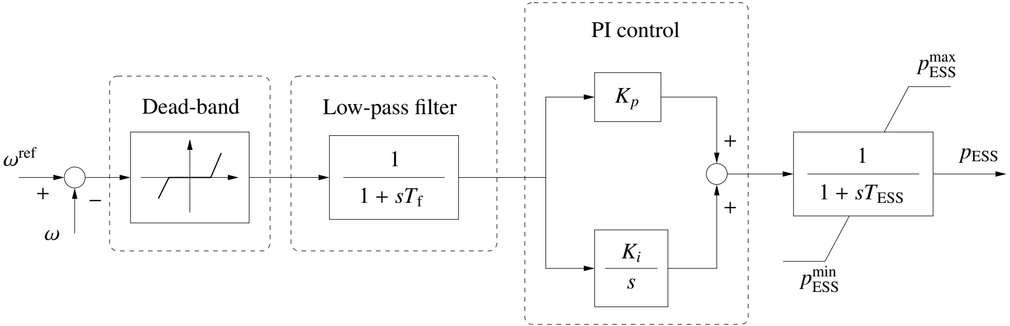
Distribution-System VPP Topology



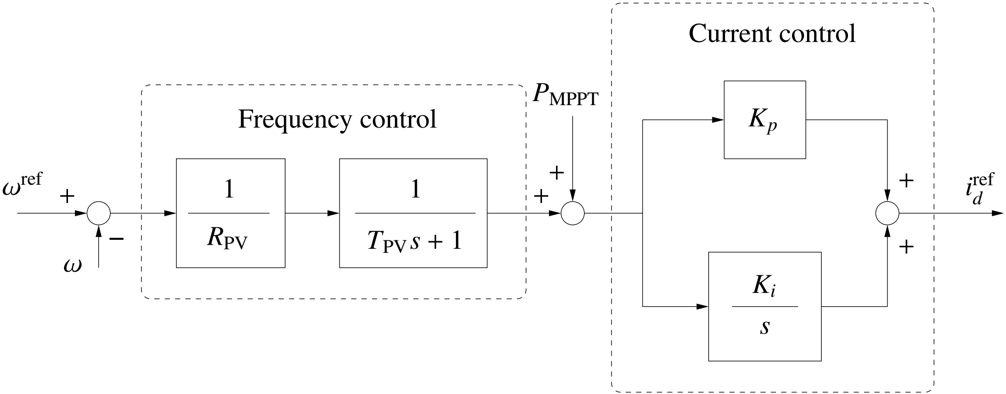
Distribution-System VPP Test System



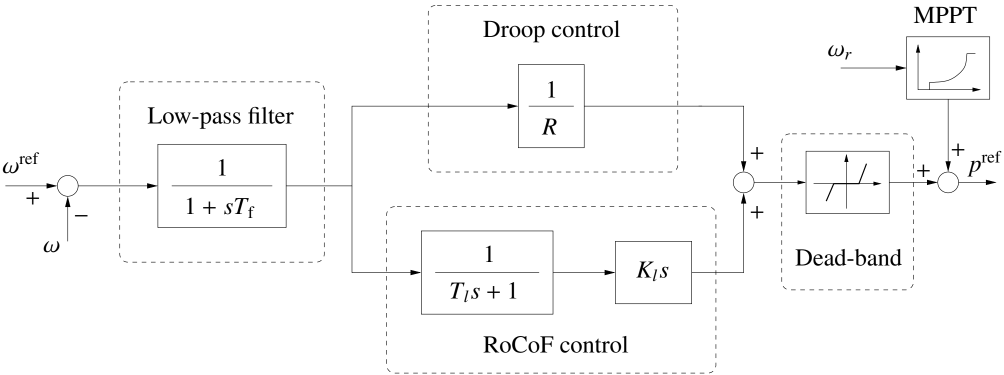
Typical Frequency Controllers of ESSs



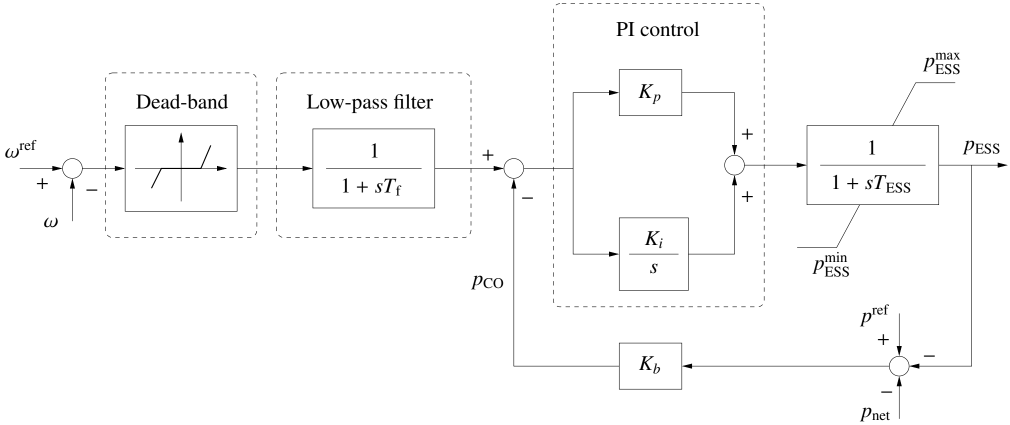
Typical Frequency Controllers of PV Power Plants



Typical Frequency Controllers of Wind Power Plants



Coordinated Frequency Controllers of VPP



Scenarios

This case study considers the impact of both TS-VPP and DS-VPP on power system transient response considering five scenarios, corresponding to five frequency control setups of the VPP, as follows:

- Without ESS and DERs frequency control.
- With ESS but without DERs frequency control.
- Without ESS but with DERs frequency control.
- With non-coordinated ESS and with DERs frequency control.
- With coordinated ESS and with DERs frequency control.

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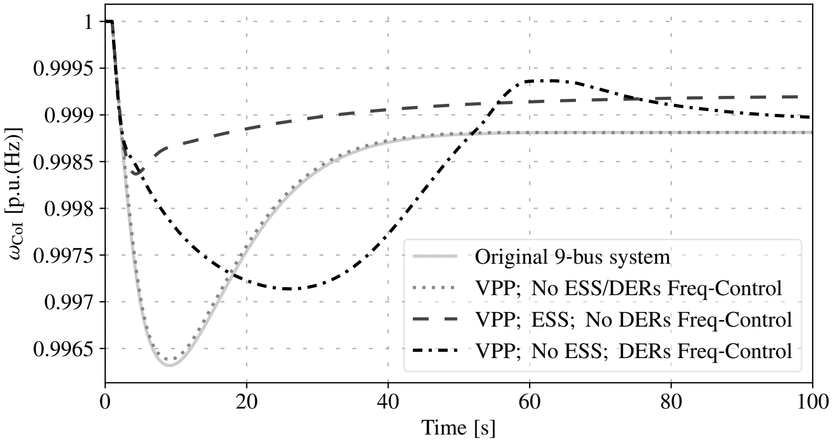
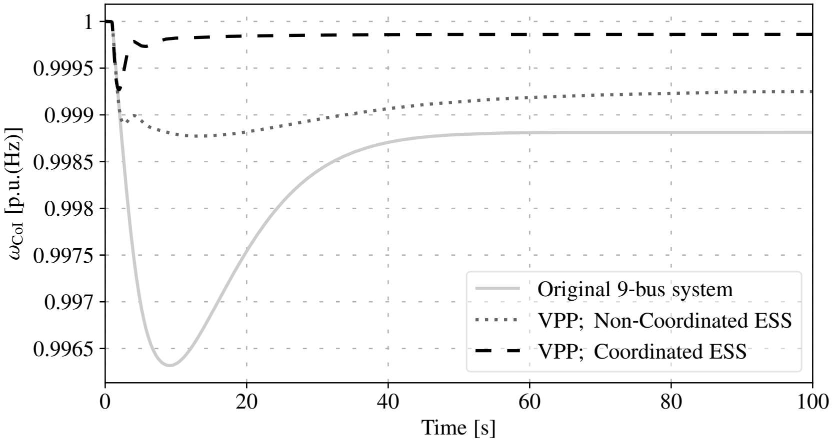
The contingency considered in this scenario is a 3% instantaneous load demand increase at

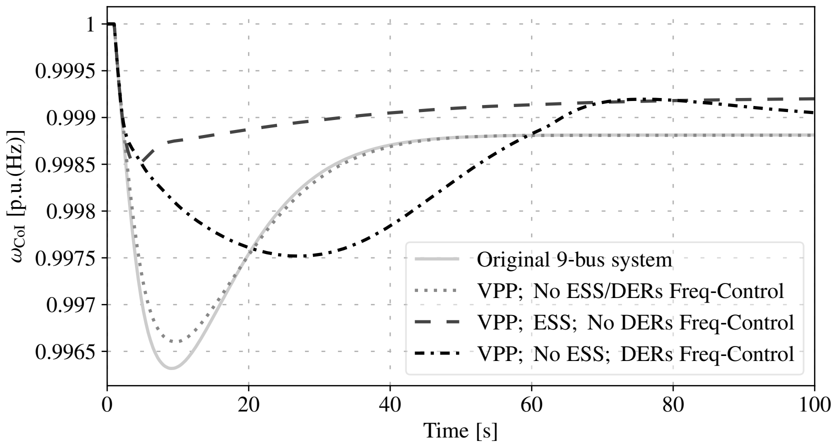
Results for TS-VPP – 1



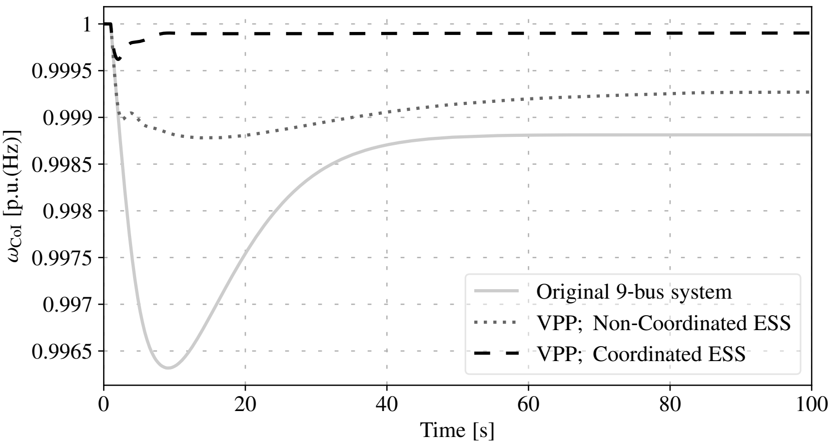
Results for TS-VPP – 2



Results for DS-VPP – 1



Results for DS-VPP – 2



Secondary Frequency Control

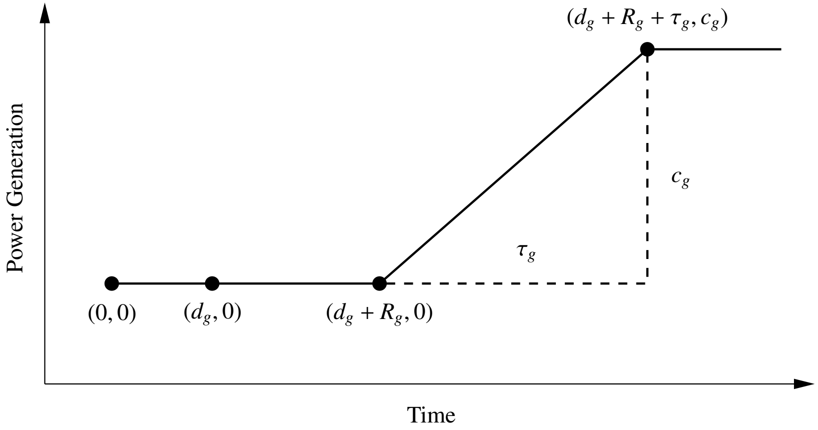
The provision of secondary frequency control by VPP is of utmost importance for managing the real-time balance between generation and demand.

TSOs have specific rules for generators that provide these ser- vices.

For example in Ireland, the TSO requires that the power output of a VPP increases linearly during the ramp-up time.

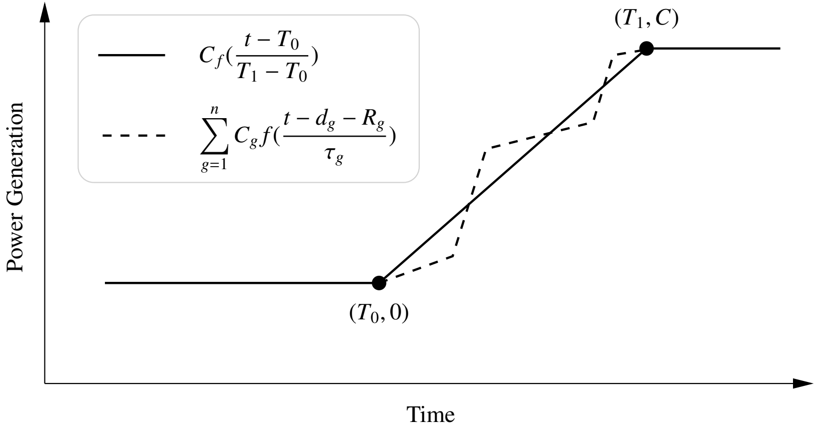
If that is not the case and the VPP generates more than the agreed linear ramp, then the TSO does not pay for the excess power.

Power Production of a Single DER



d_g and R_g, τ_g, c_g are the the delay, response time, ramping time, and capacitcy, respectively, of the DER.

Power Production of a Large Power Plant and Of a Collection of DERs



C and C_g are capacities of the large power plant and of each DER, respectively.

Scenarios

We consider two scenarios:

- MILP problem that optimally schedules the small generators of the VPP. The MILP finds the optimal scheduling of the units that compose the VPP to obtain a ramping rate that is as close to linear as possible.
- The second is based on an automatic generation control (AGC) approach.

Scenarios

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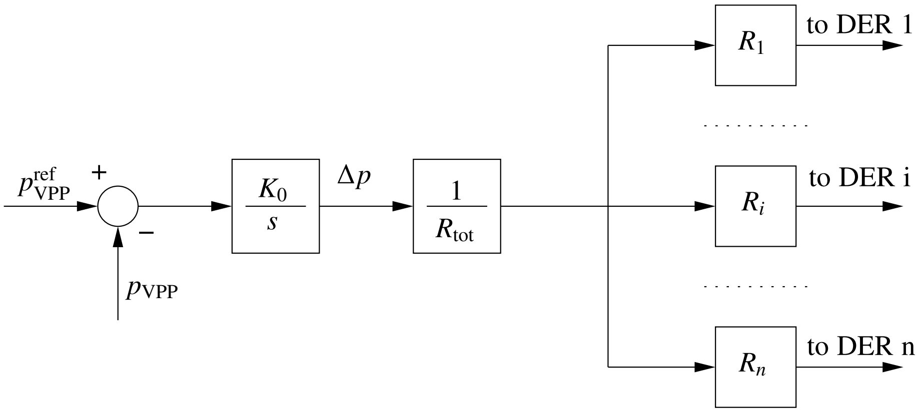
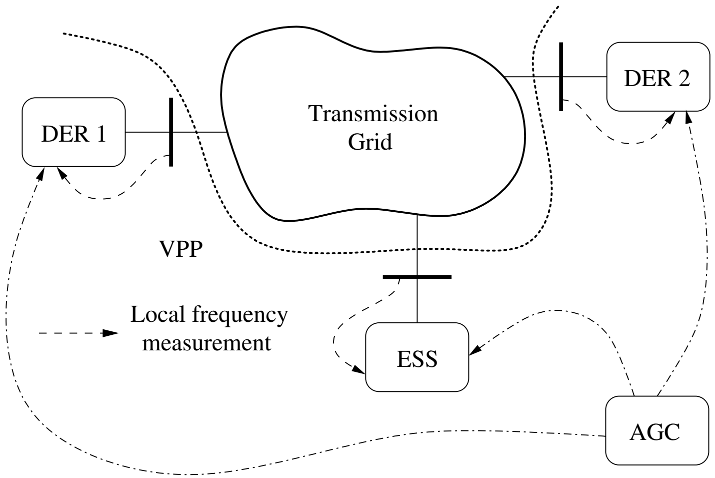
We use a modified verion of the 39-bus system and assume that at $t = 1$ s there is a 20% instantaneous load increase.

Control Scheme of the AGC



Topology of the AGC



Comparison of MILP and AGC

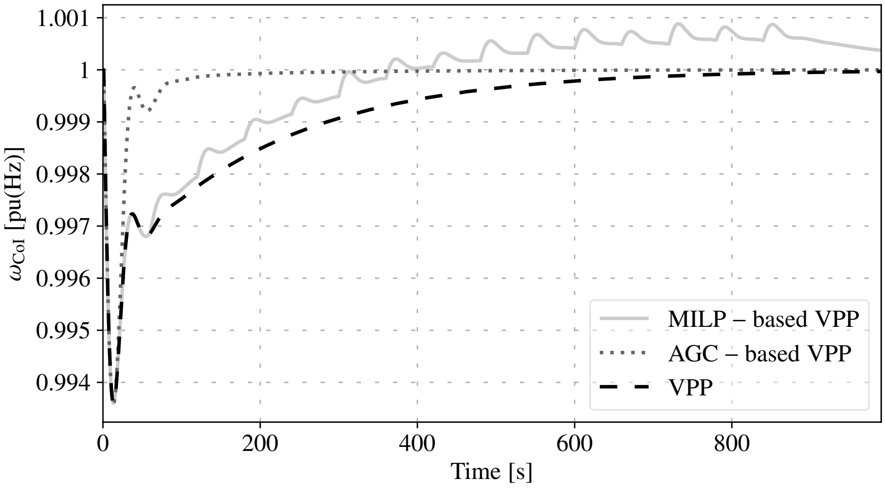


Table of Contents

Concluding Remarks – 1

Remark 1

VPPs are expected to represent a considerable amount of energy resources in grid of today and tomorrow.

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Remark 2

VPPs are expected to participate actively in the procurement and offer of ancillary services.

Concluding Remarks – 1

Remark 1

VPPs are expected to represent a considerable amount of energy resources in grid of today and tomorrow.

Remark 2

VPPs are expected to participate actively in the procurement and offer of ancillary services.

Remark 3

Most typical and crucial of the ancillary services is frequency control, as it expresses the effort to retain generation-demand equilibrium at any given moment.

Concluding Remarks – 2

Remark 4

VPPs are uniquely positioned to actively aggregate, control and manage the effects of DERs and ESSs at the highest level of coordination that ensures grid stability.

Concluding Remarks – 2

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Remark 5

VPP control has to handle the matter of system stability from a disadvantaged position as it lacks grid visibility.

Concluding Remarks – 2

Remark 4

VPPs are uniquely positioned to actively aggregate, control and manage the effects of DERs and ESSs at the highest level of coordination that ensures grid stability.

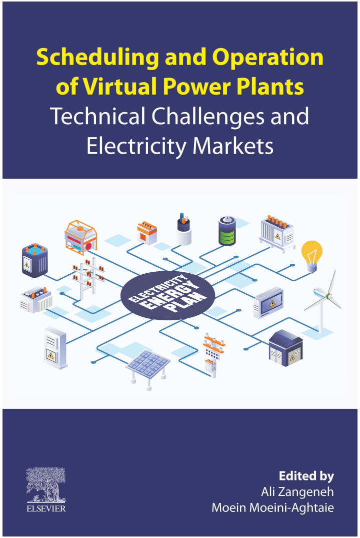
Remark 5

VPP control has to handle the matter of system stability from a disadvantaged position as it lacks grid visibility.

Remark 6

ICT, communication infrastructure, data-heavy models, sensing and novel state estimation techniques are needed to enable VPPs in this complicated role in modern power systems.

Reference


Scheduling and Operation of Virtual Power Plants
Technical Challenges and Electricity Markets
ELECTRICITY ENERGY PLAN
ELSEVIER
Edited by
Ali Zangeneh
Moein Moeini-Aghtaie

Thank you!

Part 2

Dynamic VPP Realization for Multi-time Scales Integration

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Bogdan Marinescu was born in 1969 in Bucharest, Romania. He received the Engineering degree from the Polytechnical Institute of Bucharest in 1992, the PhD from Université Paris Sud-Orsay, France in 1997 and the "Habilitation à diriger des recherches" from Ecole Normale Supérieure de Cachan, France in 2010. He is currently a Professor in Ecole Centrale Nantes and LS2N laboratory where he is the Head of the chair "Analysis and control of power grids" - http://chairerte.ec-nantes.fr/home/ - (2014-2024) and the Coordinator of the POSYTYF H2020 RIA project - https://posytyf-h2020.eu/ - (2020-2023) and DREAM Erasmus Mundus Master - https://master-dream.ec-nantes.fr/ - (2021-2027). He was active in R&D divisions of industry (EDF and RTE) and as a part-time professor (especially from 2006 to 2012 in Ecole Normale Supérieure de Cachan). His main fields of interest are the theory and applications of linear systems, robust control and power systems engineering.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883985

Dynamic VPP Realization for Multi-time Scales Integration

Tokyo, August 6th, 2024

Prof. Bogdan MARINESCU, Ecole Centrale Nantes
Coordinateur RIA H2020 POSYTYF

Content

- The Dynamic Virtual Power Plant (DVPP) concept
  - Framework: POSYTYF H2020 project
  - DVPP realization via controls
  - Main outputs of the project
- Multi time-scale controls validation in real-time simulations
  - Hardware in the loop (HIL) framework
  - Active power control validation

POSYTYF

POSYTYF Project: POwering SYstem flexibiliTY in the Future through RES

Call: LC-SC3-RES-16-2019- Development of solutions based on renewable sources that provide flexibility to the energy system

Duration: June 2020 – May 2024

Budget: 4,7 M€

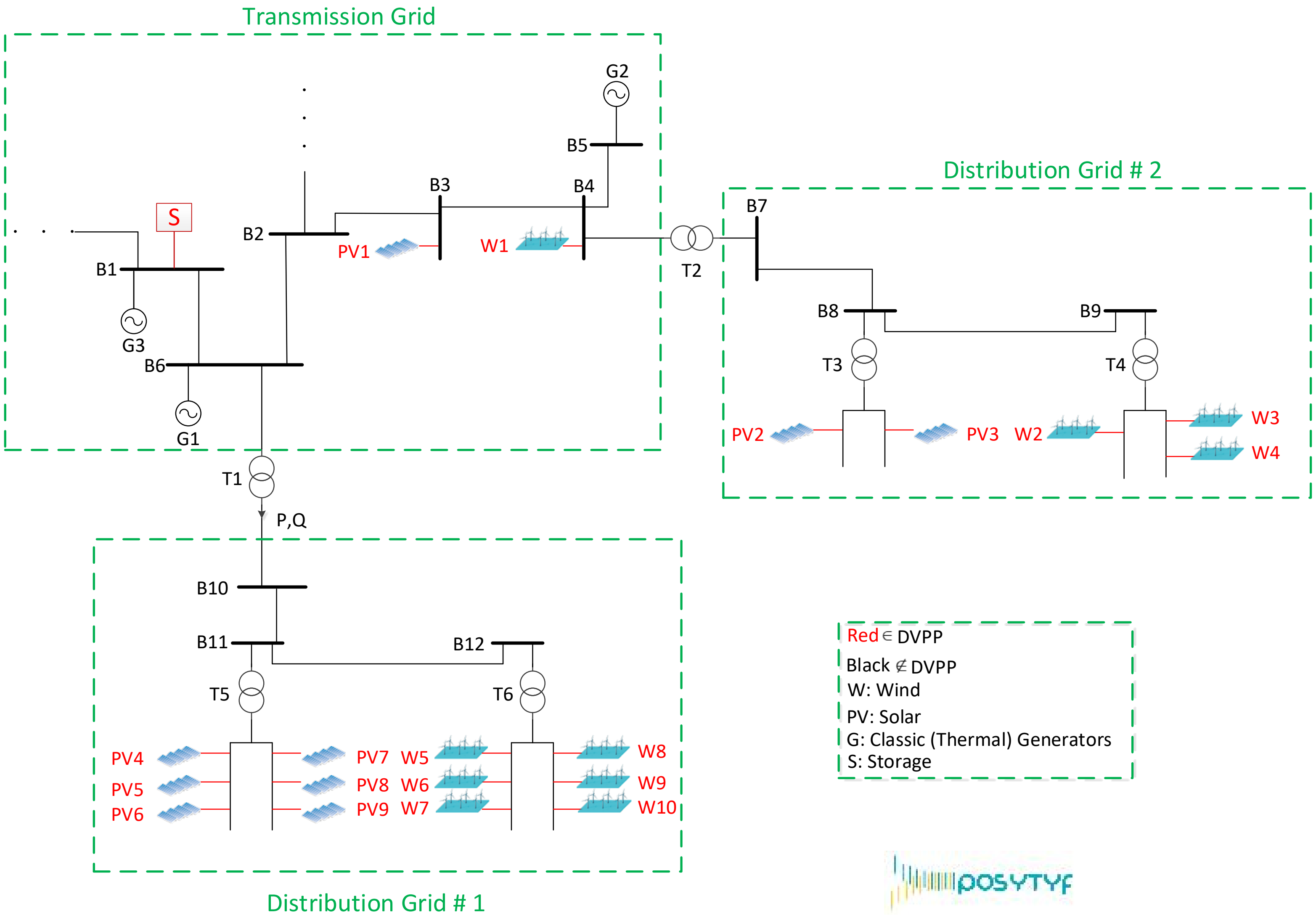
Coordinator: Ecole Centrale Nantes, France

Context:

- System stability is the main bottleneck to the further integration of Renewable Energy Sources (RES) into the power system.
- Distributed RES, if aggregated and technically/economically optimized, have the potential to provide flexibility to the grid and contribute to system stability.
- Dispatchable RES can beneficially complement non-dispatchable RES for such optimization ; alternative to electrochemical storage

Dynamic Virtual Power Plant (DVPP): a set of RES generators and control and operation methodologies to

- increase the performance of an integrated portfolio of **dispatchable** and **non dispatchable** RES
- operate together as a **virtual generator**, capable of providing flexibility and ancillary services to the energy system.

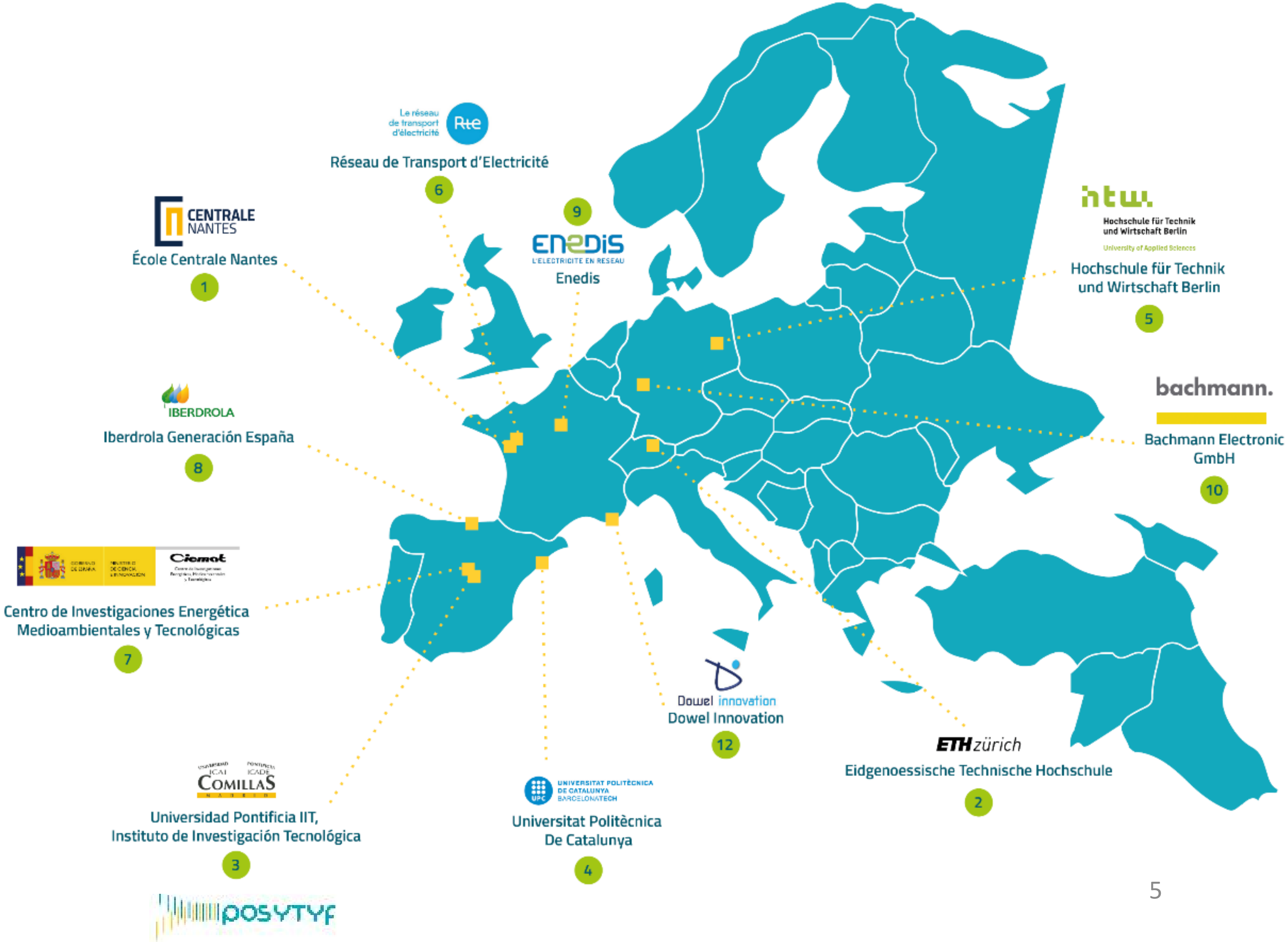


DVPP specificities:

- Both static and **dynamic** aspects + optimality
- Both local and grid objectives
- All time scales (fast V & f regulation + secondary control and markets integration)
- Multiple grid connections
- Transmission & distribution grids
- Imbricated structure
  (participating & non participating generators)
- Dynamic interactions
  - Between DVPP RES generators
  - With the neighbor dynamic elements
- Resilience/plug&play capabilities

Consortium

- Combined expertise on power systems, power electronics, automatic control and RES
- Industrial partners include (Transmission System Operators) TSO, (Distribution System Operators) DSO, RES generator, software vendor
- External advisors:
  - Prof. Costas Vournas, NTUA, Athens-Greece
  - WindEurope
  - ESTELA



Differences with existing Virtual Power Plants (VPP)

Address both ***static*** *&* ***dynamic*** *optimal control at* ***all*** *levels: device / network/ economic standpoint*

In more specific technical terms:

- Enable participation of distributed RES to ancillary services
- Manage specificities of decreasing global inertia of the system
- Deal with geographical spread of RES (also imbricated with non-participating entities)
  - Coordination/ centralization/ decentralization
  - Robustness/ disturbance rejection
  - Resilience (variable VPP perimeter)
- Aggregate RES at both transmission and distribution levels

DVPP realization: multi-time-scale dynamic system

objectives & actuators

■ very-fast dynamics & control: dozens ms – 5s

fast frequency service: ROCOF improvment

level/actuators: RES converters control inside primary level control

■ fast control : 5s-30s

frequency droop control

Q/V droop control

pitch angle/speed/ DC voltage

■ DVPP internal redispatch : 4s

level/actuators: primary control loops

■ DVPP optimization : 20s-1min

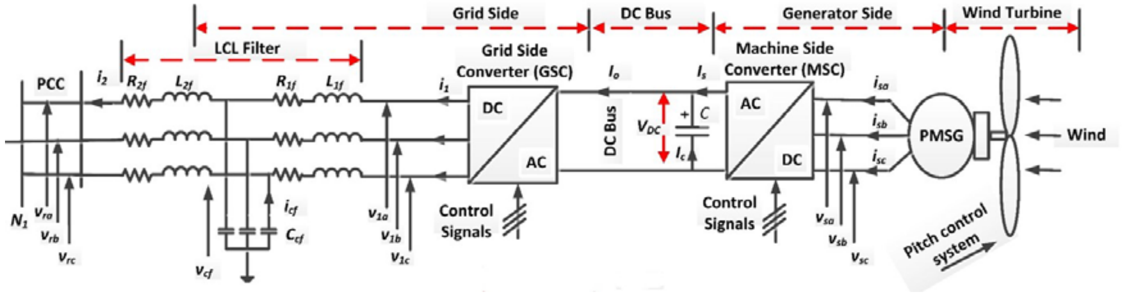
optimization/optimal operation with market & local (DVPP) signals

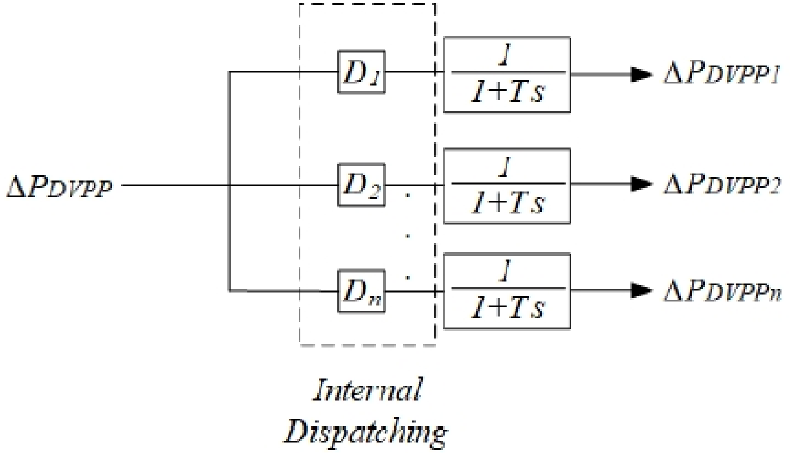
cost minimization

level/actuators: primary control loops ; static/quasi dynamic level

■ Slow controls: >1min

DVPP in secondary V & f controls





Specific controls:

■ Key in hands solutions for renewables modeling, control & operation in both situations:

Scenario A: integration in existing grids and control schemes: primary and secondary levels

Scenario B: power systems of future with high (100%) power electronics rate

■ primary

very fast for V and f grid services

advanced robust: H-infinity, fuzzy, model matching with aggregation of objectives in a desired transfer function

centralized, decentralized, centralized synthesis & decentralized implementation (resilience, plug & play)

■ secondary (V and f) compliant with actual schemes of control

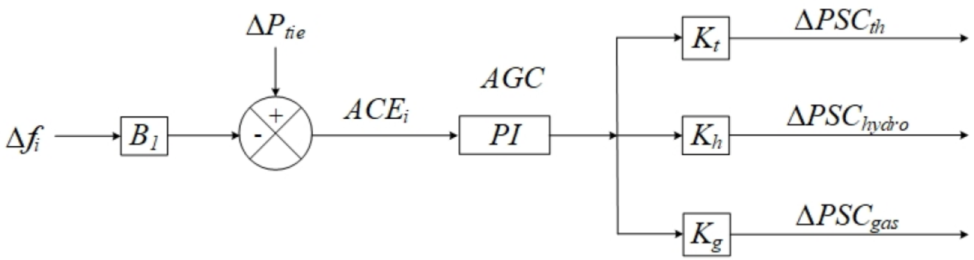
- participation along with classic thermal plants
- decentralized for V

■ real-time operation for whole time scales (fast to slow dynamics)

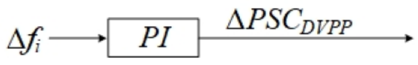
fast V & f regulation + secondary control and markets integration + internal redispatchig + cost optimization

Zoom on P/f control: DVPP participation to secondary frequency control

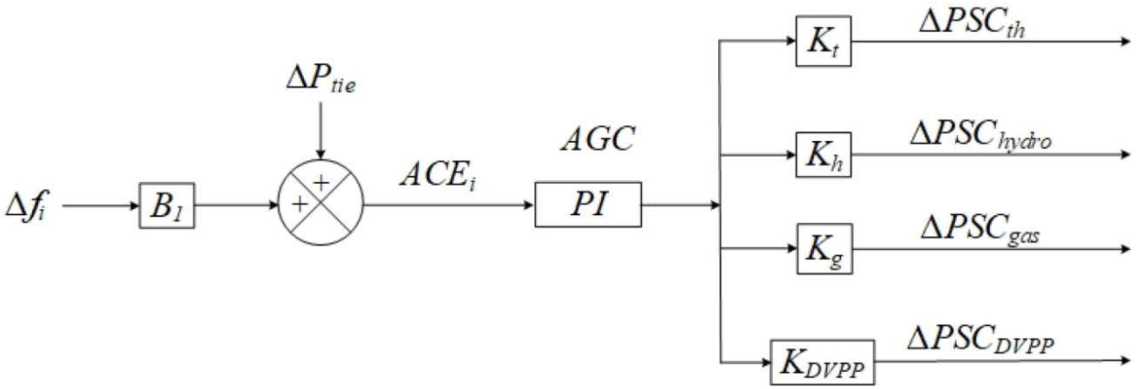
indirect participation:



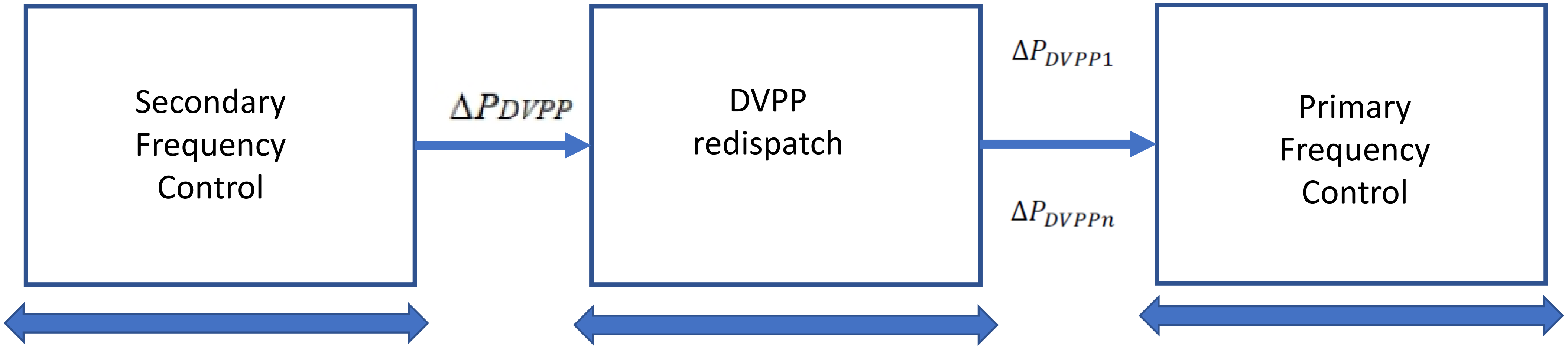
$$ACE_i = \Delta P_{tie} + B_i \Delta f_i$$



direct participation



- Need for an *internal* DVPP redispatch



Time-scales separation and compliance:

~sec ~ 4sec ~douzens of seconds

- The internal redispatch:
  - Optimization (for economic performances also)
  - Real-time control: hierachic control with primary and secondary

Validations in hardware and real time-simulations

- Hardware 10kw bench in HTW Berlin: microgrid
- Hardware in the loop 20kw platform in EC Nantes-LS2N: Full hardware grid connected chain & grid emulation

Real time simulator: OPAL-RT

- Model of the grid
- Control schemes for the hardware devices

Digital signals

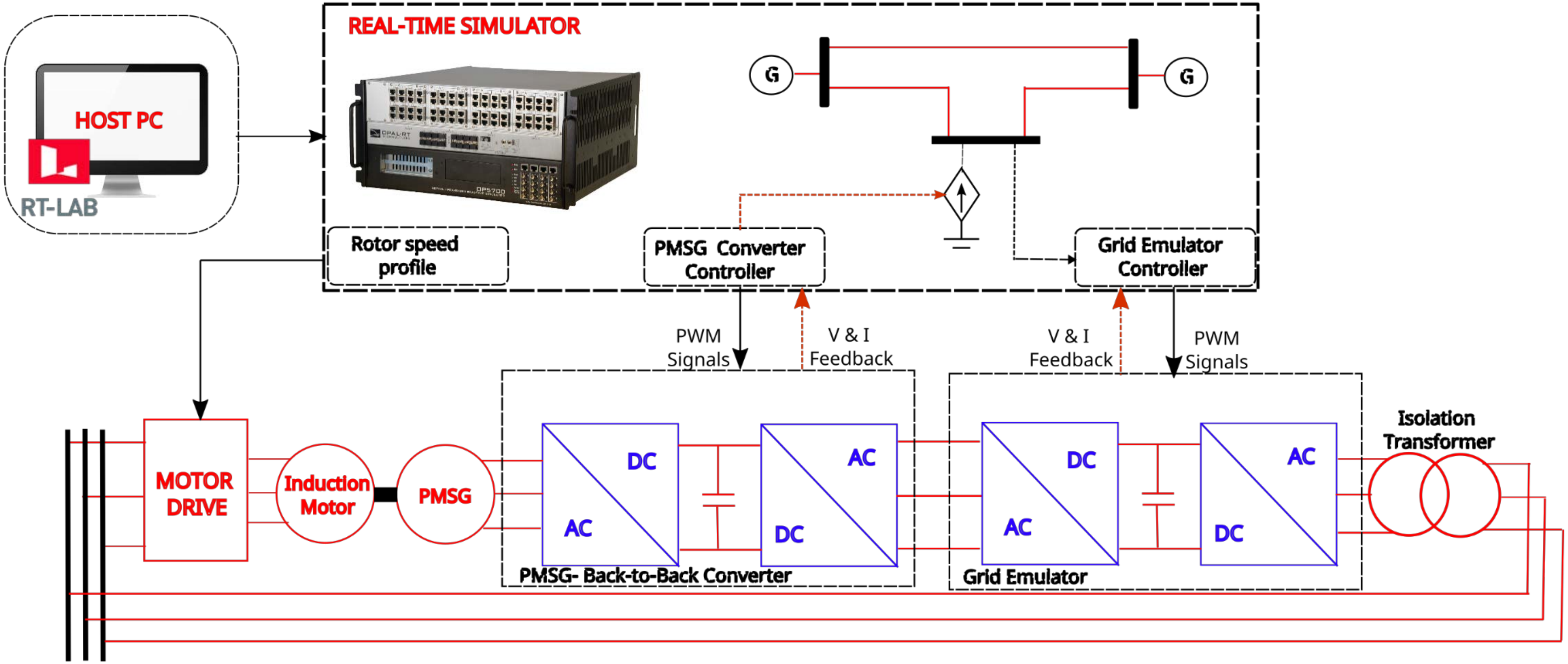
Analog signals

Host PC

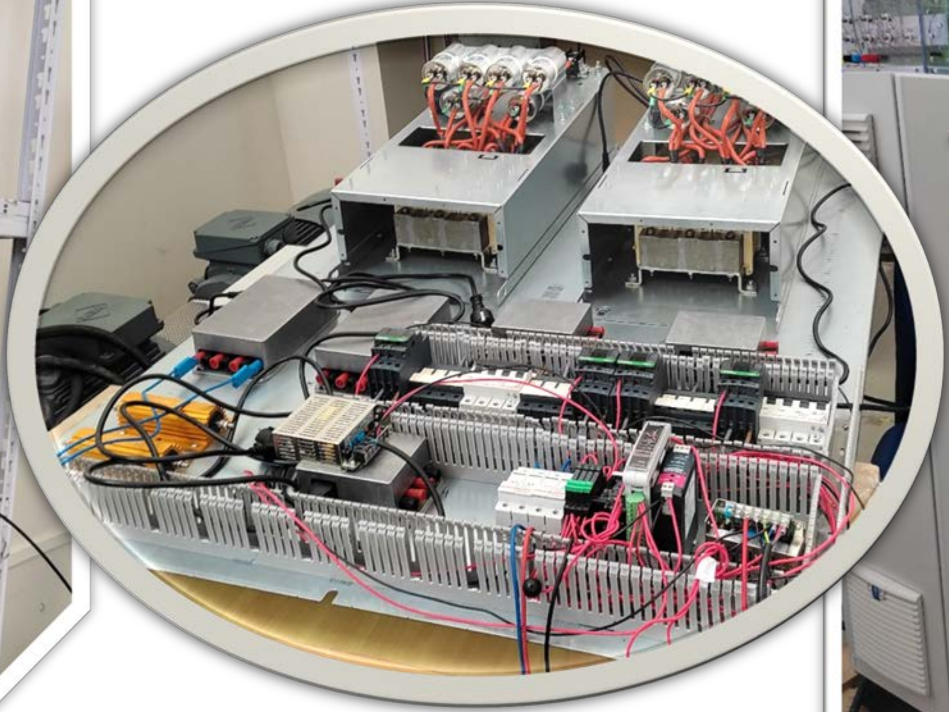
Hardware devices 20kW

- Grid emulator
- Converters
- Harmonic filters
- Loads
- 4 Generators:
  synchronous
  PMSG,
  DFIG,
  PV/DC source

Permanent Magnet Synchronous Generator(PMSG)- Test Bench

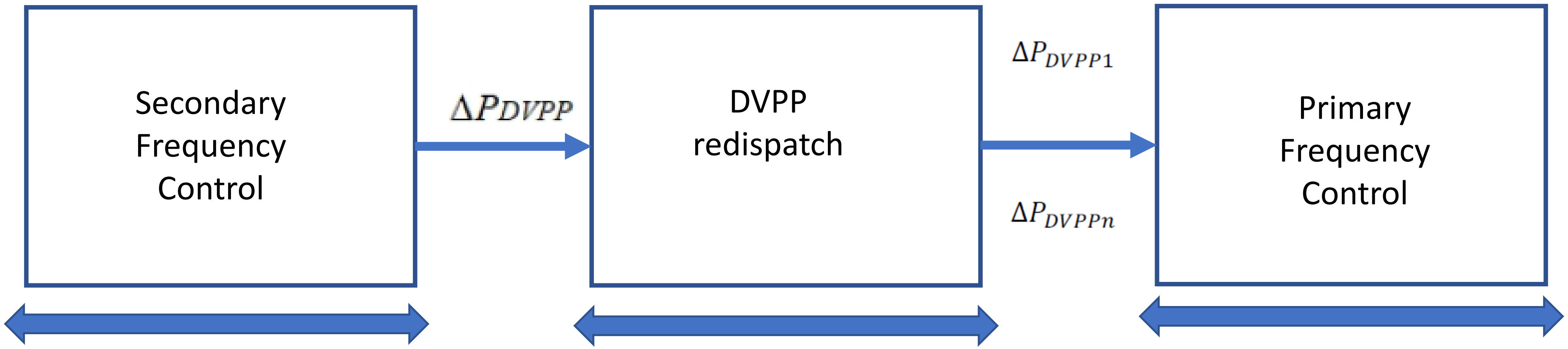



OPAL-RT



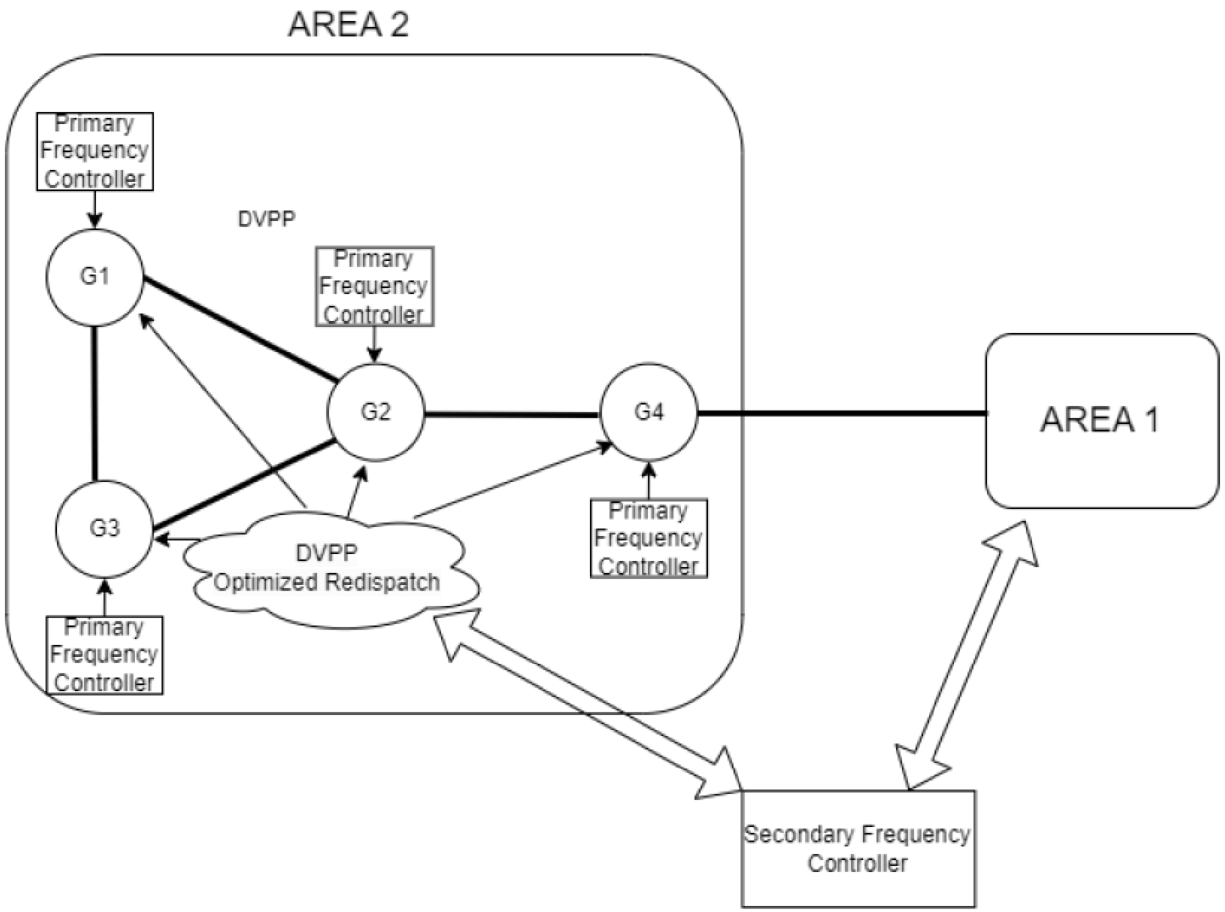
Validations at several time and grid scales

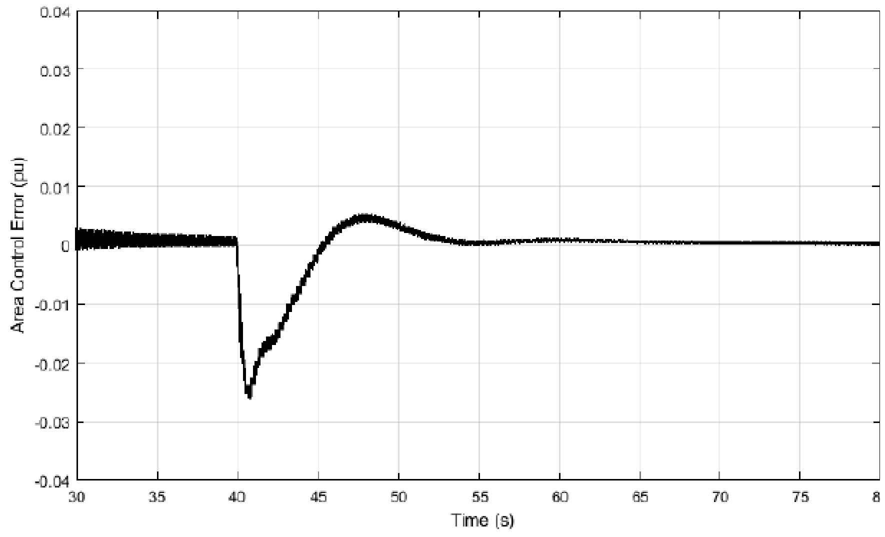
- Local fast control for grid V & f services
- Primary/internal redispatch/secondary controls: OPAL-RT/GAMS interface



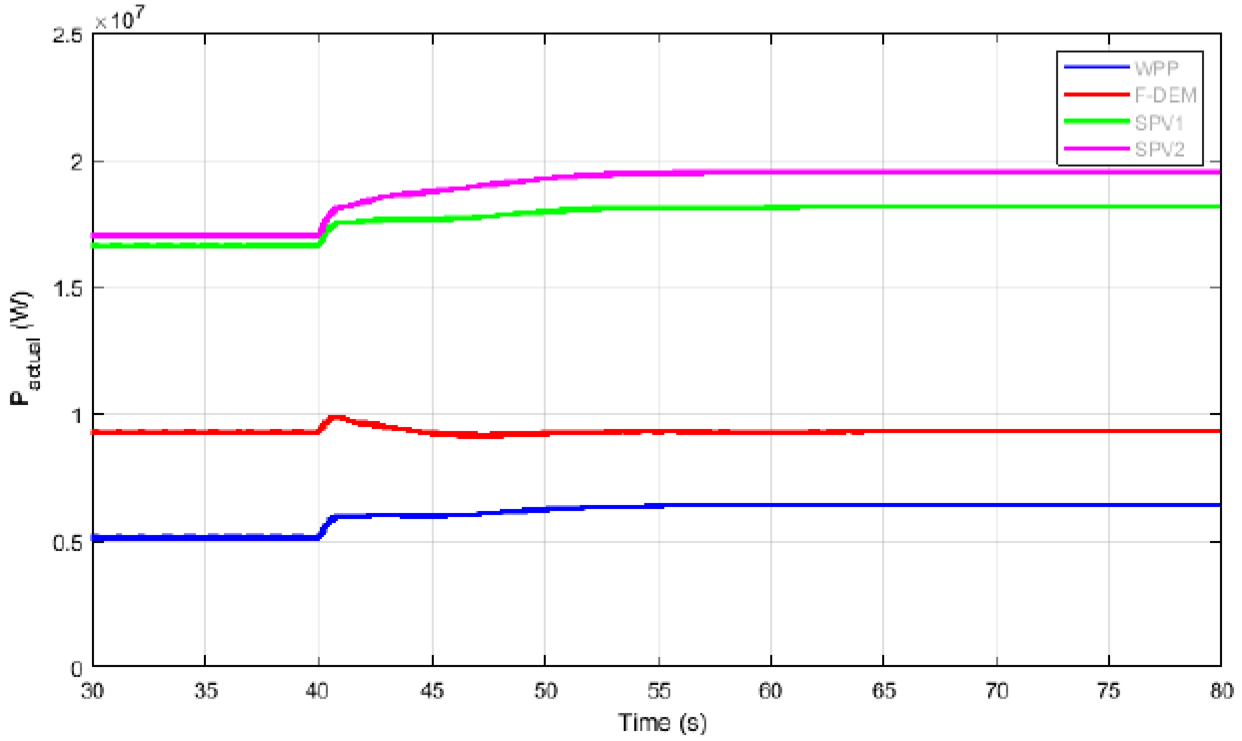
- DVPP composed by 4 RES

(Area 2)





Area control error for a load increase



DVPP response after internal redispatch

Thanks!

Part 3

Optimal Bidding of Renewable-based VPPs in Energy and Ancillary Service Markets

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Alvaro Ortega received his ME and PhD in Electrical Engineering from The Higher Technical School of Industrial Engineering, University of Castilla - La Mancha (Spain) in 2013, and from University College Dublin (Ireland) in 2017, respectively. In September 2020, he joined the Institute for Research in Technology (IIT) at Comillas Pontifical University, where he currently is an Assistant Professor of Electric Power Systems. He is currently an editor of the IET Generation, Transmission and Distribution, and a Member of the IEEE PES Distributed Energy Resources and IEEE PES Power System Stability Controls Subcommittees. His current fields of research include optimal integration and operation of converter-interfaced renewable energy sources; and frequency estimation, control, and stability in low-inertia systems.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883985

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Optimal Bidding of Renewable-based VPPs in Energy and Ancillary Service Markets

Álvaro Ortega Manjavacas

COMILLAS UNIVERSIDAD PONTIFICIA ICAI

Comillas Pontifical University – Institute for Research in Technology

6th August 2024

1. Introduction

Work Context

- Learn how to **optimally configure and operate a DVPP composed of RESs and flexible loads**

- Main goal: **outperform solutions based on electrochemical energy storage** systems (i.e., batteries).

- Let's try to answer the following questions, **by looking at the problem from a business perspective**.
  - How can we maximize the DVPP economic benefits when **trading energy in the different mid-term electric energy markets**?
  - Can we also benefit from **participating in ancillary service markets**?
  - Can we **anticipate to the many uncertainties** that characterize the problem? And can we adapt to them quickly?

1. Introduction

Renewable Energy Sources (RESs)

- Crucial asset in the decarbonization process: **“cheap” and clean**
- Most of them rely on sources of stochastic nature → **Non-dispatchable**
- Generally, **reduced size** when compared with traditional power plants
- RESs are in disadvantage with respect to electricity market participation
    - **Exposed to penalties**
    - **Barriers** to enter in some markets (e.g., ancillary service markets)
    - **Little-to-none market power** (when looked at them individually)

CAUTION: Not participating in markets does not mean you cannot sell energy!

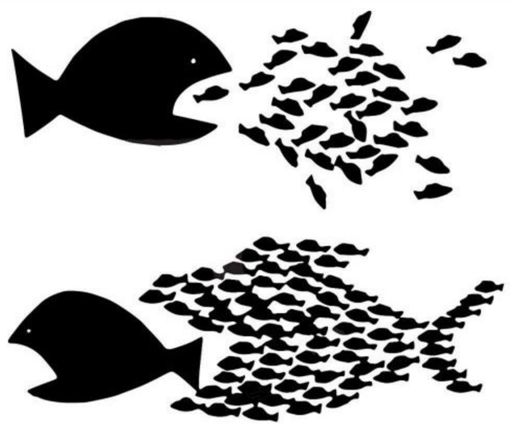
1. Introduction

Solution 1: Include a battery in your life

- **Decreasing costs,** specially during the last decade
- **Fast** charging and discharging **response** (for both active and reactive power)
- **Modularity** for different sizes
- But…
    - Their **costs** still are relatively **high**
    - **Shortage** of raw **materials**
    - Relatively **short life time**
    - **Self-discharge**
    - **Short autonomy**
    - **Environmental impact** at the time of disposal

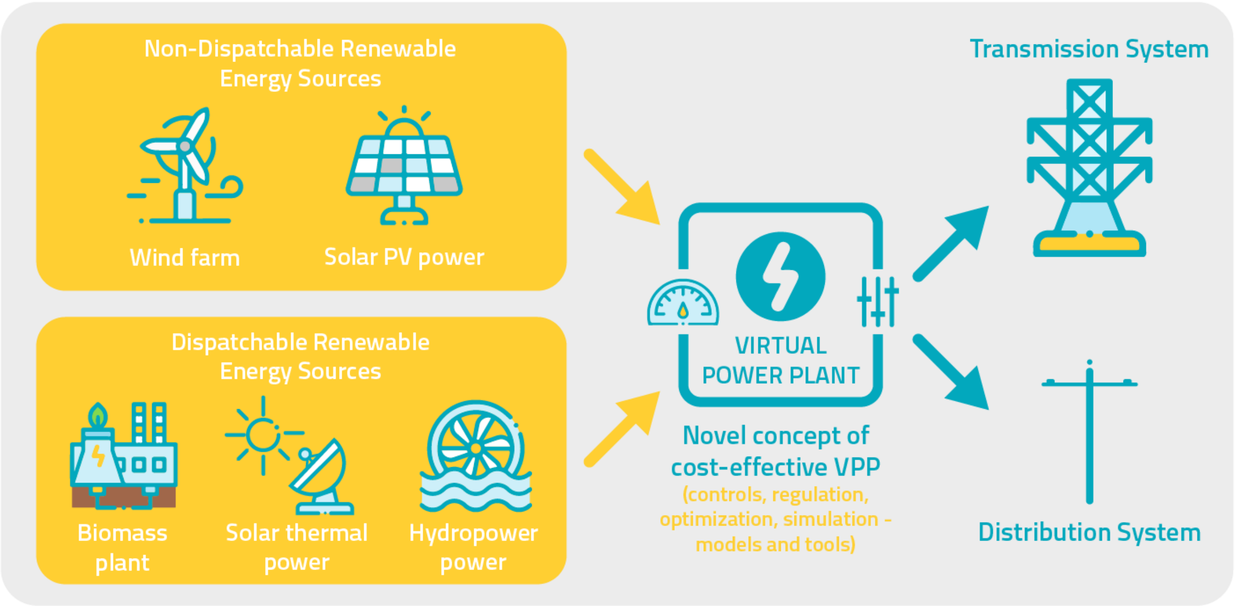
Source: https://electrek.co/2019/02/18/tesla-big-battery-pay-for-itself/

1. Introduction



Solution 2: "In unity, there is strength"

- To **combine independent resources** that work as a single unit
- Better if they are of **different “nature”**
- If there are renewable **dispatchable resources** (e.g., hydroelectric power) in the portfolio, better yet.
- And if we add some **flexible demand**…



1. Introduction

How can we maximize the DVPP economic benefits when trading energy in the different mid-term electric energy markets?

- Despite their relatively **low operational costs**, non-dispatchable renewable sources show limited **competitiveness** against conventional power plants due to their **stochastic sources**, and relatively **small size**

- Each country has particular **regulations** that characterize its electricity **market structure**
  - **Sequence** of market trading floors
  - **Requirements** for market participants
  - **Penalties** if not compliance with schedule
  - …

1. Introduction

How can we maximize the DVPP economic benefits when trading energy in the different mid-term electric energy markets?

- For small DVPPs, a **price-taker approach** can be used.
- The l**arger** DVPPs, the larger benefits, but also the **higher impact on the market price…**
- If DVPP is “too” large, a **price-maker approach** should be used, requiring representing the remaining participants.
- Last (but not least!), we can’t forget about **uncertainties.**

1. Introduction

Given appropriate control strategies and structures, can we also benefit from participating in ancillary service markets?

- **Minimum capacities** are typically required for Ancillary Service Providers
- Small distributed energy resources are **generally below** such capacities
- **Aggregation** in the form of a DVPP may allow such units to **become ancillary service providers**
- **Uncertainties** in production of non-dispatchable units might **compromise the provision** of the committed service

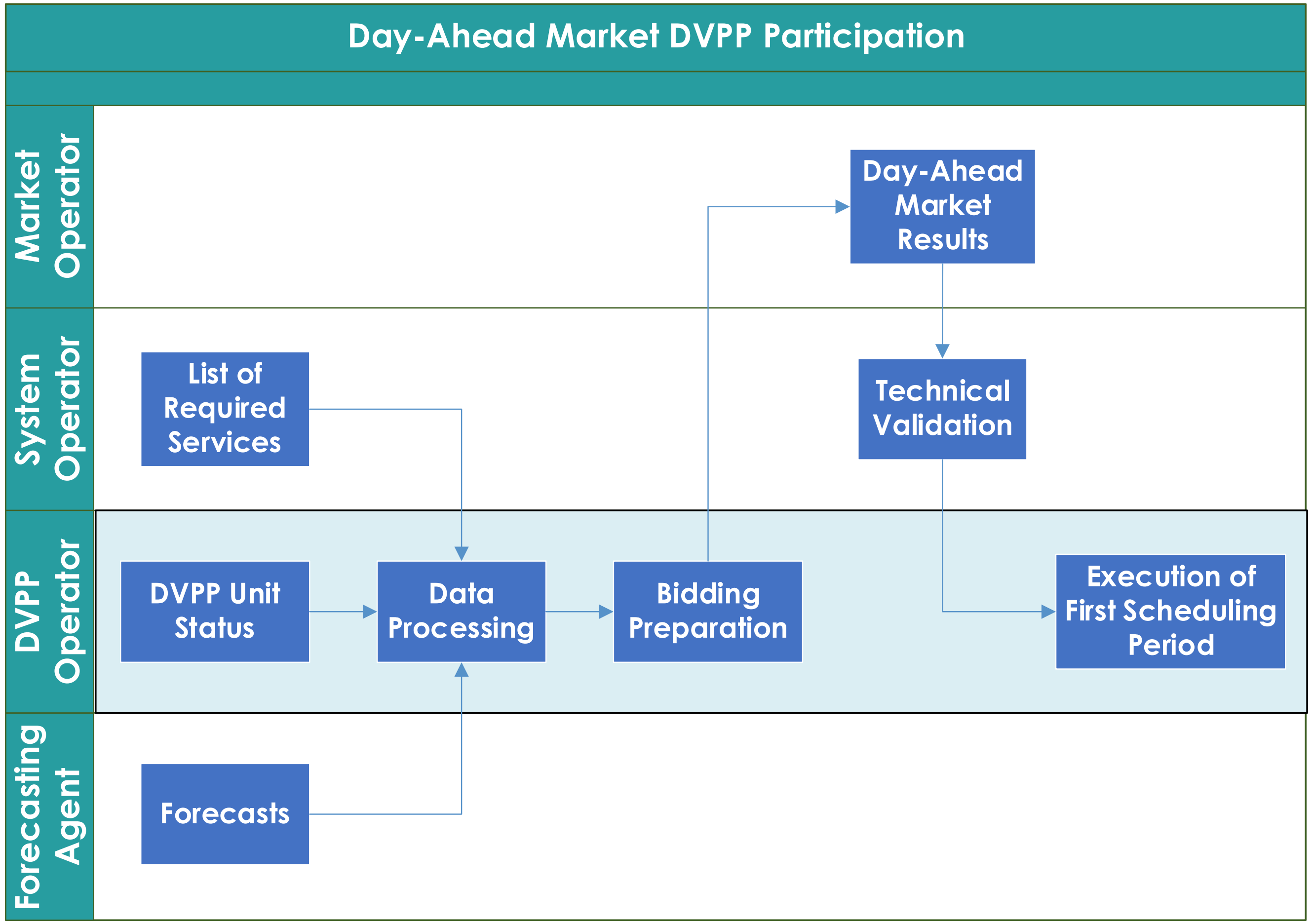
2. Optimal electricity market bidding of DVPPs under uncertainty

Problem Formulation – Business Models for DVPPs

- **Maximize:**
  - Energy market profit
  - Ancillary Service Market profit
  - Demand *Utility*
- **Minimize:**
  - Operation and demand costs
  - Energy bought from main grid (DVPP self-supply)
  - Potential Penalties

2. Optimal electricity market bidding of DVPPs under uncertainty

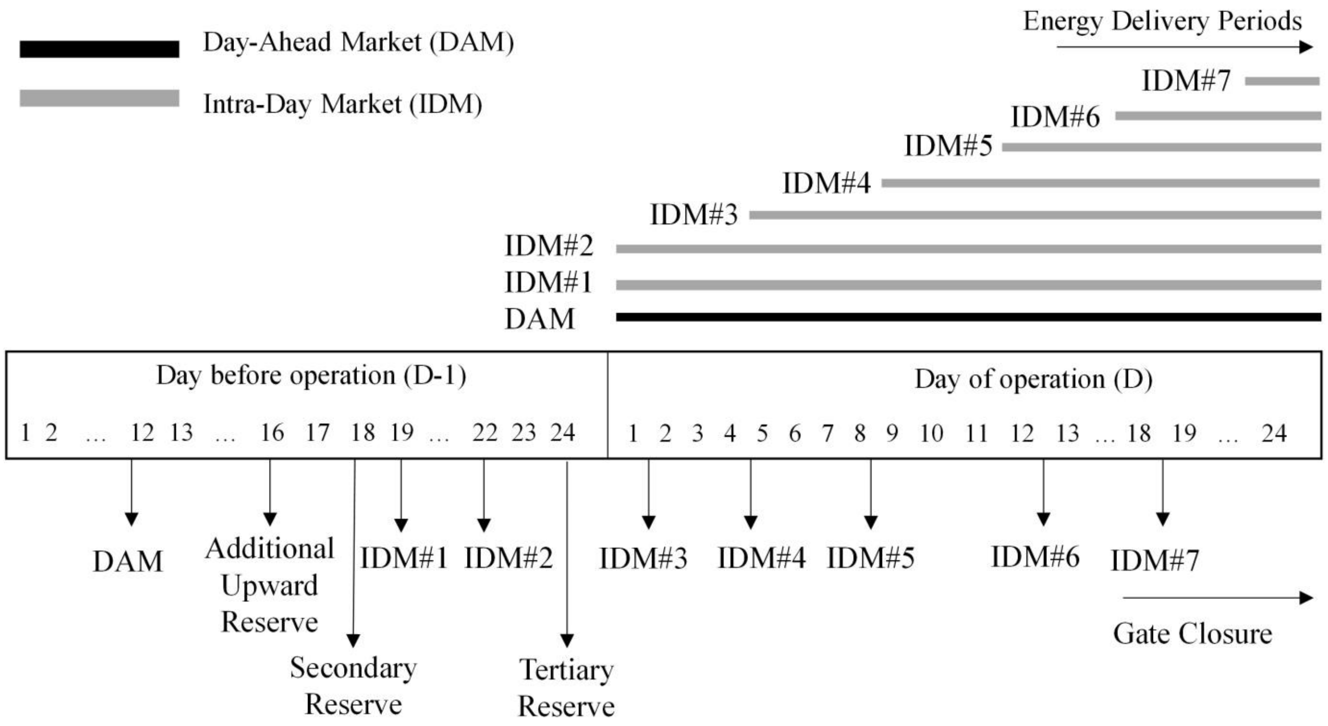
Electricity Markets – Market Participation Sequence



2. Optimal electricity market bidding of DVPPs under uncertainty

Electricity Markets – Iberian System Market Sequence

- **Different time windows**
- **Different payment mechanisms for each market**
- **Different goals for each market**
- **Market couplings**



3. Optimal Participation of DVPPs in Electricity Markets

Problem Formulation – Input Data

- **<u>Most input data</u>** required to parametrize the optimization problem **are time independent**, i.e., their value is constant for all time periods

- **Other parameters** are characterized by the presence of **<u>uncertainties</u>** that need to be considered in the optimization problem, such as:
  - Day-ahead market **prices**
  - Ancillary service market **prices**
  - Intra-day market **prices** (e.g., 7 in the case of the Iberian market)
  - **Available electricity production** from non-dispatchable resources (wind, PV, solar-thermal, …)
  - **Hourly consumption** of flexible demands within the DVPP

3. Optimal Participation of DVPPs in Electricity Markets

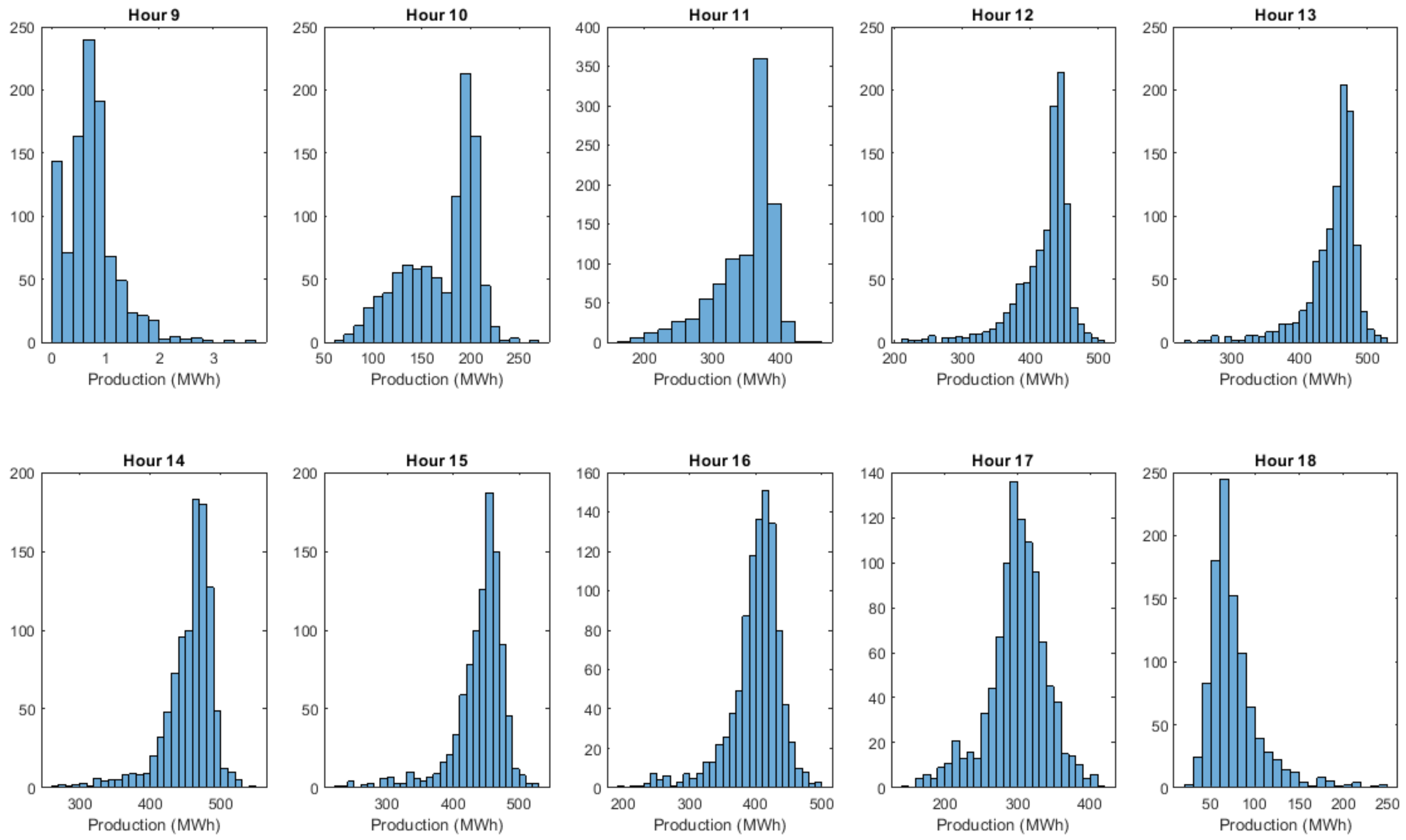
Problem Formulation – Uncertainties

- **Plenty of alternatives** to design and implement an optimization algorithm to solve this problem
- From the point of view of **data availability**, the so-called ***"Robust Optimization"*** is arguably the preferred choice
- In Robust Optimization, the goal is to **find the maximum profit** for the **worst possible scenario** of uncertainties
- In Robust Optimization, **uncertain parameters** (e.g., X_t), are characterized by means of the forecast of the **median** of the distribution, $\tilde{X}_t$, which can vary within an interval delimited by **usually asymmetric thresholds**

$$X_t \in \left[\tilde{X}_t - \check{X}_t, \tilde{X}_t + \hat{X}_t\right], \qquad \forall t \in T$$

3. Optimal Participation of DVPPs in Electricity Markets

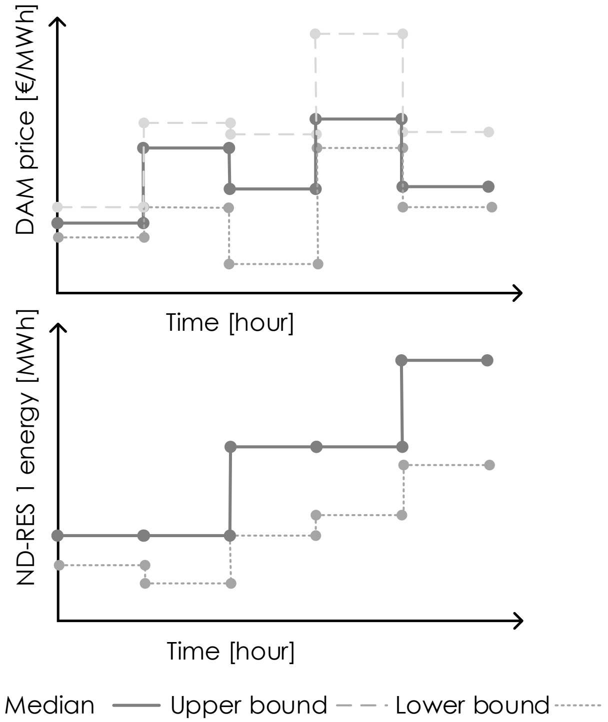
Problem Formulation – Uncertainties



Histograms of probabilistic forecasts of available energy at the solar field of a solar-themal power plant in Spain – December 9, 2018

3. Optimal Participation of DVPPs in Electricity Markets

Illustrative Example – Worst-case scenario selection

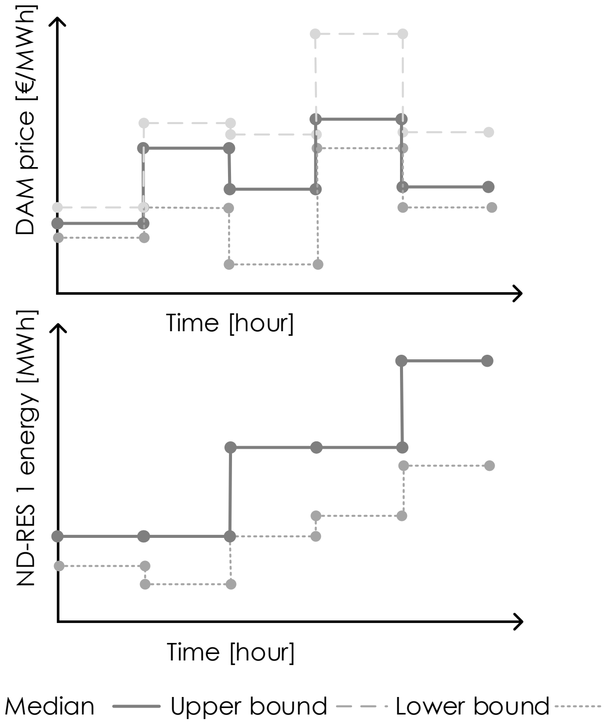


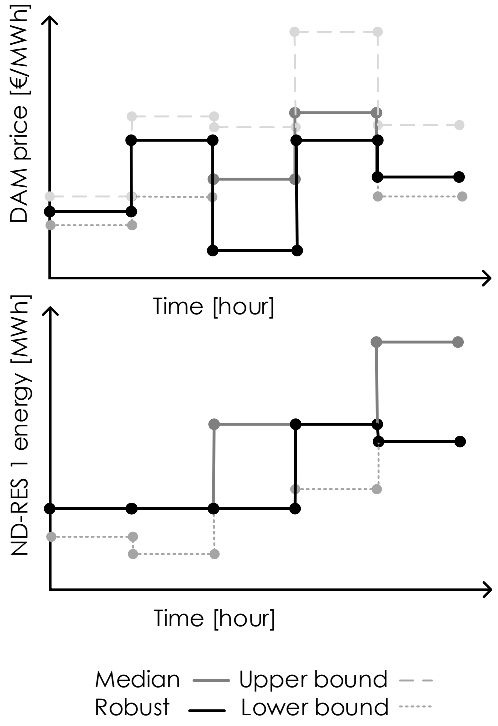
Number of hours in the horizon = 5

Level of *pessimism* = 2 (out of 5)

3. Optimal Participation of DVPPs in Electricity Markets

Illustrative Example – Worst-case scenario selection





Number of hours in the horizon = 5

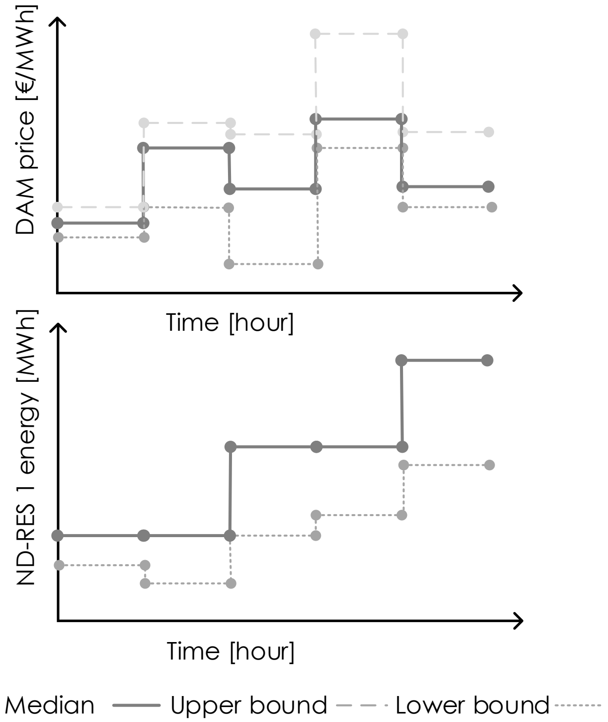
Level of *pessimism* = 2 (out of 5)

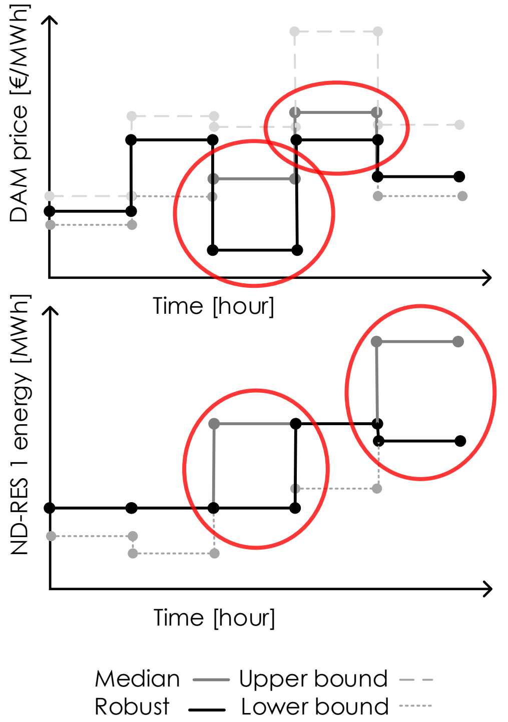
Energy Robustness

Total profit = 204 €

3. Optimal Participation of DVPPs in Electricity Markets

Illustrative Example – Worst-case scenario selection





Number of hours in the horizon = 5

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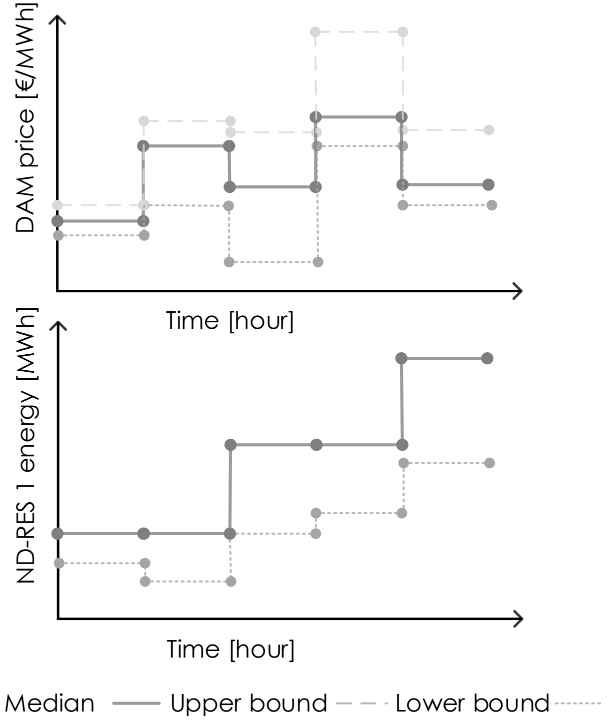
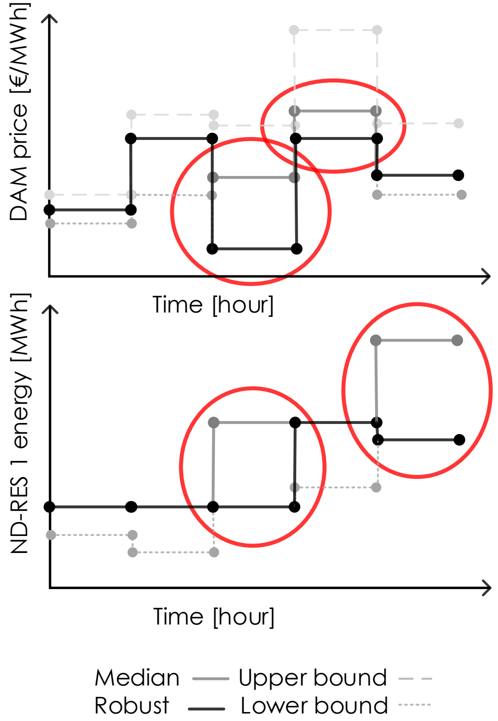
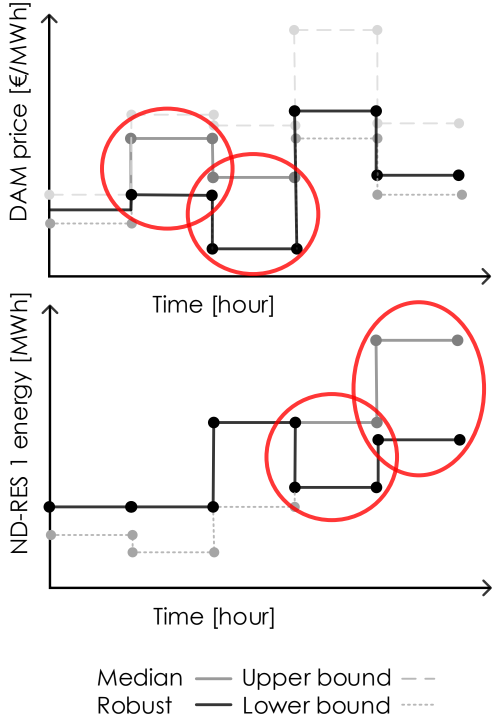
3. Optimal Participation of DVPPs in Electricity Markets

Illustrative Example – Worst-case scenario selection







Number of hours in the horizon = 5

Level of *pessimism* = 2 (out of 5)

<u>Energy</u> Robustness

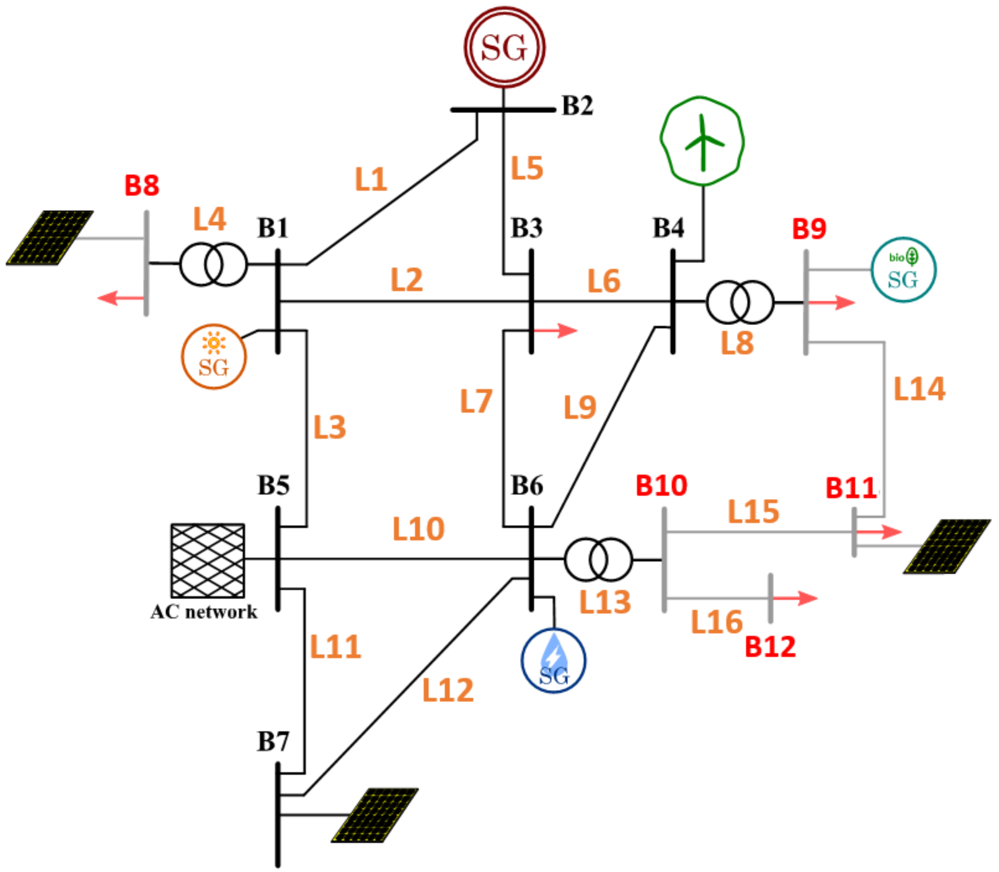
Total profit = 204 €

<u>Profit</u> Robustness

Total profit = 179 €

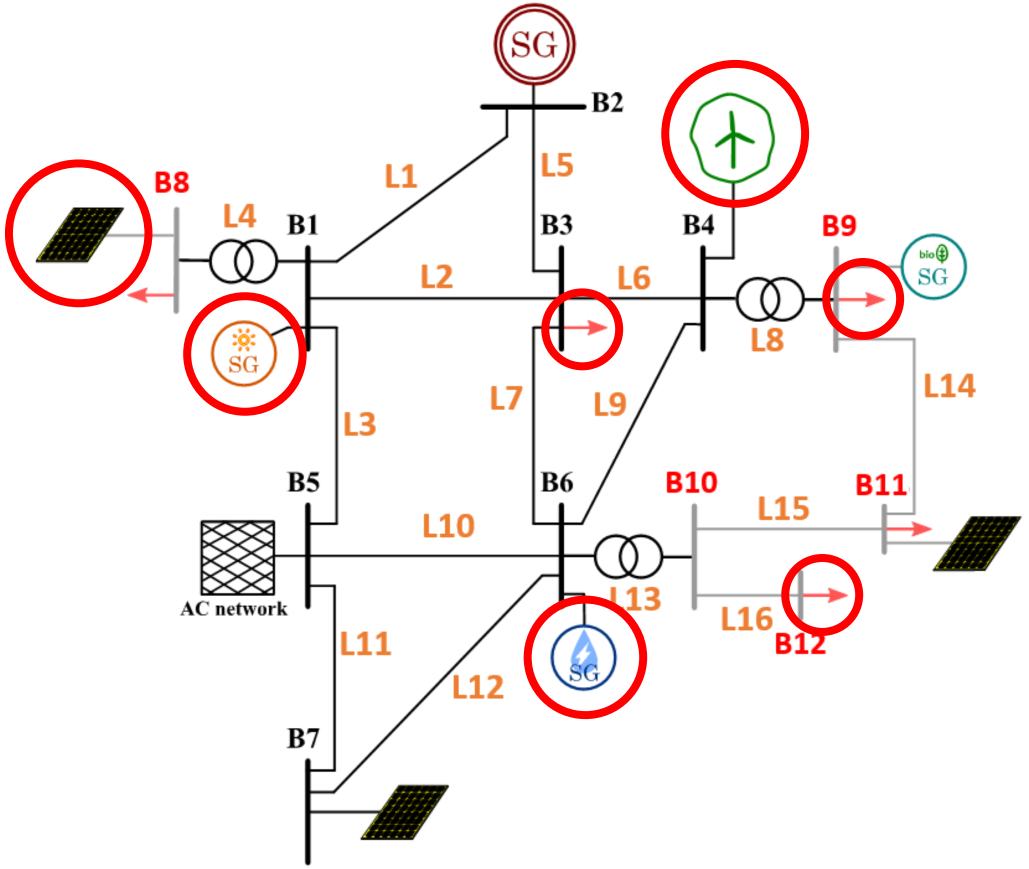
4. Example of Case Study

Renewable-based DVPP in a Southern-Spanish Region



4. Example of Case Study

Renewable-based DVPP in a Southern-Spanish Region



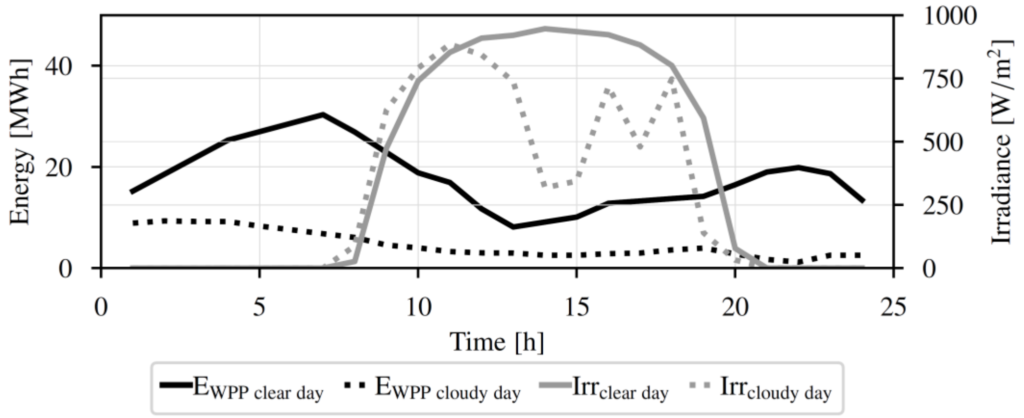
RESOURCES IN THE DVPP

- **Hydroelectric Power Plant** (110 MW) – Bus 6
- **Wind Farm** (50 MW) – Bus 4
- **PV Power Plant** (50 MW) – Bus 8
- **Solar-Thermal Unit with Storage** (50 MW) – Bus 1
- **Industrial Load** (55 MW peak) – Bus 3
- **Airport** (69 MW peak) – Bus 12
- **Residential Load** (50 MW peak) – Bus 9

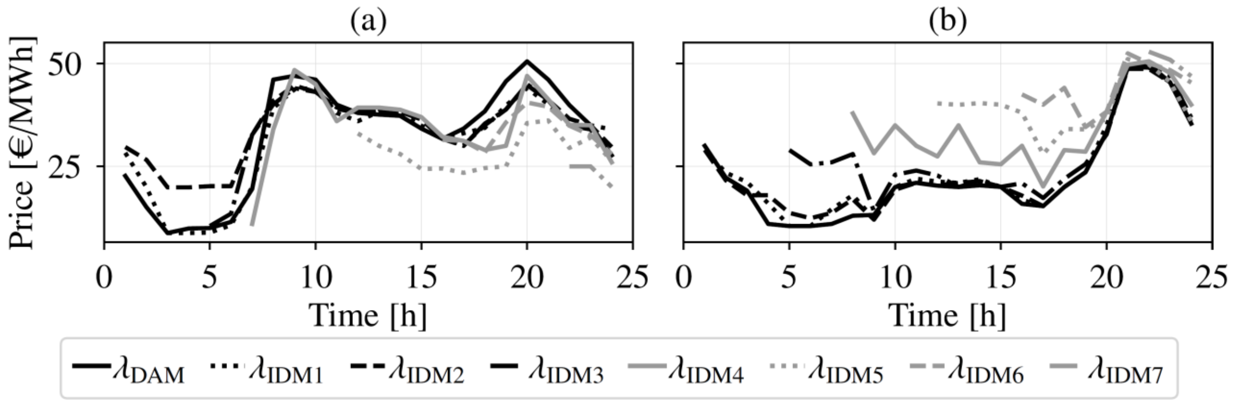
24 time periods (1 day)

4. Example of Case Study

Renewable-based DVPP in a Southern-Spanish Region



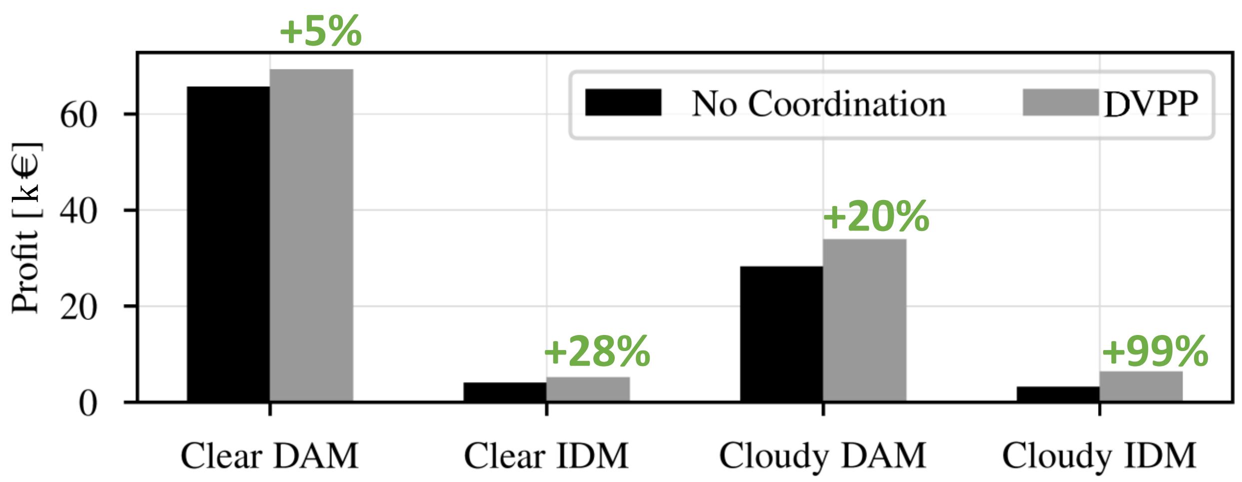
Median of forecasted production of wind and solar plants (sunny and cloudy days)



Median of forecasted prices of the day-ahead and intra-day markets (sunny (a) and cloudy (b) days)

4. Example of Case Study

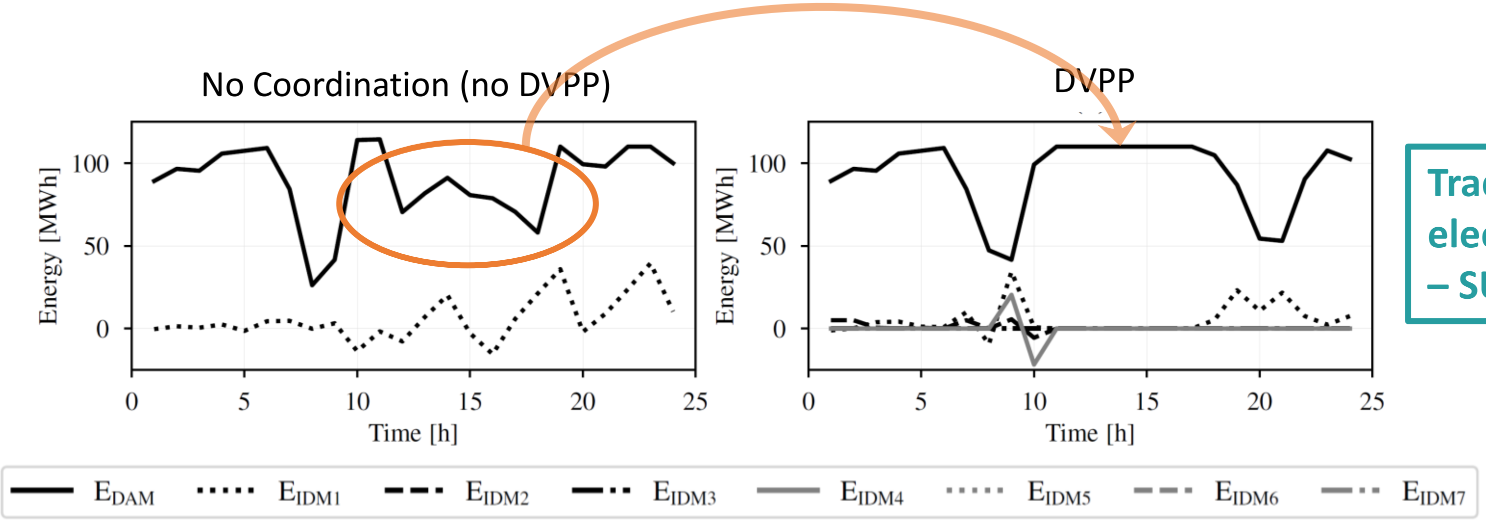
Renewable-based DVPP in a Southern-Spanish Region



Profit (in thousands of €) of scenarios with and without DVPP for two days with different weather conditions

4. Example of Case Study

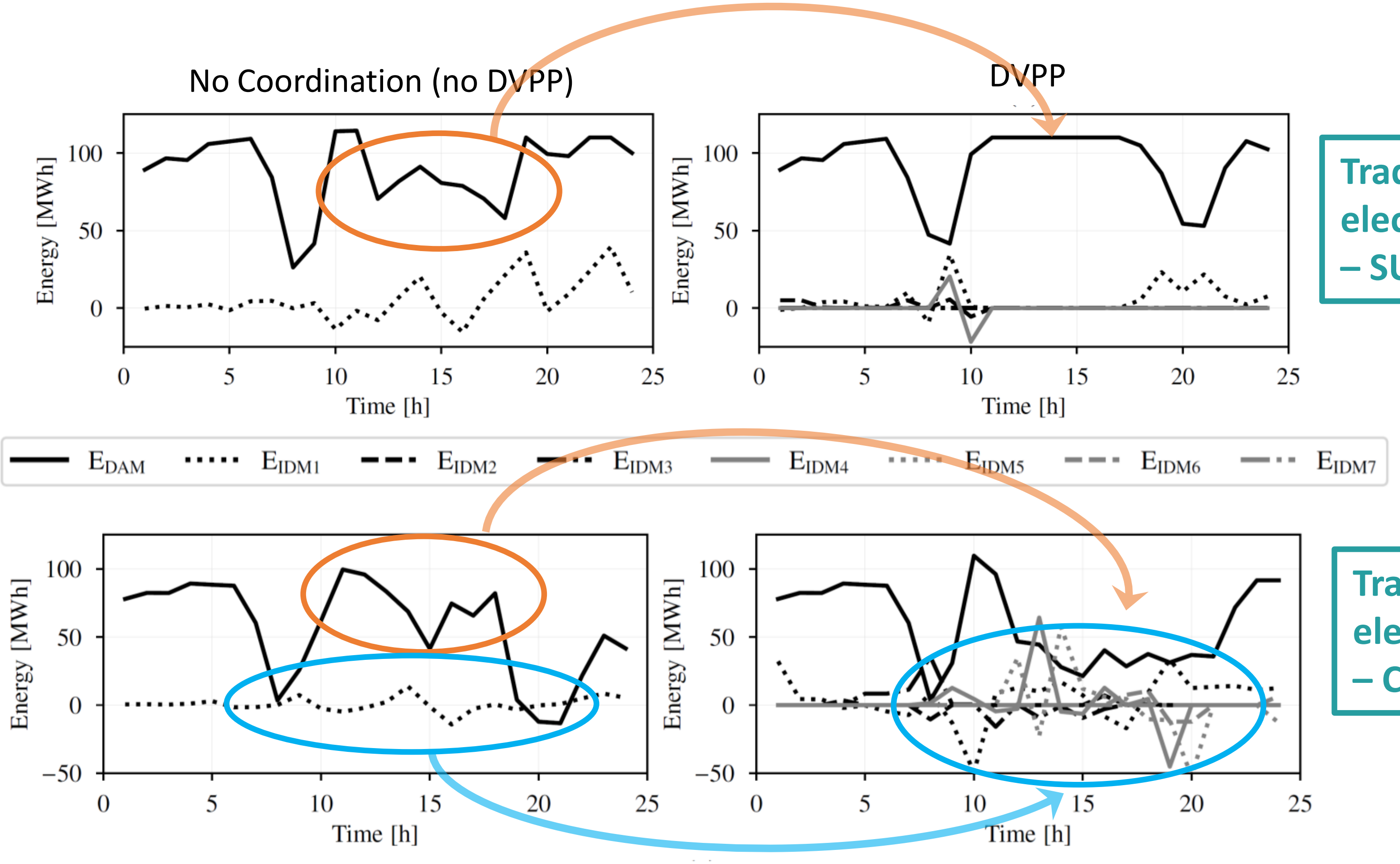
Renewable-based DVPP in a Southern-Spanish Region



Traded energy in electricity markets – SUNNY day

4. Example of Case Study

Renewable-based DVPP in a Southern-Spanish Region

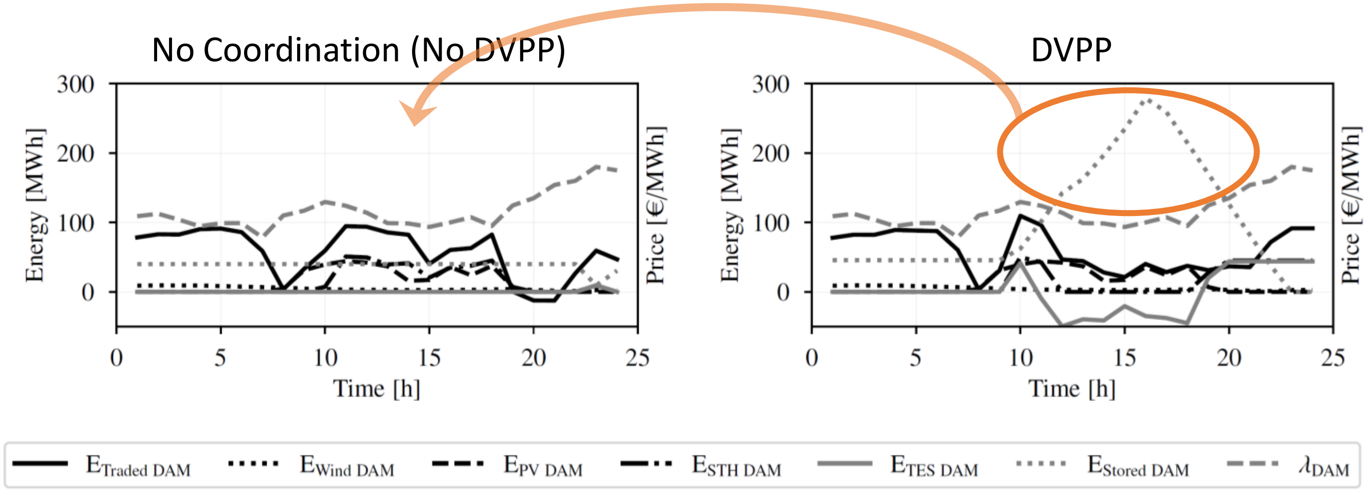


Traded energy in electricity markets – SUNNY day

Traded energy in electricity markets – CLOUDY day

4. Example of Case Study

Renewable-based DVPP in a Southern-Spanish Region



Energy generated / consumed by each DVPP unit

5. Regulatory Aspects

Regulatory Challenges for DVPPs

- Most of the regulatory barriers for the configuration and operation of DVPPs are related to the framework associated with:
    - **The aggregation activity** itself
    - Wheter or not **portfolio-level bidding is allowed**
- There may be **restrictions** regarding the **nature, type and/or size** of the assets in the portfolio.
- **Variety** in regulation at European level.
- **Inconsistencies** between national regulations and EU directives.
- **All of this can discourage the DVPP participation in electricity markets.**

5. Regulatory Aspects

Nature of Regulatory Barriers and Recommendations

- Regulation of **New Resources**
  - **Storage**
  - **Aggregator**
- Definition of **Market Products** and **Bidding Formats**
  - **Facilitate conditions** for participation in different markets
  - **Reconsider** ancillary services and other related *products*
  - **Standardize** products and bidding formats

5. Regulatory Aspects

Nature of Regulatory Barriers and Recommendations

- Inefficient **Price Signals** / **Non-existent Markets**
  - **Facilitate** medium and short-term **price signals**
  - Creation of **local flexibility markets**
- **Advanced Metering Infrastructure**
  - Define a **standard for data acquisition, communication and processing**
  - Stablish **infrastructures** to ensure **privacy, security and** ownership of data (consumers)
  - **Transparency** in data handling and accessibility
- **Flexibility** in Portfolio **Configuration**

6. Conclusions (for now...)

Summary and Remarks

- **DVPPs as aggregators** of diverse energy resources.
- Advantages of DVPPs:
  - Improvement in the **integration of renewable energies**.
  - **Flexibility and quick response** to market demand**.**
  - Potential to **optimize operational costs** and **increase market competitiveness**.
- Challenges faced:
  - **Regulatory and market barriers**.
  - Need for advanced **technological infrastructure** for management and operation.
  - **Uncertainties** associated with the variability of renewable energy sources and market prices.

6. Conclusions (for now…)

Implications and Recommendations

- **Technological Development**:
  - Solutions for the **efficient management** of DVPPs.
  - Improve real-time **prediction and adaptability**.
- **Policies and Regulations**:
  - The need for a **more flexible and adaptive regulatory framework** to facilitate the operation and expansion of DVPPs.
  - **Standardization** at the European level to facilitate the cross-border expansion and operation of DVPPs.
- Explore **new storage and control technologies** that can be integrated within DVPPs.

Thank you!

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Modelling, operation, and control of virtual power plants

Tutorial

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