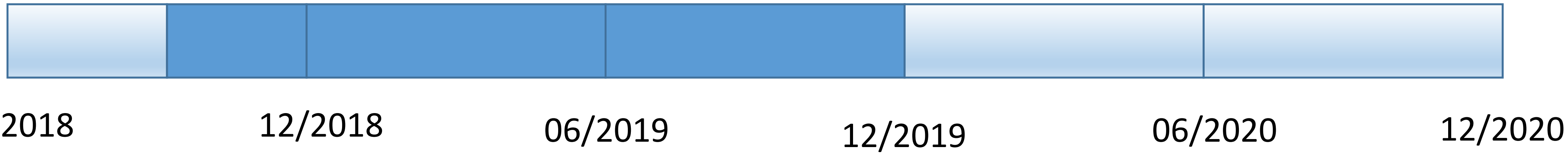
Levi Cases

CENTRO STUDI DI ECONOMIA E
TECNICA DELL'ENERGIA
"GIORGIO LEVI CASES"

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

NEBULE

NEw economic, regulatory and technical drivers for a full exploitation of smart micro-grid based electrical power systems maximizing the connection of the distriBUted renewabLE resources



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Assegni di ricerca (Tipo A)			
Dipartimento	Inizio	Durata	Costo Lordo Ente
DEI	Ottobre 2018	12 m	25.000 Euro
DII	Gennaio 2019	12 m	25.000 Euro
DSEA	Gennaio 2018	24 m	50.000 Euro
DTG	Marzo 2019	12 m	25.000 Euro
DEI	Giugno 2019	12 m	25.000 Euro
DII	Giugno 2019	12 m	25.000 Euro
DTG	Gennaio 2020	12 m	25.000 Euro
		Totale Assegni	**200.000 Euro**
Missioni e Conferenze			
		Totale	**24.000 Euro**
Attrezzature			
Attrezzature per attività sperimentale			16.000 Euro
4 Notebook per gli assegnisti			8.000 Euro
		Totale	**24.000 Euro**
Consumables			
		Totale	**12.000 Euro**
Coordinamento progetto			
Coordinamento/dissemination			6.000 Euro
Organizzazione workshop			4.000 Euro
		Totale	**10.000 Euro**
		Totale Progetto	**270.000 Euro**

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Aram Khodamoradi

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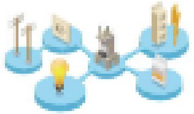
Introduction

Clean Energy Package presented in the European Commission on 30 November 2016



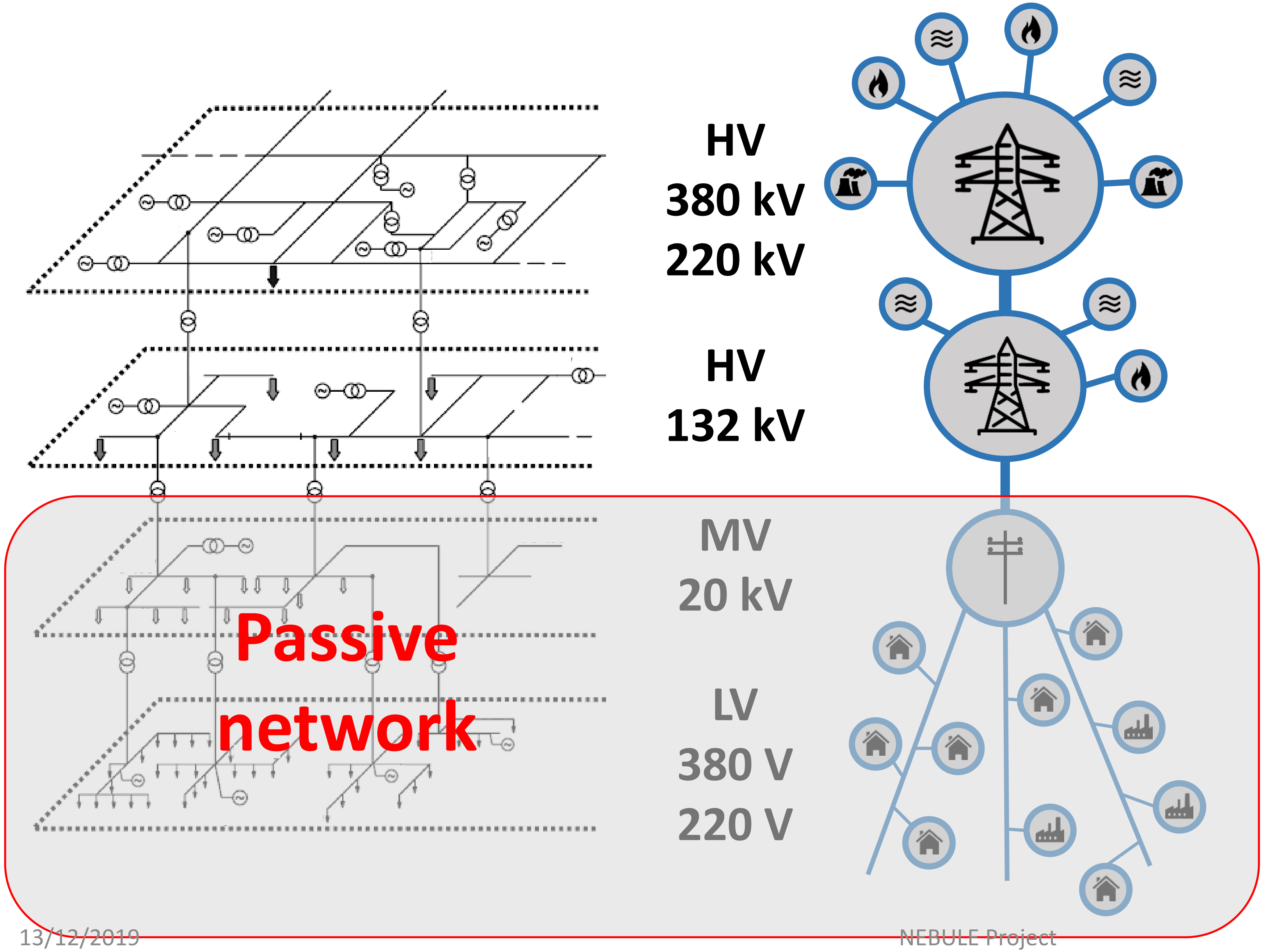
Directives/Regulations	Publication in the G.U.U.E.
Energy Efficiency Directives	Dir. (EU) 2018/2002 (21/12/2018)
Directive on the energy performance of buildings	Dir. (EU) 2018/844 (19/06/2018)
Directive on the promotion of the use of energy from renewable sources	Dir. (EU) 2018/2001 (21/12/2018)
Regulation on governance of the Union for Energy and Climate Action	Dir. (EU) 2018/1999 (21/12/2018)
Regulation on the internal market in electricity	Dir. (EU) 2019/943 (14/06/2019)
Directive concerning common rules for the internal market in electricity	Dir. (EU) 2019/944 (14/06/2019)
Regulation on risk preparation in the field of elected energy	Dir. (EU) 2019/941 (14/06/2019)
Regulation establishing an Agency for the Cooperation of Energy Regulators (ACER)	Dir. (EU) 2019/942 (14/06/2019)

Introduction

By 2030, half of European electricity should be renewable

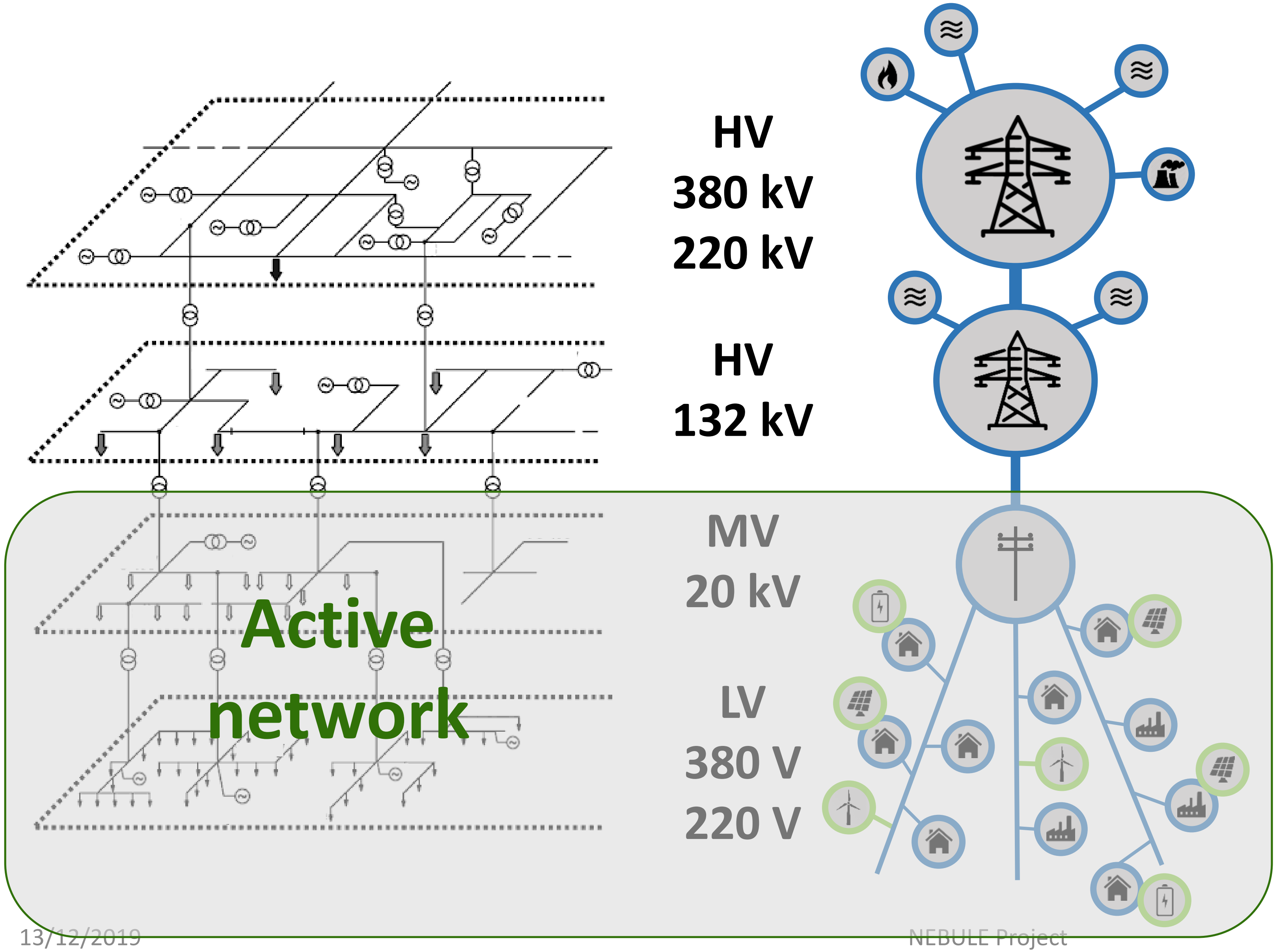
- ❑ Energy and ancillary services markets will need to enable the participation of small-scale users (**aggregated**), leading to ***local energy markets*** and ***local ancillary services markets***
- ❑ **Distribution network management** highly affected by Market frameworks
- ❑ **Micro-grids (LV)**, composed by a large number within a small geographic area of responsive customers, need to manage the single offers by end-users for both system's security and economical efficiency
- ❑ **E-LAN**: extends the Micro-grid concept to allow **independent control of the power flow at every grid port or section** (grid can even be meshed)

Power system ancillary services



Power system managed through large plants (> 10 MVA) connected to HV voltage level

Power system ancillary services



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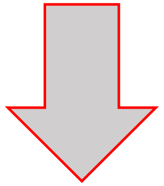
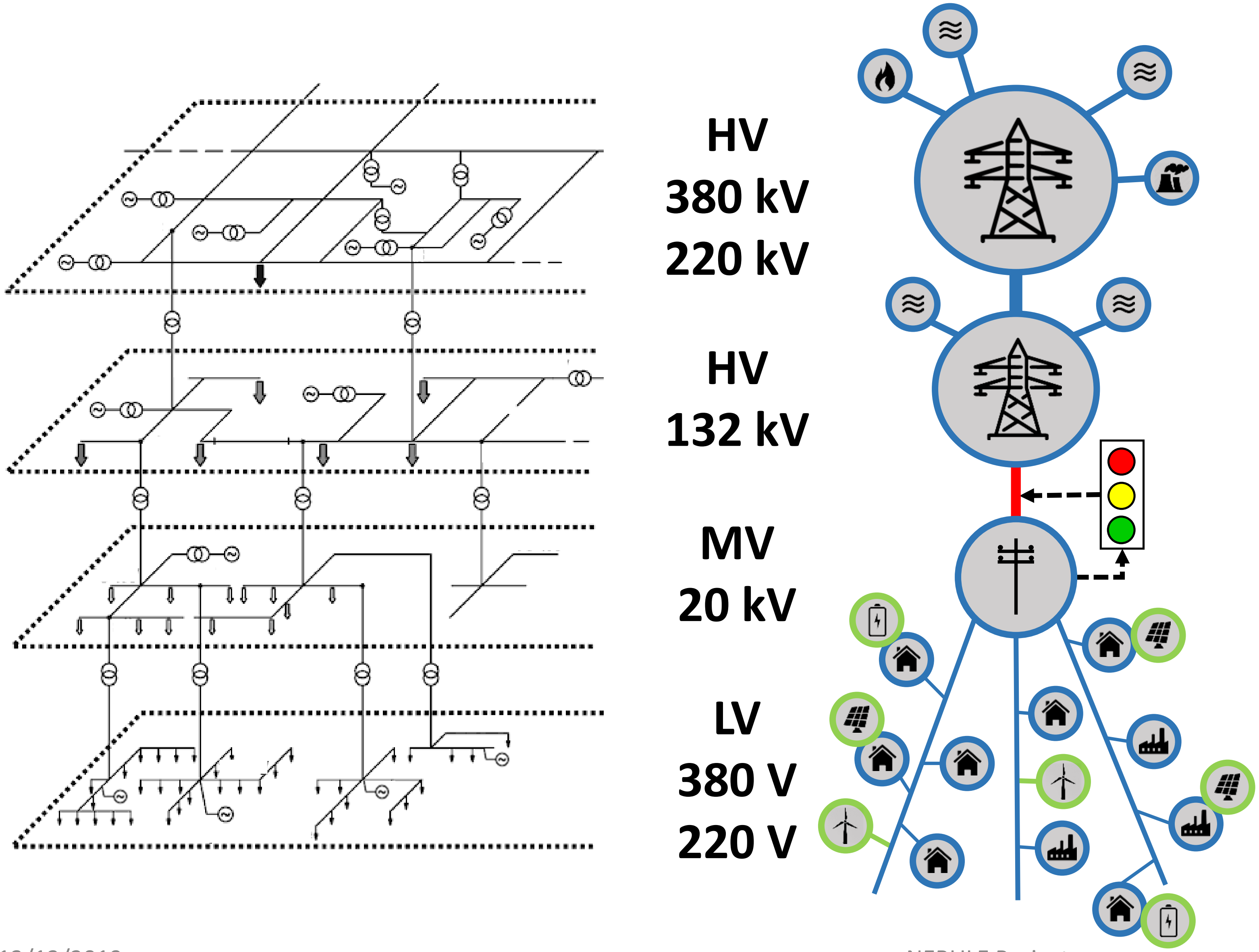


Widespread diffusion of DG at distribution network level

Power system ancillary services



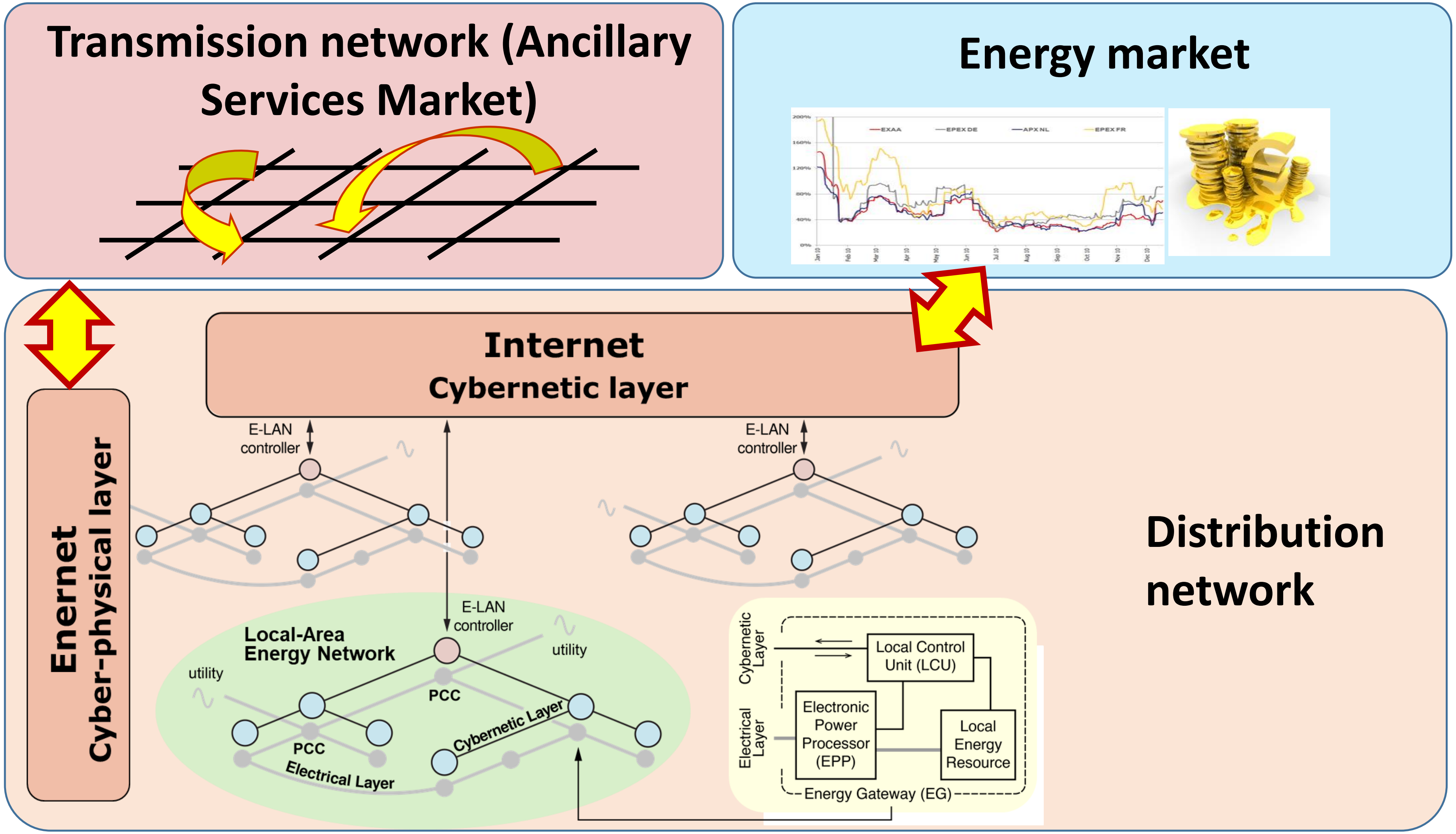
Power system managed through large plants (> 10 MVA) connected to HV voltage level

Widespread diffusion of DG at distribution network level

ARERA'S RESOLUTION 300/17

Opening of the Ancillary Services Market to the distributed energy resources connected to MV and LV level in aggregated form

NEBULE Project: Concept and approach



Transmission network (Ancillary Services Market)

Energy market

Internet
Cybernetic layer

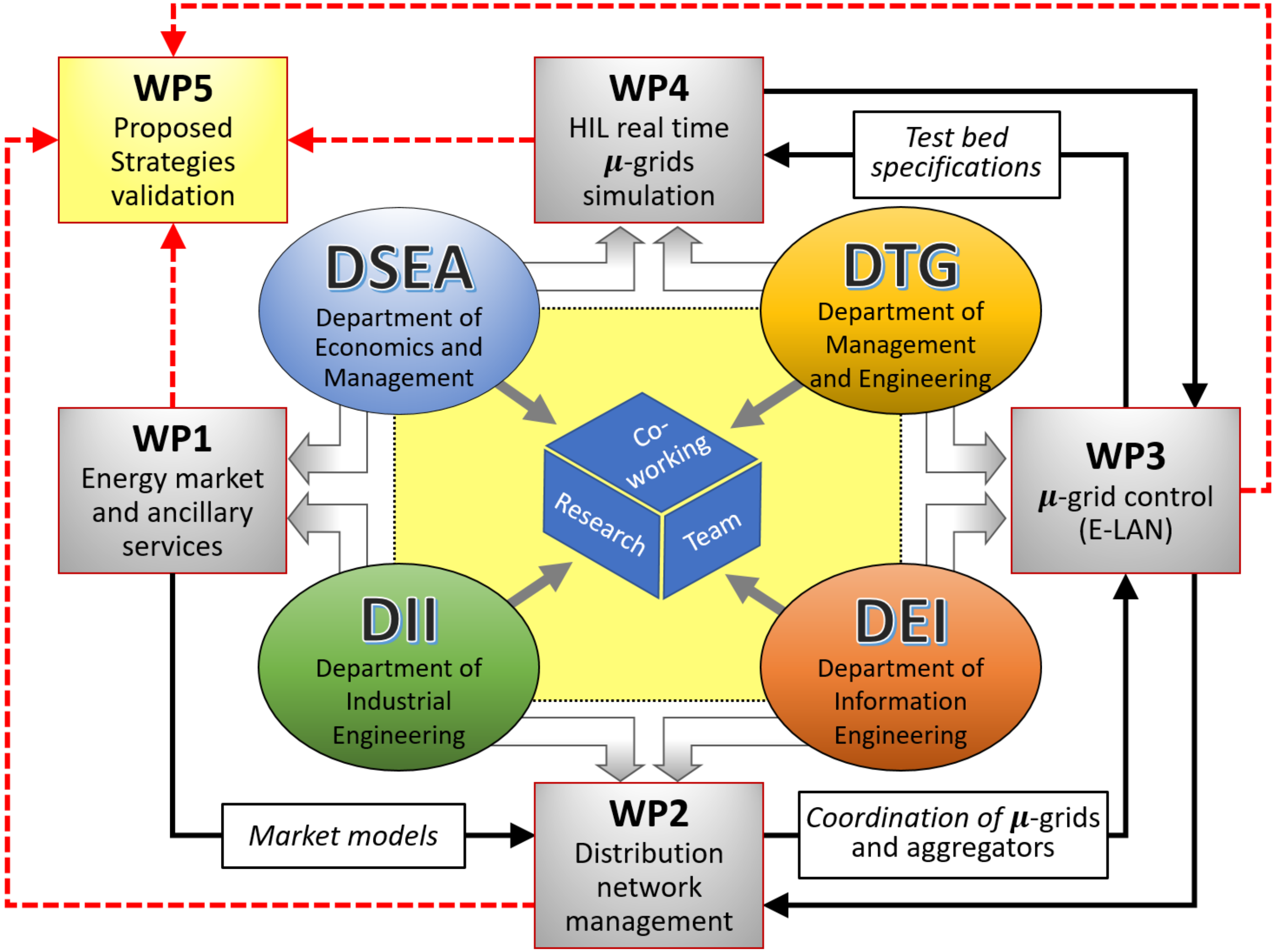
Enernet
Cyber-physical layer

Distribution network

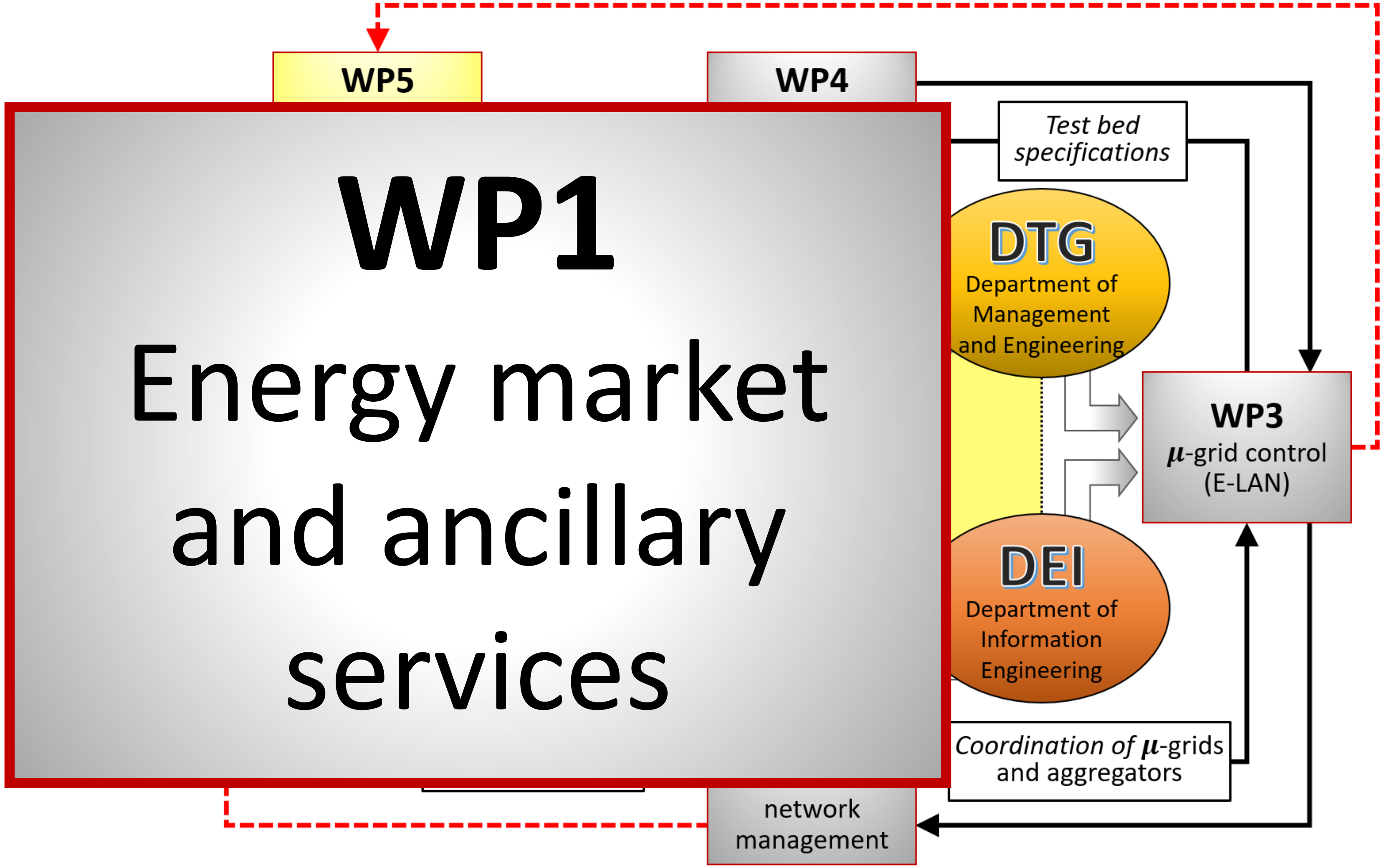
NEBULE Project: four main domains of research

- ❑ **Business/Economics domain**: Identify new customer-oriented services made available by technology innovations in the field of micro-grids, evaluate the socio-economic impact of prosumers’ aggregation, and design incentive mechanisms to foster their adoption.
- ❑ **Power & Energy domain:** Analyze the functional improvement allowed by micro-grid-based layered architecture of electrical systems and their role in an electricity market based Distribution Management System (DMS).
- ❑ **Control & Communication domain:** Exploit the control potential of DERs equipped with power electronics in conjunction with smart dispatching functionality implemented by a micro-grid supervisor (E-LAN).
- ❑ **Physical experimental micro-grid domain**: Test micro-grids feasibility, stability and cost effectiveness, by synergistic control of power electronics interfacing DERs, storage and responsive loads.

NEBULE Project



NEBULE Project



WP1

Energy market and ancillary services

Business model opportunities through end-users aggregation

In a changing electricity market landscape system flexibility becomes crucial. As part of the solution, the aggregation of renewable energy can significantly accelerate the integration of intermittent electricity sources, complement demand flexibility and decrease the reliance on renewable energy support schemes

They offer network services like:

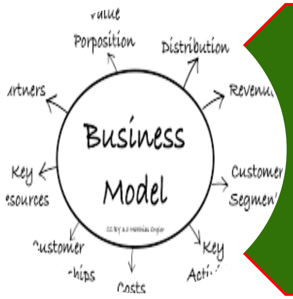
- Dispatching,
- Frequency control
- Voltage regulation

They benefit of:

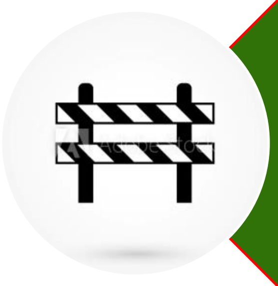
- Affordable rates,
- Local control,
- Cleaner energy

Research questions

What are the main technical, environmental, market and social benefits of the activities carried out by aggregators?



What are the business models (BMs) that allow aggregators to be competitive in the market?

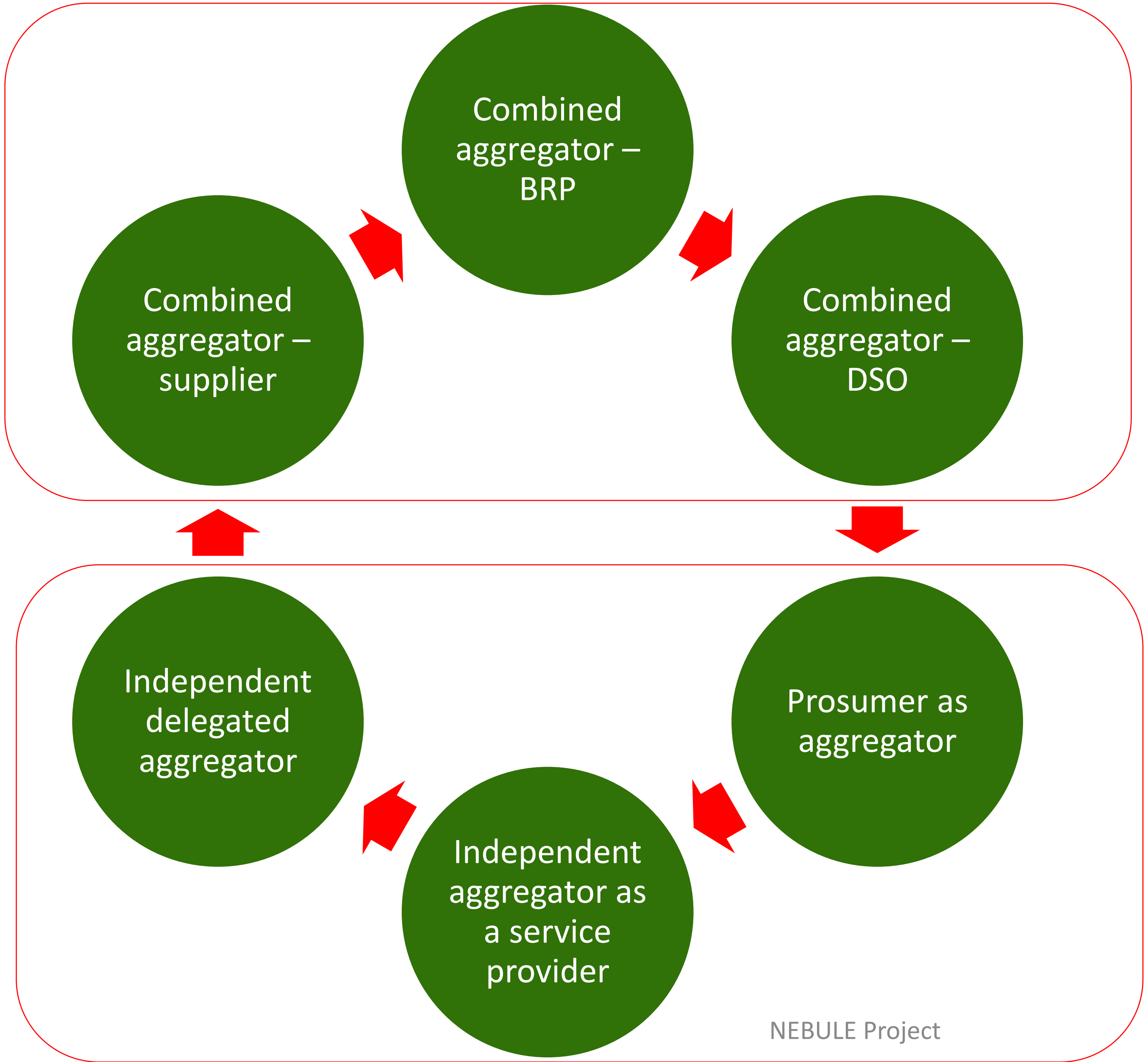


What are the main barriers that prevent the proper implementation of the BM?

Business models for aggregation (1/2)

Business Model	Explanation
Combined aggregator – supplier	Supply and aggregation are offered as a package and there will be one BRP per connection point.
Combined aggregator –BRP	There are 2 BRPs on the same connection point, the BRP (independent aggregator) and the BRP (supplier). The supplier is compensated for imbalances.
Combined aggregator – DSO	NOT tackled: regulated and unregulated roles should not be combined.
Independent aggregator as a service provider	The aggregator is a service provider for one of the other market actors but does not sell at own risk to potential buyers.
Independent delegated aggregator	The aggregator sells at own risk to potential buyers such as the TSO, the BRP and the wholesale electricity markets.
Prosumer as aggregator	Large-scale prosumers choose to adopt the role of aggregator for their own portfolios.

Business models for aggregation (2/2)



Combined aggregator – BRP

Combined aggregator – supplier

Combined aggregator – DSO

Independent delegated aggregator

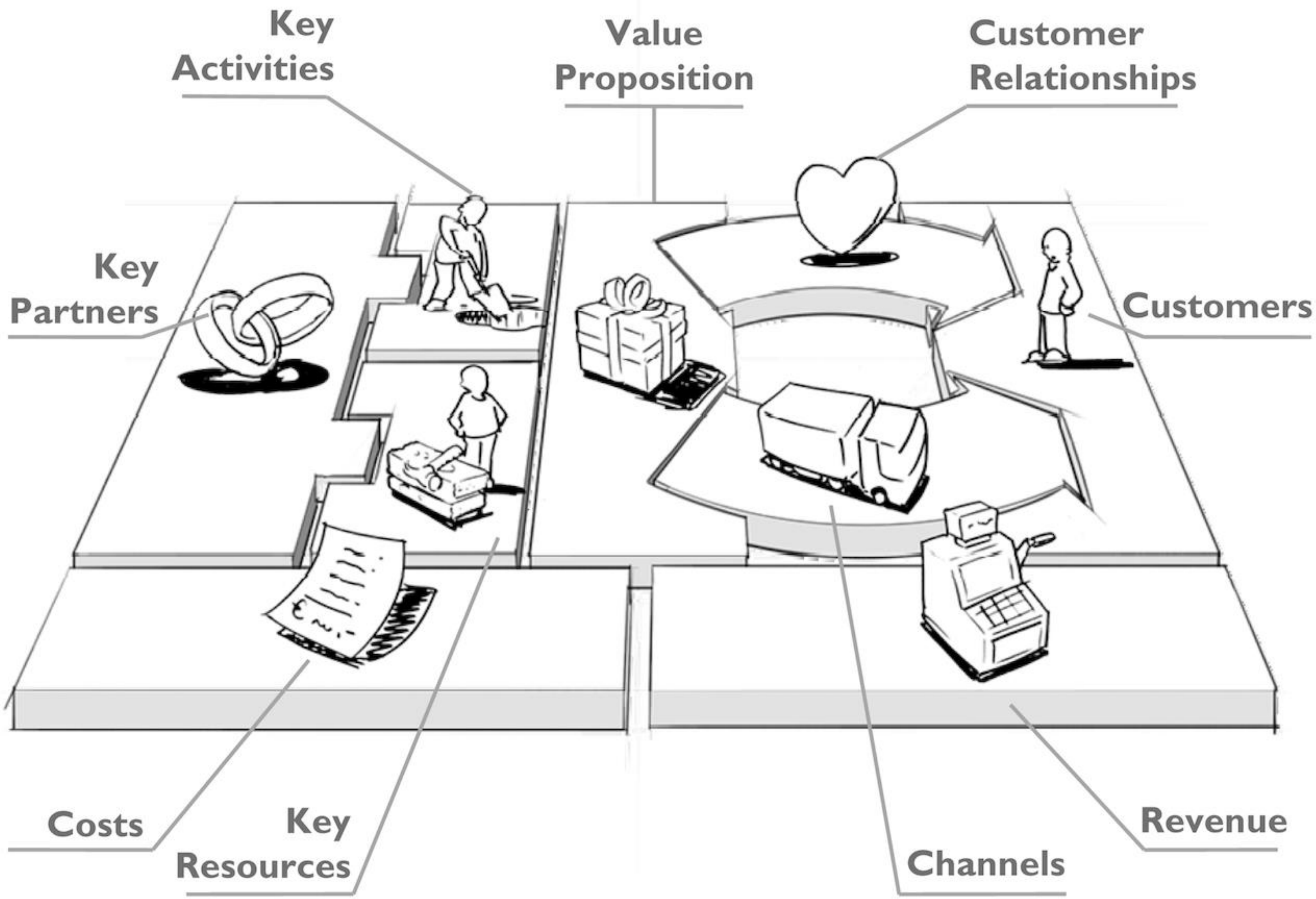
Prosumer as aggregator

Independent aggregator as a service provider

Aggregators with a combined role

Aggregators with an independent role

Building blocks of aggregator business models



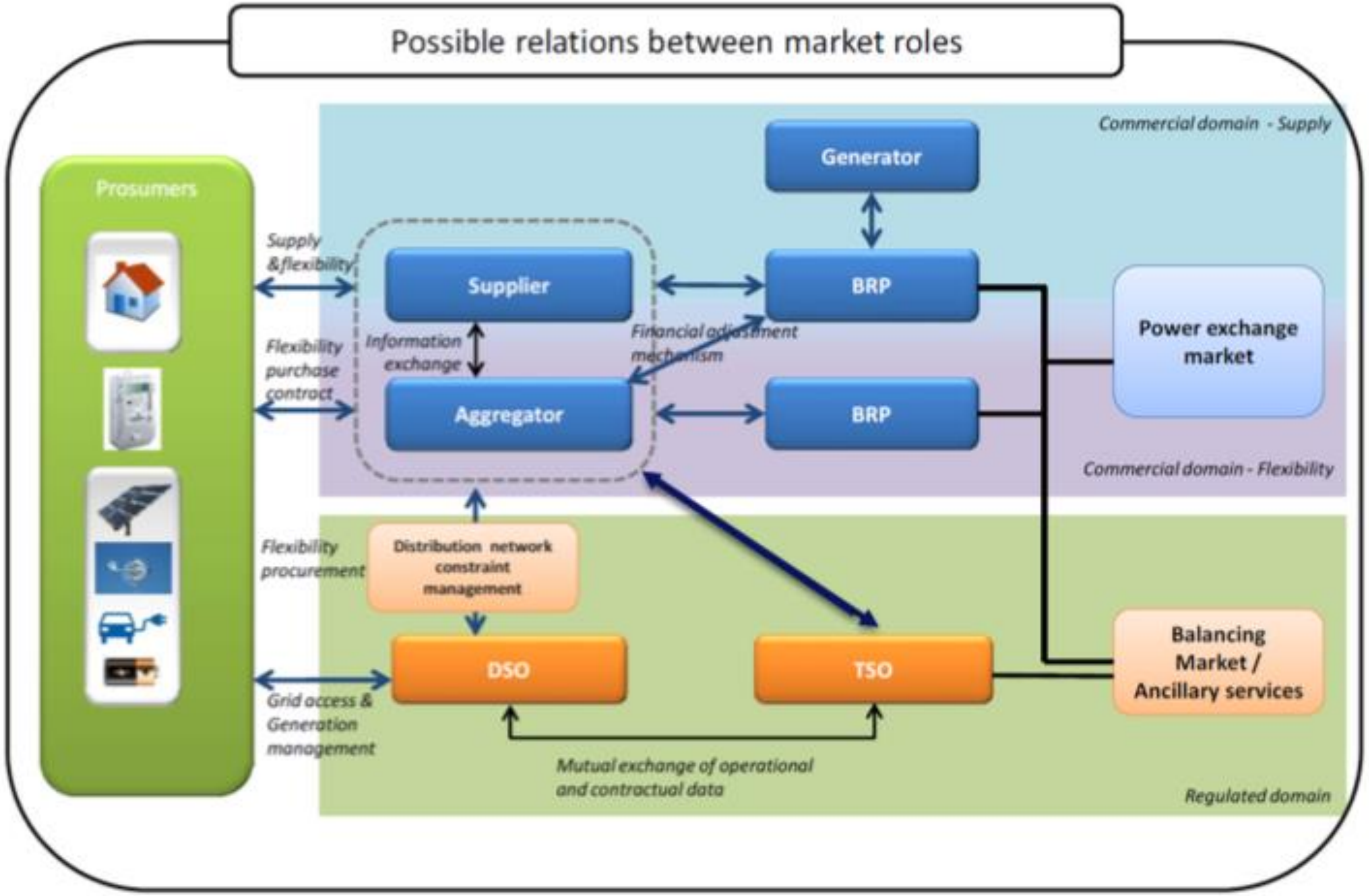
“A business model describes the rationale of how an organization creates, delivers, and captures value”

(Osterwalder, 2010, p. 14)

Customer segments and value proposition

Aggregators can deliver services to the following users:

- BRPs (power exchange market)
- TSOs and DSOs (balancing the market and ancillary services)
- Different wholesale electricity markets: intraday, day-ahead and futures markets
- Prosumers on a specific site



Key resources and activities

Aggregators can choose to carry out various types of aggregation in order to create value on multiple markets

Market

		Wholesale and retail markets	Reserve and capacity markets	Supply to end electricity consumers	Reduction of grid charges	Own balancing
Technology	Wind					
	PV					
	Biogas					
	Hydro					
	CHP					
	Storage (batteries)					
	Demand response (industrial)					
	Demand response (domestic)					

The figure can be split up into 3 main providers of aggregation services:

1. Demand response (industrial domestic)
2. Distributed generation: Wind, PV, Biogas, Hydro and non-conventional CHP
3. Storage

Channels and customer relationships

The aggregation business is a relatively new business across Europe and, therefore, a key differentiator with competitors is the ability to reach new interesting providers of aggregation services (demand side management, distributed generation assets and storage).

Aggregators that are also energy suppliers

- Use their existing residential and commercial customers, contracted prosumers and industry events

Independent aggregators

- Need to target new clients through the phone/websites and social media.

Partners

The aggregators have different financial and non-financial stakeholders.

The most important non-financial stakeholders are technology and software providers

Revenue streams and cost structure

Revenue stream

1. Customer-tailored and not standardized.
    1. For example in the case of a BRP using the flexibility or in the case of the energy consumption of a prosumer being optimized, this revenue model can be volume dependent.
2. Will be generated through a predefined availability and or activation fee.
    1. In the case of the TSO and the DSO being the user of flexibility.

Cost components aggregators

- Remunerations Providers
- Software and other technology
- Contracts
- Staff

The case study: Next Kraftwerke

	Combined aggregator – supplier	Combined aggregator-BRP	Combined aggregator – DS0	Independent delegated aggregator	Aggregator as service provider	Prosumer as aggregator
Next Kraftwerke (Germany)	x	x		x		
Next Kraftwerke (France)	/	x		x		
Next Kraftwerke (Belgium)	/	x		x		

Next Kraftwerke is the operator of the largest Virtual Power Plant (VPP) in Europe.
The company connects power-producing assets from renewable sources such as biogas, wind, and solar with commercial and industrial power consumers and power-storage systems.

Value created by Next Kraftwerke

	Wholesale and retail markets	Reserve and capacity markets	Supply to end electricity consumers	Reduction of grid charges	Own balancing
Next Kraftwerke (Germany)	Wind, PV, Biogas, Hydro, CHP, Industrial DSM	Biogas, Hydro, CHP			Wind, PV, Biogas, Hydro, CHP, Industrial DSM
Next Kraftwerke (France)	Wind, PV, Biogas, Hydro, CHP, Industrial DSM	Biogas, Hydro, CHP			Wind, PV, Biogas, Hydro, CHP, Industrial DSM
Next Kraftwerke (Belgium)	Wind, PV, Biogas, Hydro, CHP, Industrial DSM	Biogas, CHP, Industrial DSM			Wind, PV, Biogas, Hydro, CHP, Industrial DSM

Value created by Next Kraftwerke

Value proposition: Increase revenues of customers with flexible tariffs

	Wholesale and retail markets	Reserve and capacity markets	Supply to end electricity consumers	Reduction of grid charges	Own balancing
Next Kraftwerke (Germany)	Wind, PV, Biogas, Hydro, CHP, Industrial DSM	Biogas, Hydro, CHP			Wind, PV, Biogas, Hydro, CHP, Industrial DSM
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Next Kraftwerke: Customer segments

	Wholesale and retail markets	Reserve and capacity markets	Supply to end electricity consumers	Reduction of grid charges	Own balancing
Next Kraftwerke (Germany)	Wind, PV, Biogas, Hydro,	Biogas, Hyd			Wind, PV, Biogas, Hydro, CHP, Industrial DSM
Next Kraftwerke (France)					Wind, PV, Biogas, Hydro, CHP, Industrial DSM
Next Kraftwerke (Belgium)	Wind, PV, Biogas, Hydro, CHP, Industrial DSM	Biogas, CHP, Industrial DSM			Wind, PV, Biogas, Hydro, CHP, Industrial DSM

Customer

Next Kraftwerke is focusing on:

- Small/medium-scale generators;
- Large industrial consumers.

Next Kraftwerke: Key resources and activities

	Wholesale and retail markets	Reserve and capacity markets	Own balancing
Next Kraftwerke (Germany)	Wind, PV, Biogas, Hydro, CHP, Industrial DSM	Biogas, Hydro, CHP	Wind, PV, Biogas, Hydro, CHP, Industrial DSM
Next Kraftwerke (France)	Wind, PV, Biogas, Hydro, CHP, Industrial DSM	Biogas, Hyd CHP	Wind, PV, Biogas, Hydro, CHP, Industrial DSM
Next Kraftwerke (Belgium)	Wind, PV, Biogas, Hydro, CHP, Industrial DSM	Biogas, CHP, Industrial DSM	Wind, PV, Biogas, Hydro, CHP, Industrial DSM

Key resources
- trading platform
- platform for plant optimization and management
- Algorithm for optimisation of consumption

Activities
- Scheduling and optimisation of production
- sale of ancillary services
- software sale

Next Kraftwerke: Channels and customer relationships

Channels

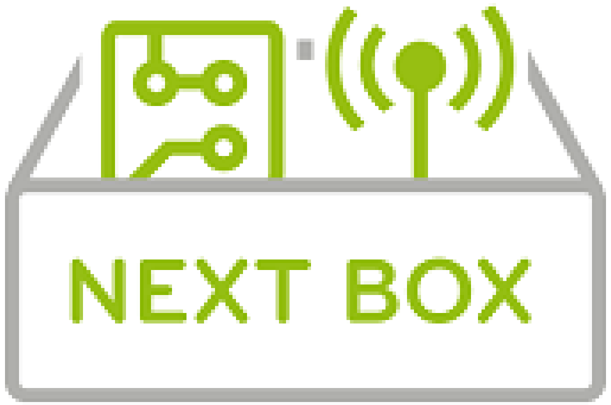
- Small-and medium-scale providers: industry network, social media.
- Larger clients: site visits

Customer relationship

- Automated or customised through customer support and assistance mechanisms

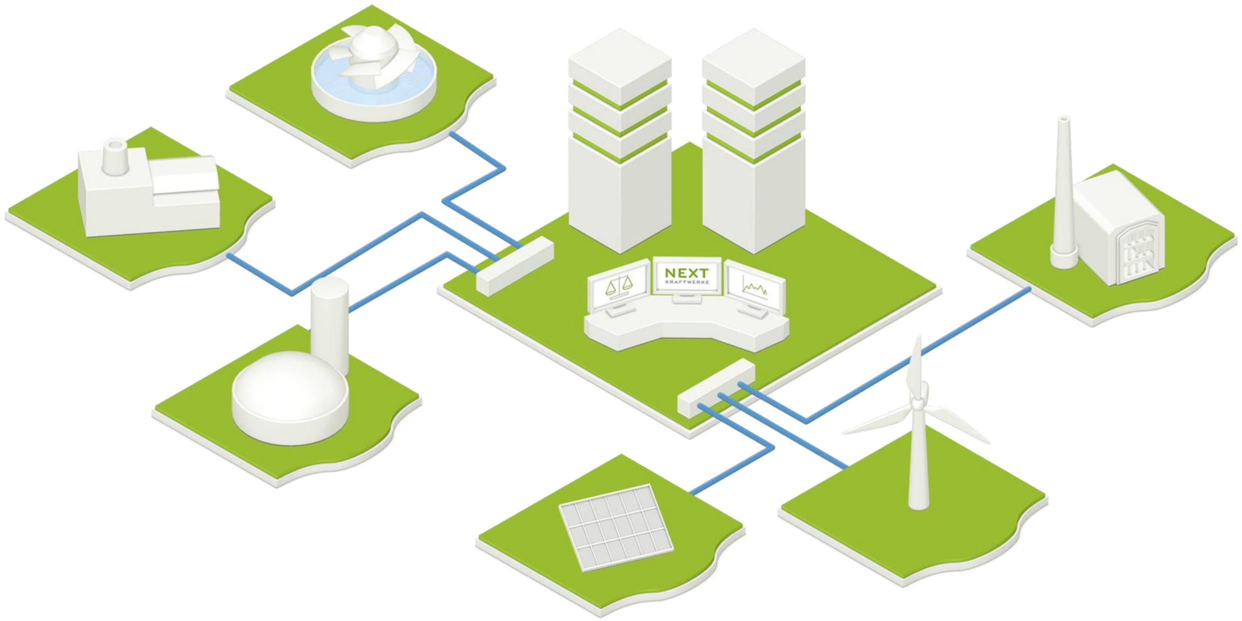
Next Kraftwerke: Partners

Next Kraftwerke Germany was created with venture capital and, as an independent company, owns Next Kraftwerke Germany in France and Next Kraftwerke Belgium.



Next Kraftwerke developed their own platform “Next Box”.

- It allows to connect almost 2000 of decentralized electricity producers and consumers for a total portfolio size of 2 GW.
- It sends information on the operation of the remote unit to the central control system and allows for starting up or shutting down units.



Next Kraftwerke: Revenue streams and cost structure

Revenue stream

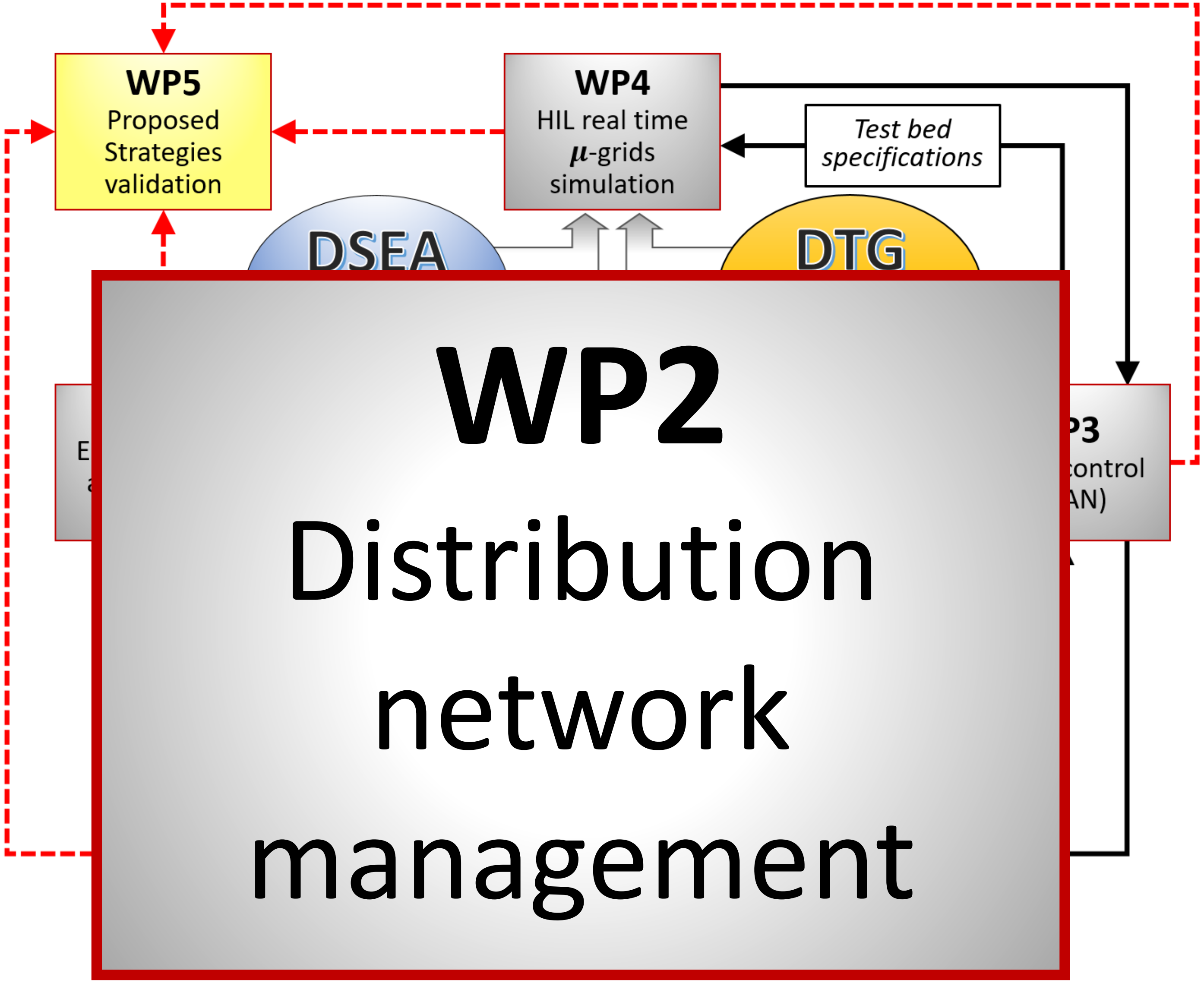
1. Next Kraftwerke offers or plans to offer on:
   - All reserve power markets;
   - The wholesale market

This allows Next Kraftwerke to put the flexibility of the client where it is worth most to maximise the overall revenue.

Cost components aggregators

	Providers: most important costs	Other important costs inherent in the business model
Next Kraftwerke (Germany)	Distributed generation providers	1)Development costs software and technology, 2) Staff costs
Next Kraftwerke (France)	Distributed generation providers	1)Development costs software and technology, 2) Staff costs
Next Kraftwerke (Belgium)	Distributed generation providers	1)Development costs software and technology, 2) Staff costs

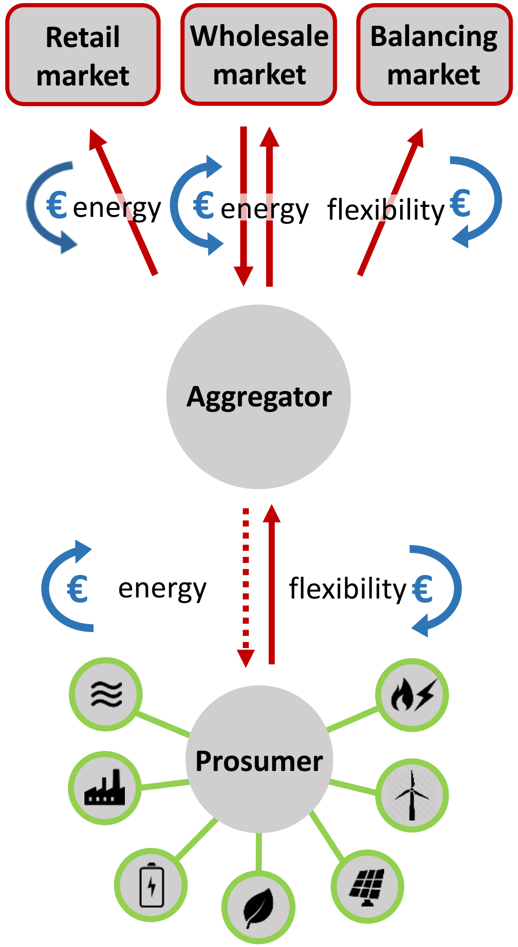
NEBULE Project



WP2

Distribution network management

The role of aggregators



Opportunities through aggregation:

- ➢ Reduced system complexity
- ➢ New service provider for grid stability with locally distributed ancillary services
- ➢ New revenue streams and a direct market contribution for prosumers

Underlying policy implications:

- ➢ Need of a solid and comprehensive regulatory framework
- ➢ Transparent admission criteria and process for energy and balancing markets
- ➢ Redefinition of the DSO role
- ➢ Updated TSO-DSO communication schemes

Past/ongoing activities

1. **The evolution of the ancillary services market in Italy:**
    - Analysis of the market trends as regards the new aggregator subjects
2. **Market frameworks and their impact on the distribution network management**
    - Study of the proposed market models (and possible effects on the aggregators)
    - Application of the selected market model to investigate the issues/opportunities
3. **Demand Response and time-based services**
    - Analysis of the aggregated response by end-users to implement optimal distribution network dispatching

The evolution of the ancillary services market in Italy

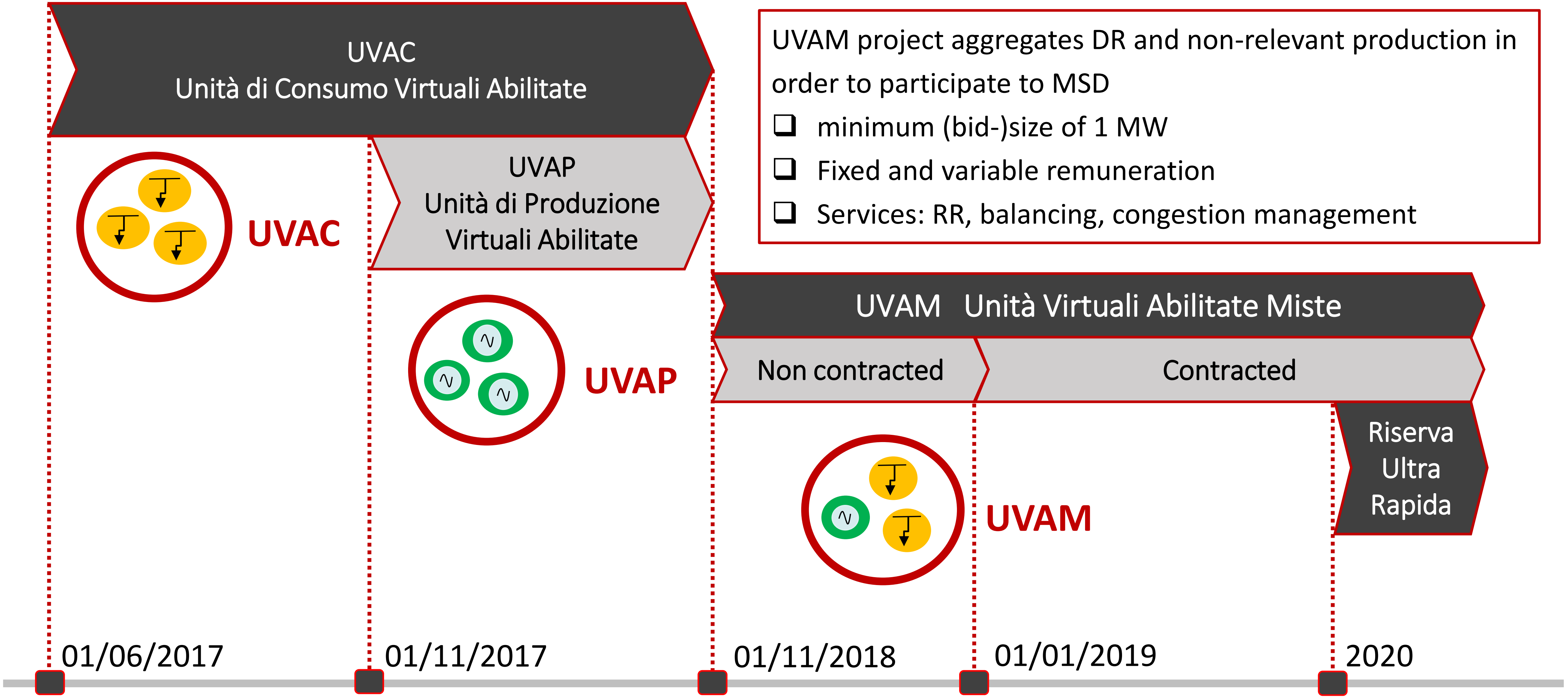
- ☐ According with the regulatory process, aggregators are foreseen in the Italian ancillary services market (MSD)

- ☐ Based on the raw data from GME (Italian market operator), an analysis of the ongoing trend of MSD has been done with the aim of:
  - ➢ Quantifying the consistency of these subjects in the Italian market
  - ➢ Stressing the current issues with the selected approach

TERNA Pilot Projects (post resolution 300/2017)

UVAM project aggregates DR and non-relevant production in order to participate to MSD

- ☐ minimum (bid-)size of 1 MW
- ☐ Fixed and variable remuneration
- ☐ Services: RR, balancing, congestion management



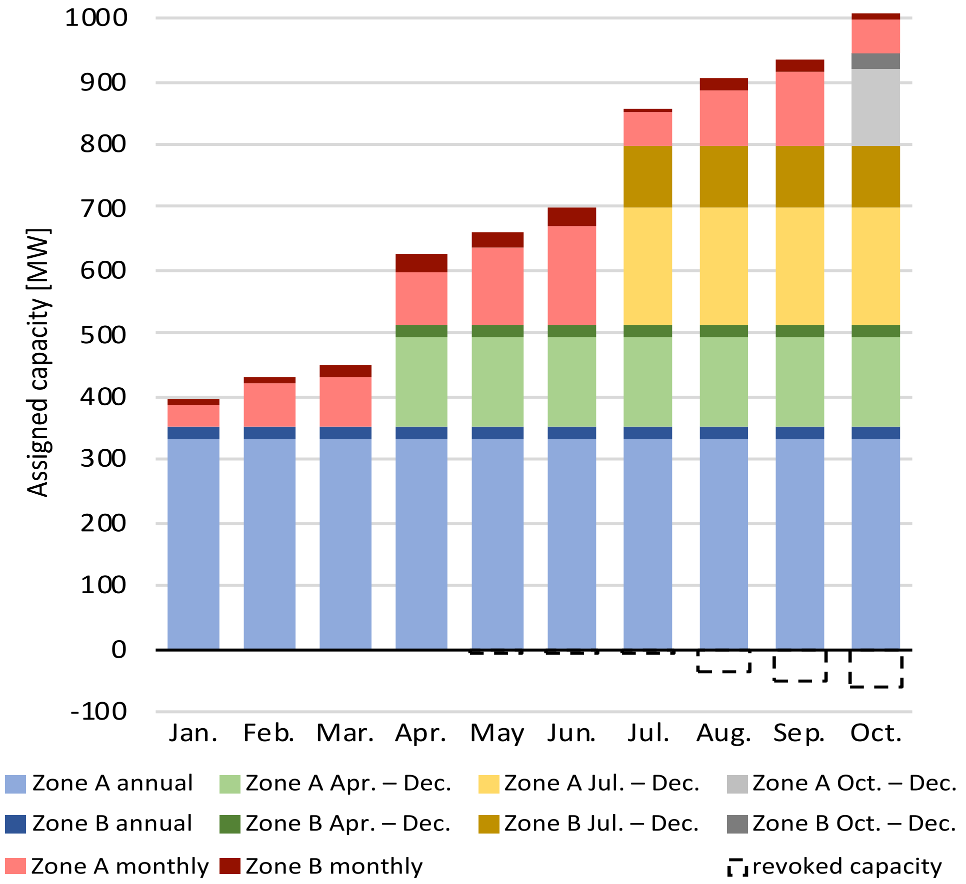
Contracted UVAM incentive scheme

The UVAM project:

- intends to aggregate ***1000 MW*** of distributed flexibility to make it available for Terna in MSD and MB
- Minimum aggregation size of 1 MW

The incentive scheme:

- Started in 01 January 2019
- Provides a fixed capacity payment through an auction scheme with pay-as-bid
    - price cap placed at 30000 €/MW/year
- Mandatory upward bids in the ASM:
    - for at least 4 consecutive hours between 14.00-20.00 from Monday to Friday
    - Price cap placed at 400 €/MWh



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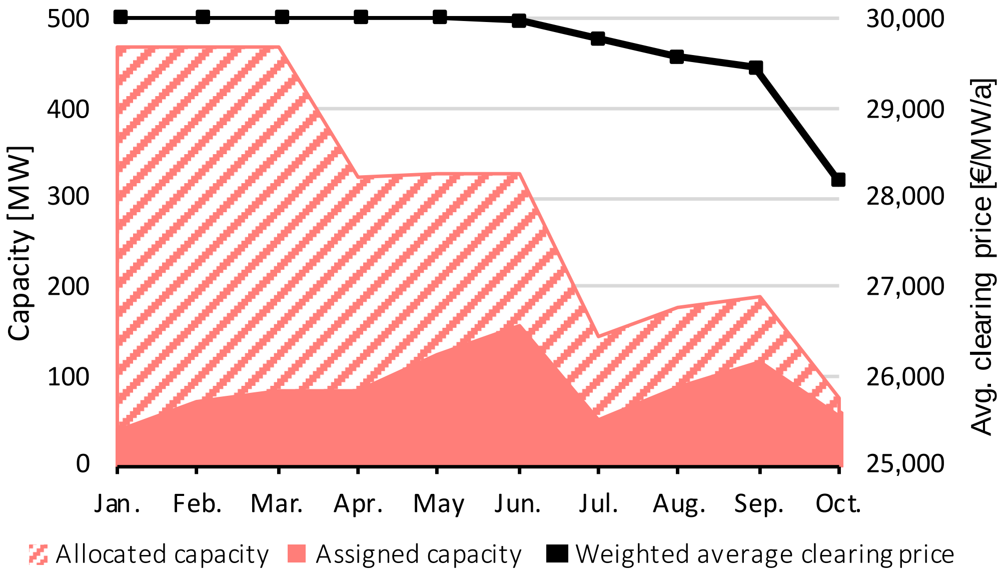
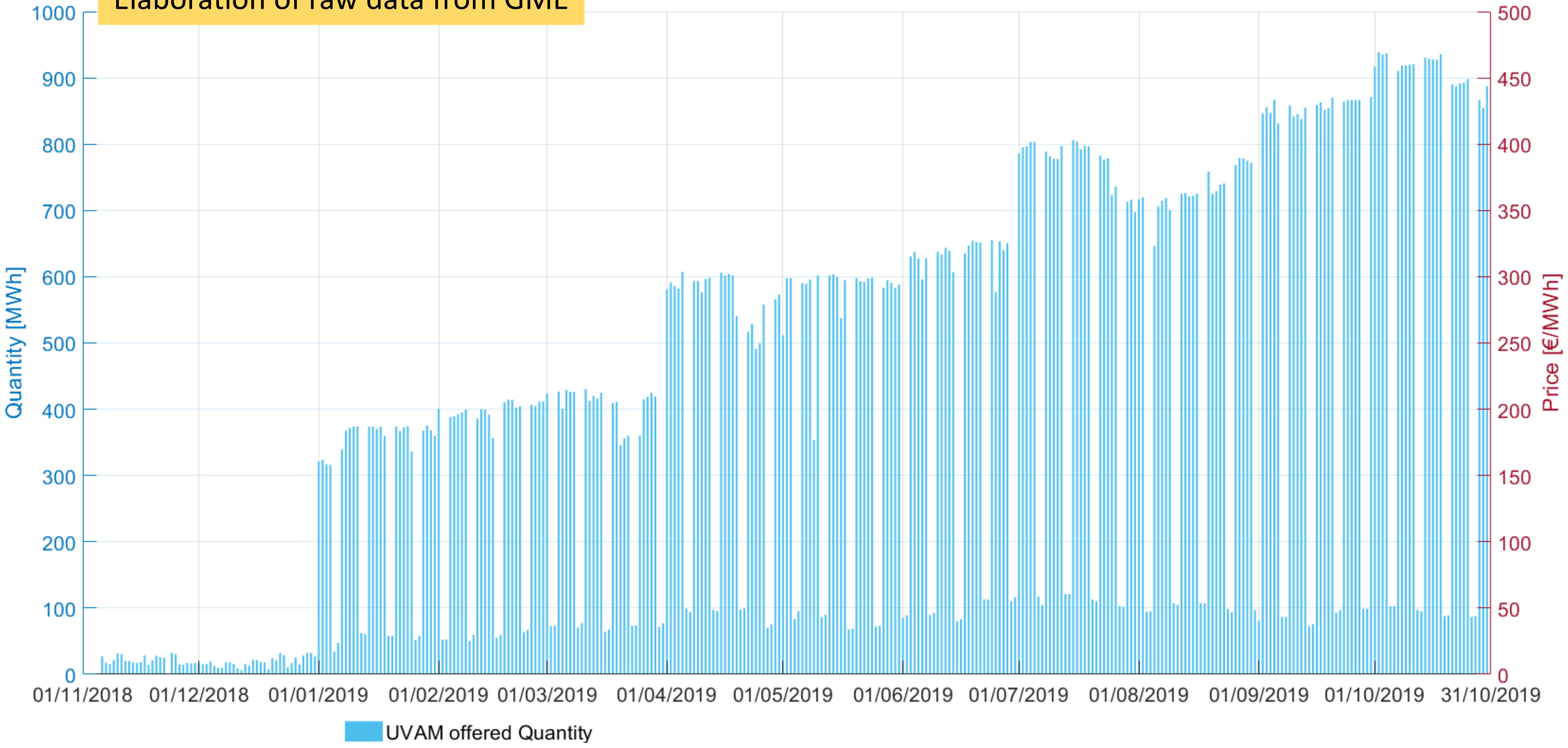


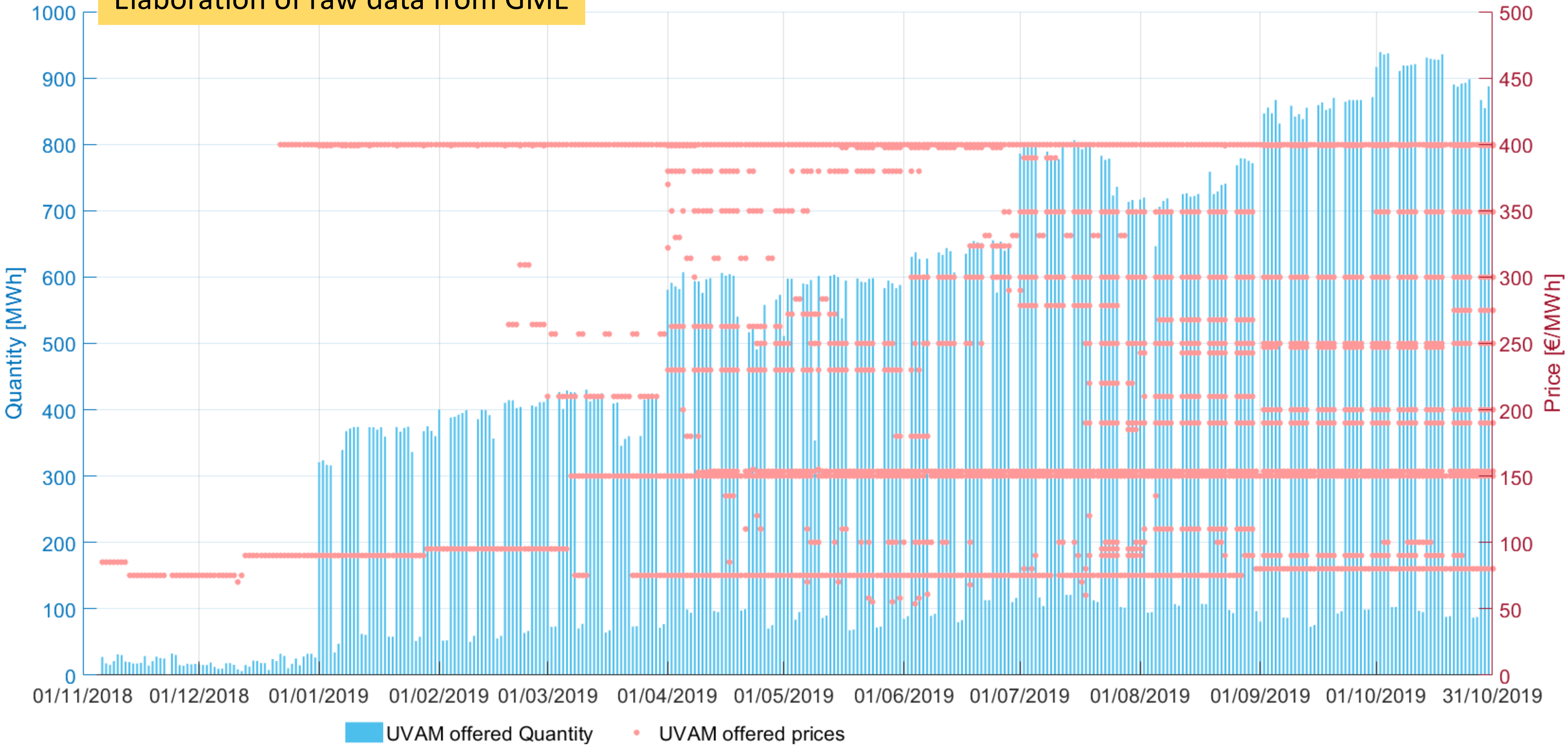
Project UVAM offered quantities

Elaboration of raw data from GME



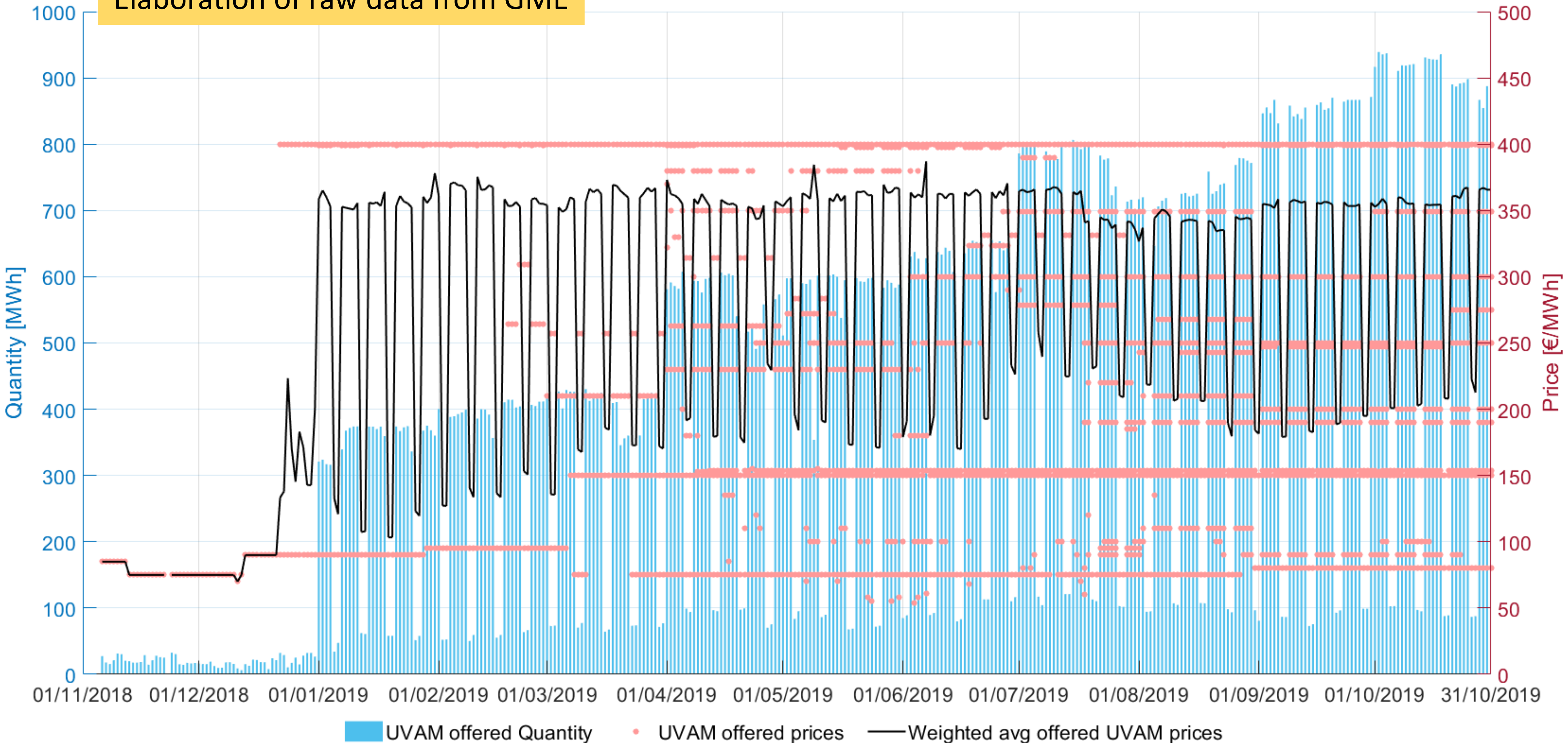
Project UVAM offered price

Elaboration of raw data from GME



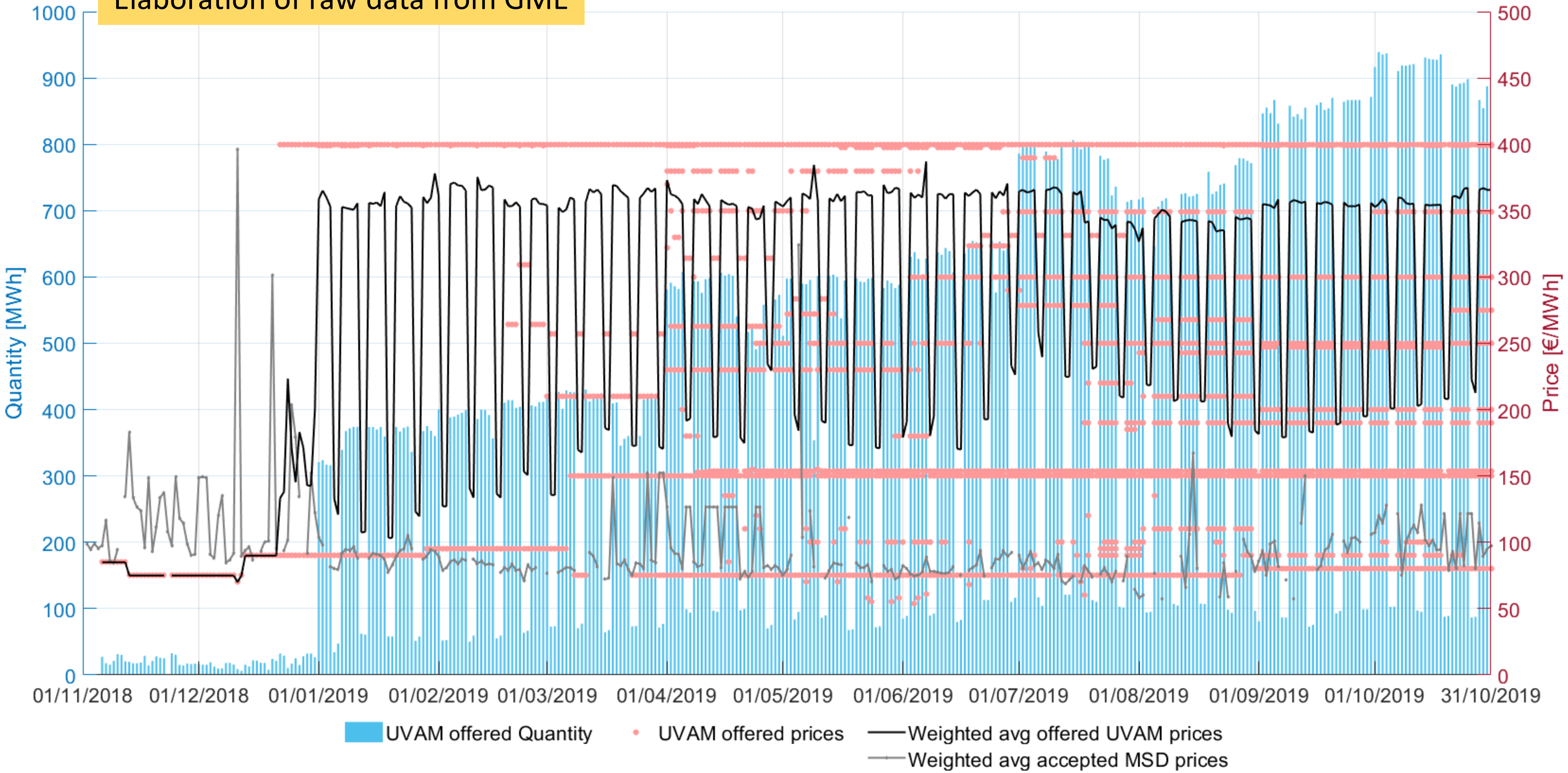
Project UVAM average offered price

Elaboration of raw data from GME



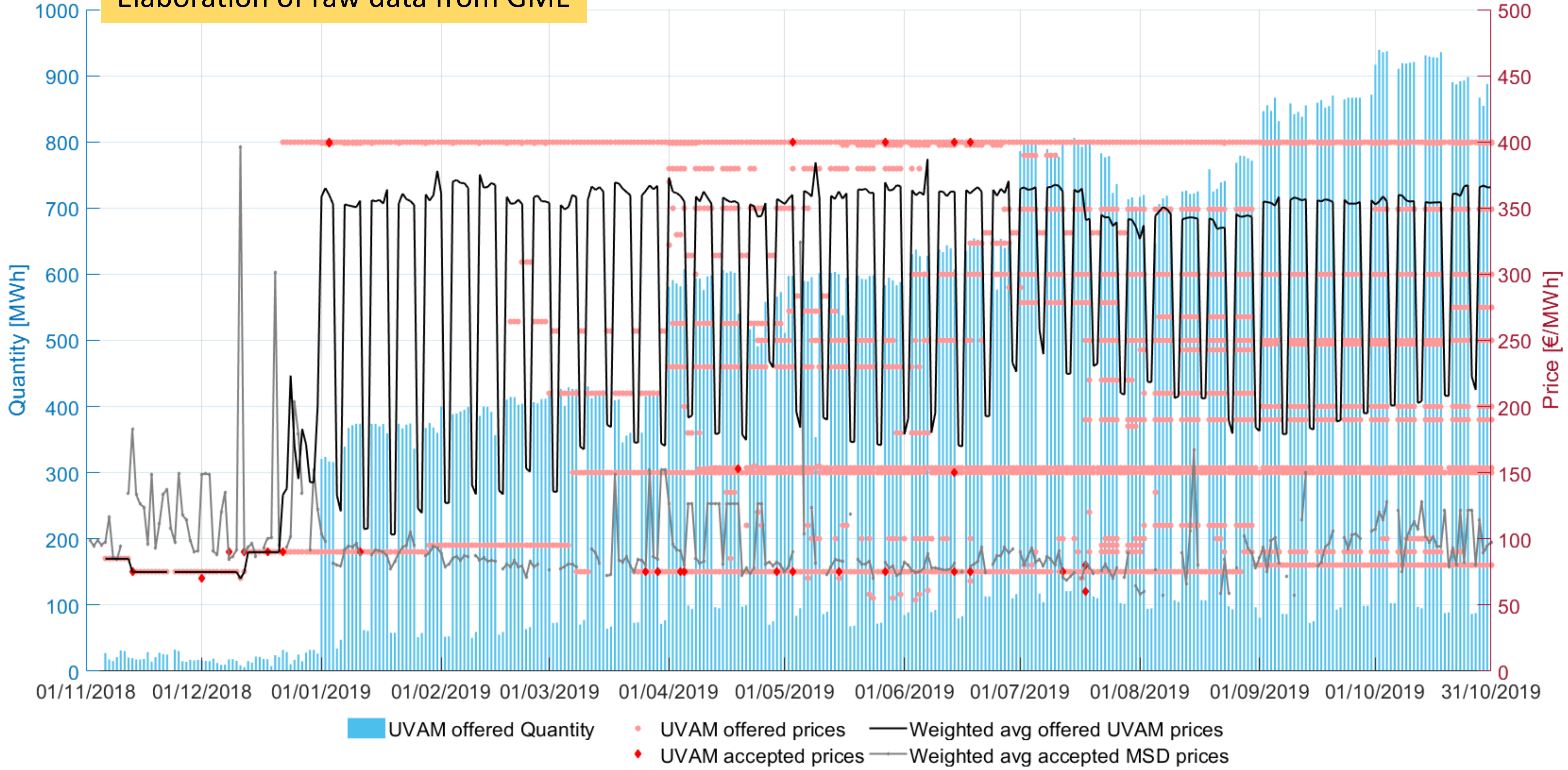
Project UVAM average market price

Elaboration of raw data from GME



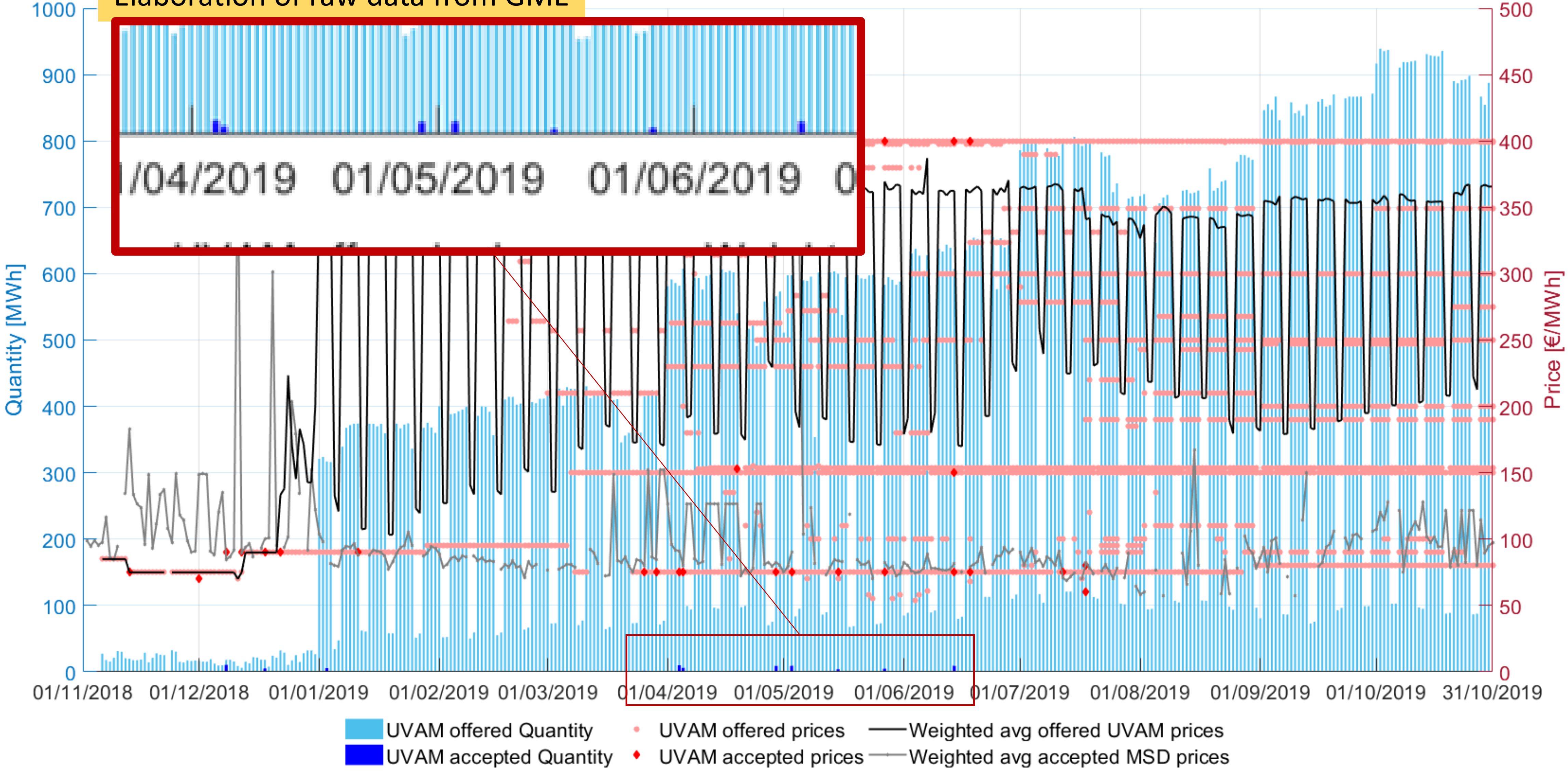
Project UVAM accepted price

Elaboration of raw data from GME

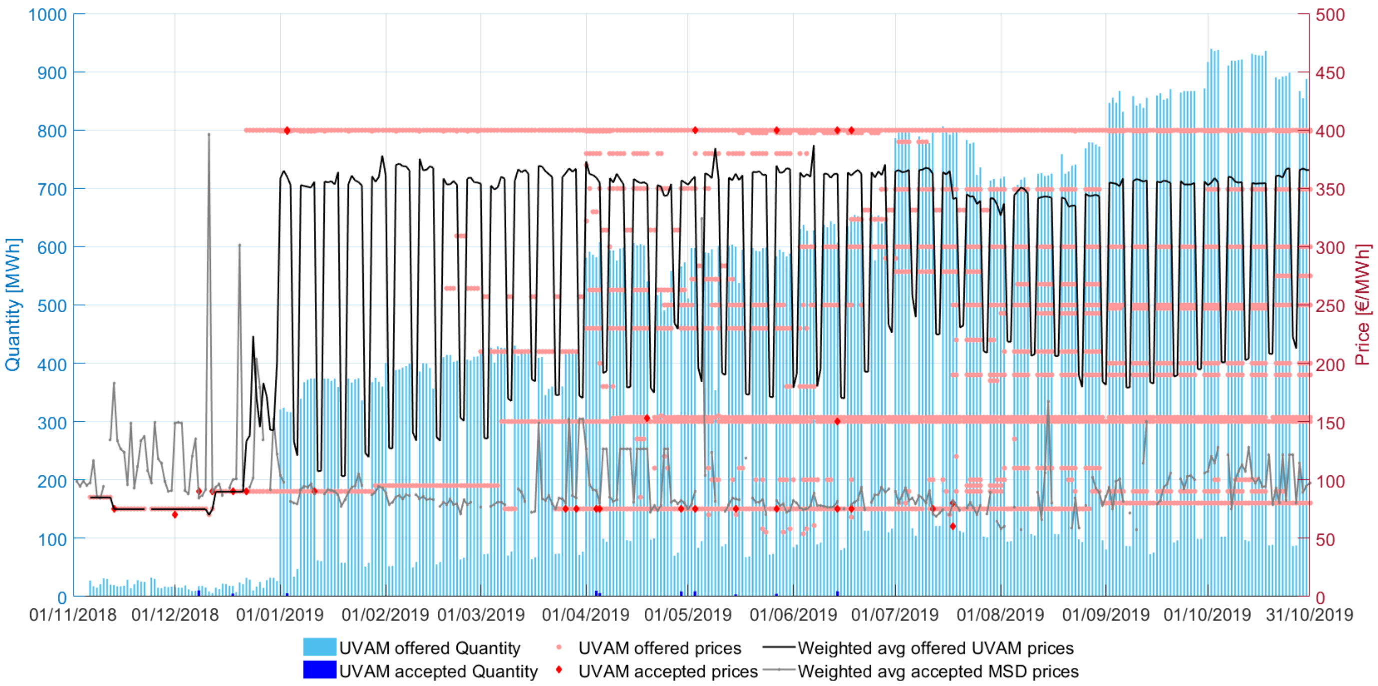


Project UVAM accepted quantity

Elaboration of raw data from GME



Project UVAM results – Upward bids



- ☐ Weighted avg UVAM offer price: **341 €/MWh**
- ☐ Weighted avg market offer price: **90 €/MWh**
- ☐ Total accepetd UVAM quantity: **879 MWh**

⇩

0,1% of all UVAM offers / **0,02%** market share

Main outcomes of the analysis:

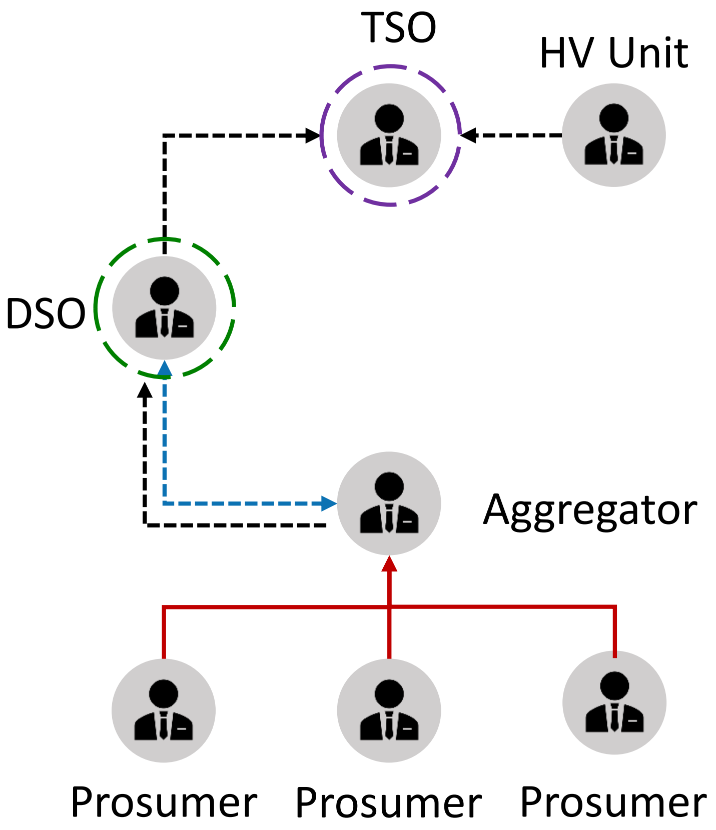
- ☐ Successful stimulation of 1 GW of new flexibility from previously non participating units
- ☐ ~71% of all UVAMs have a single POD
  - → comparably little virtual aggregation
- ☐ Auction performance
  - → Promising in terms of quantities
  - → price competitiveness remains poor
- ☐ Poor market efficiency
  - → prices close to 400 €/MWh
  - → rare activations

Market frameworks and distribution network management

- Several Market Models (MM) have been proposed in literature for the involvement of end-users
- Different MM have different impacts on the aggregators’ strategies
- The current Italian approach basically extends the current frameworks to small units, after pre-qualification (MM1)
- A common trend is to foresee a local marketplace enabling the DSO to actively select the required services

Possible TSO/DSO coordination schemes

MM2 – Local AS Market Model

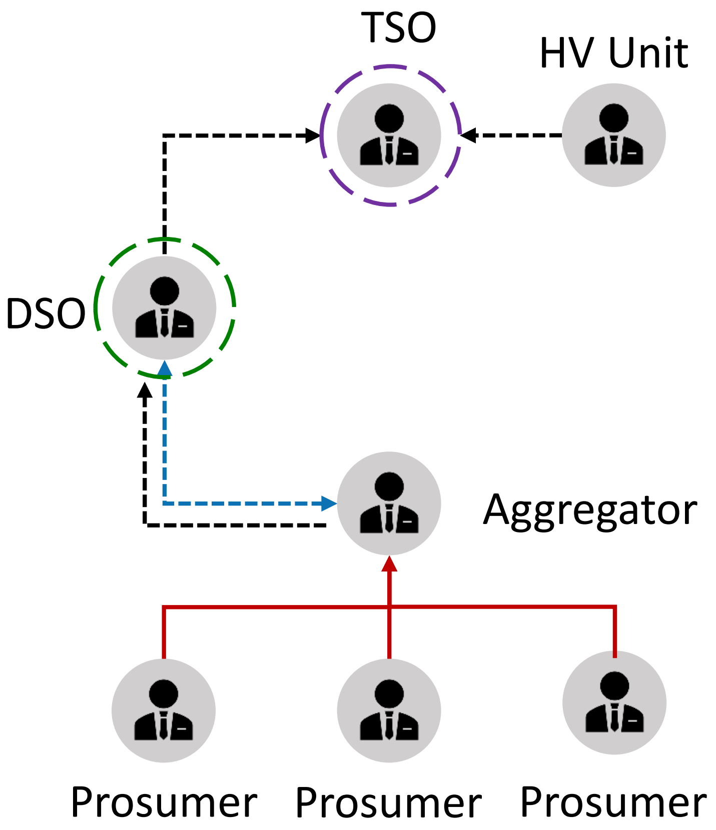


- ☐ A local market for AS is designed for the **pre-qualification** of offers
- ☐ The local market operator (possibly the DSO itself), after selecting the **feasible offers**, transfers them to the centralized market

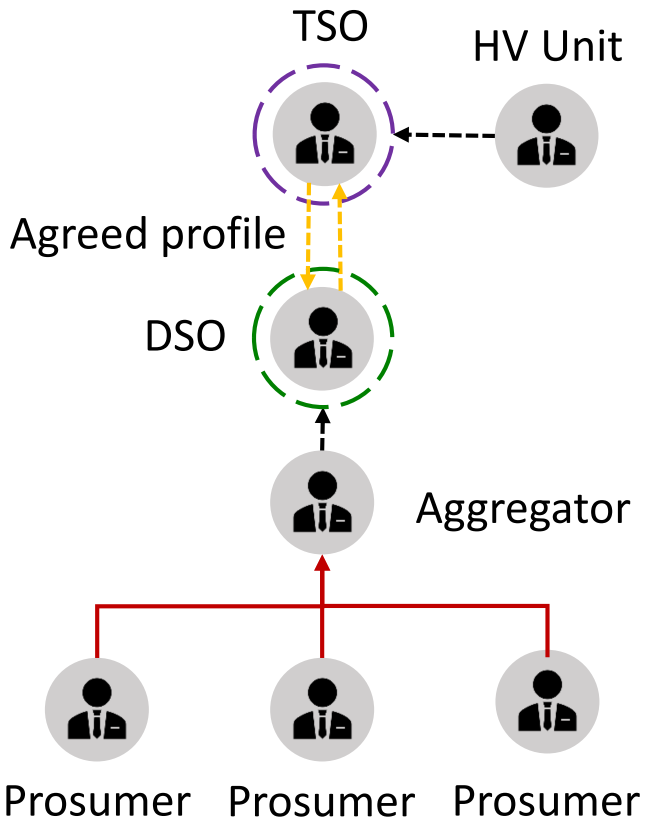
Legend: 🟥 Aggregation   Pre-qualification   Market bids   ○ Centralized Market   ○ Local Market

Possible TSO/DSO coordination schemes

MM2 – Local AS Market Model



MM3 – TSO/DSO Agreed Profile Model



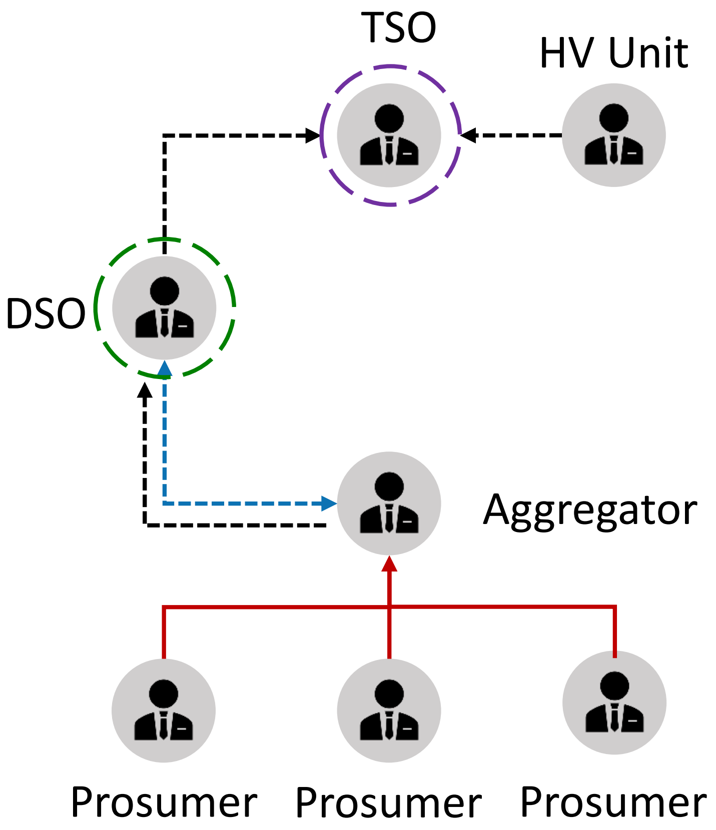
❑ TSO and DSO **agree on a power profile** at the interface

❑ The DSO can select offers on the local market to **fulfil obligations** with TSO and manage the **local contingencies**

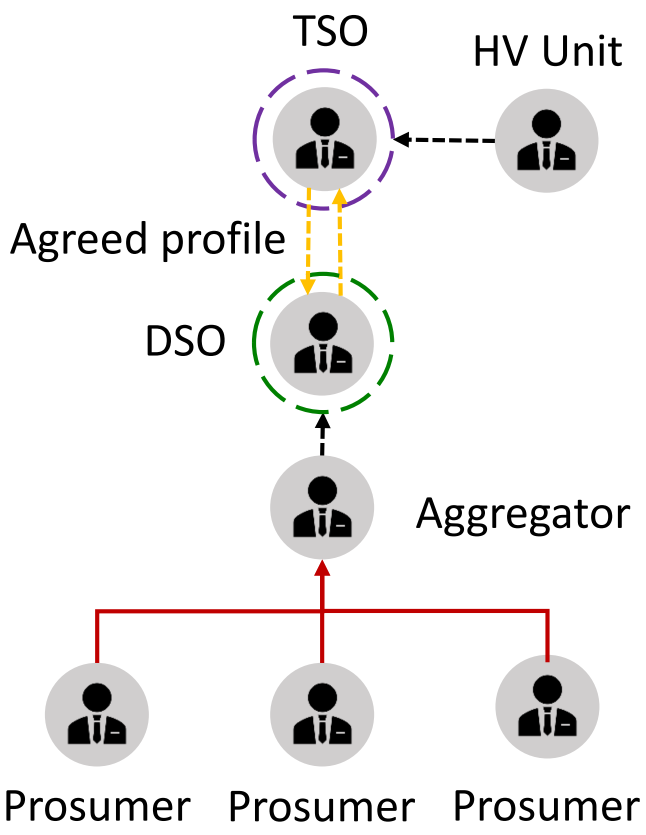
Legend: ↑ Aggregation ↑ Pre-qualification ↑ Market bids ↑ Agreed Profile ◯ Centralized Market ◯ Local Market

Possible TSO/DSO coordination schemes

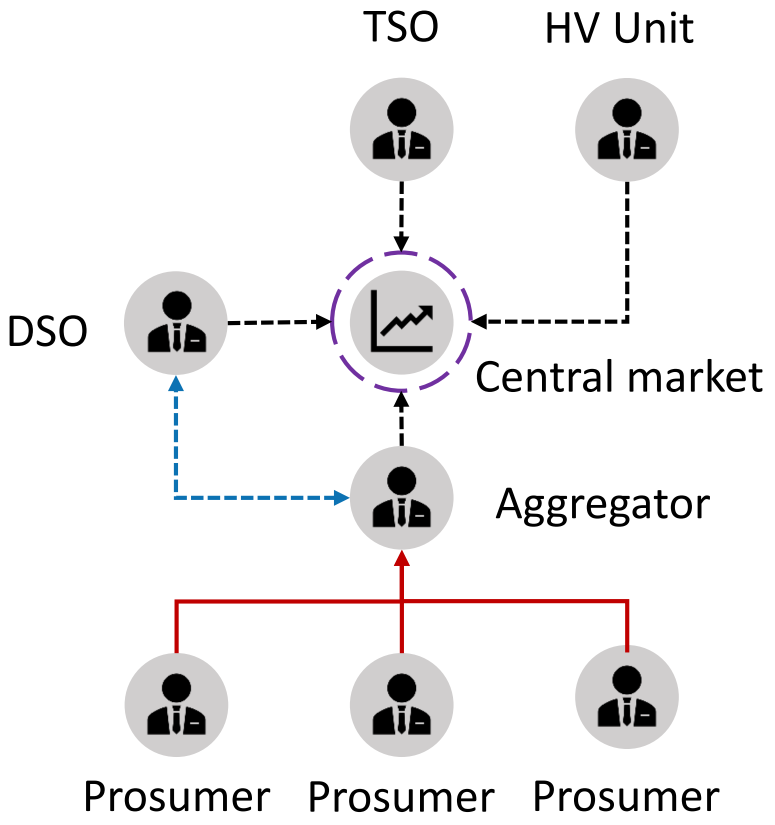
MM2 – Local AS Market Model



MM3 – TSO/DSO Agreed Profile Model



Common TSO-DSO AS Market Model



Legend: ↑ Aggregation ↑ Pre-qualification ↑ Market bids ↑ Agreed Profile ◌ Centralized Market ◌ Local Market

Market frameworks and distribution network management

- ❑**MM3 allows avoiding the pre-qualification** stage while allowing a double effect (ancillary services for transmission and distribution networks)

- ❑Based on MM3, **Demand Response** could be strongly incentivized (including prosumers and storage-capable loads)

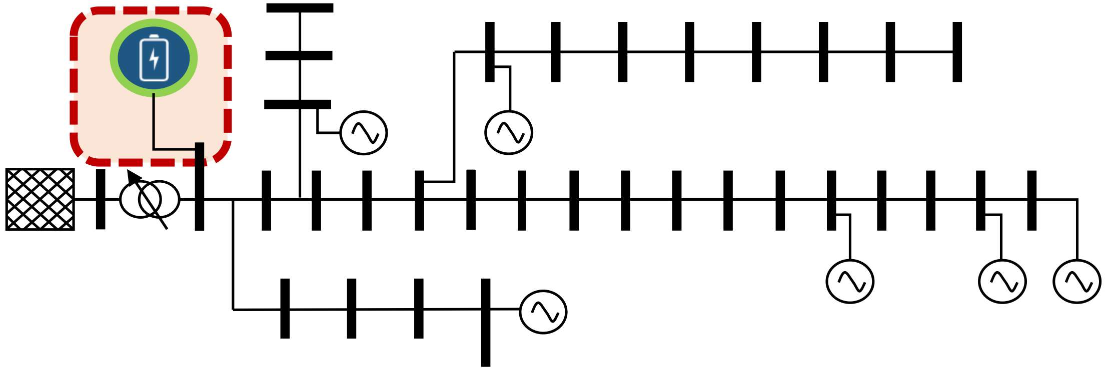
- ❑First application of MM3 on a reference distribution network:
  - ➢Base scenario: Simple control of the power profile at the interface
  - ➢Advanced scenario: optimal dispatching of distribution network with distributed units
  - ➢Full smart grid scenario: application of spot prices (price signals at the MV network buses)

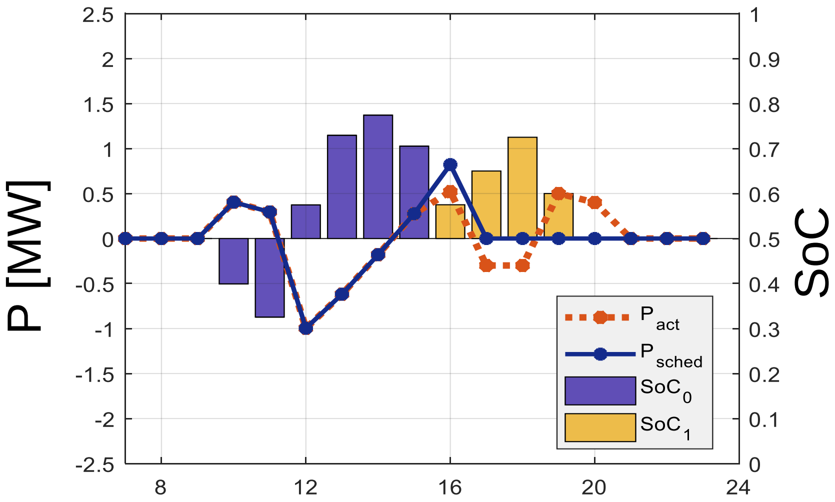
Example of TSO/DSO coordination: MM3 application

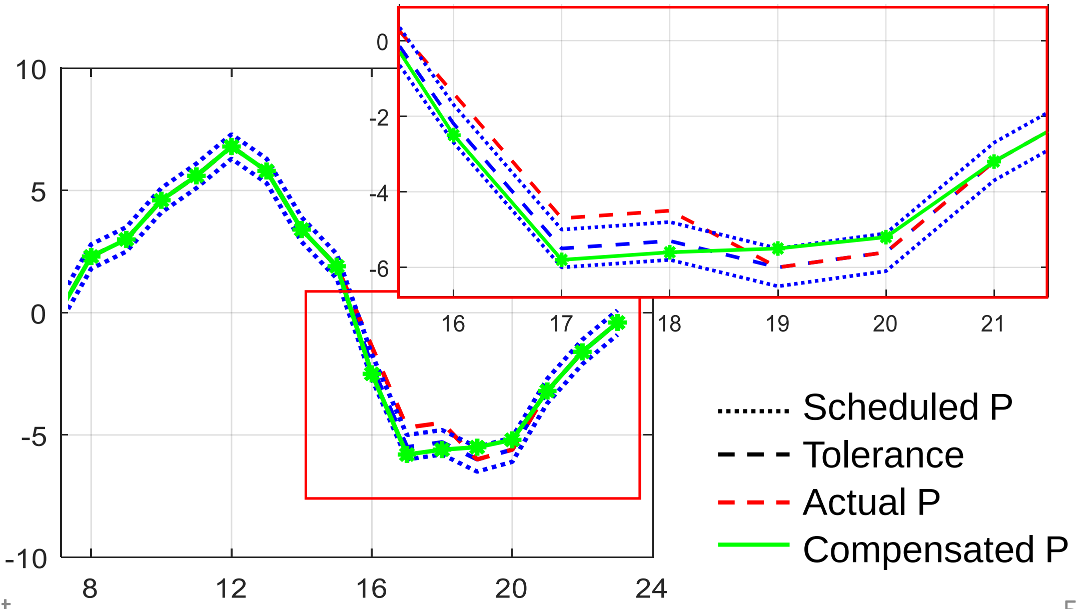
Base scenario:

Simple control of the power profile at the interface

- ☐ DSO is in charge of keeping the power exchange profile close to forecast
- ☐ DSO can manage a storage unit close to PS (**central unit**)







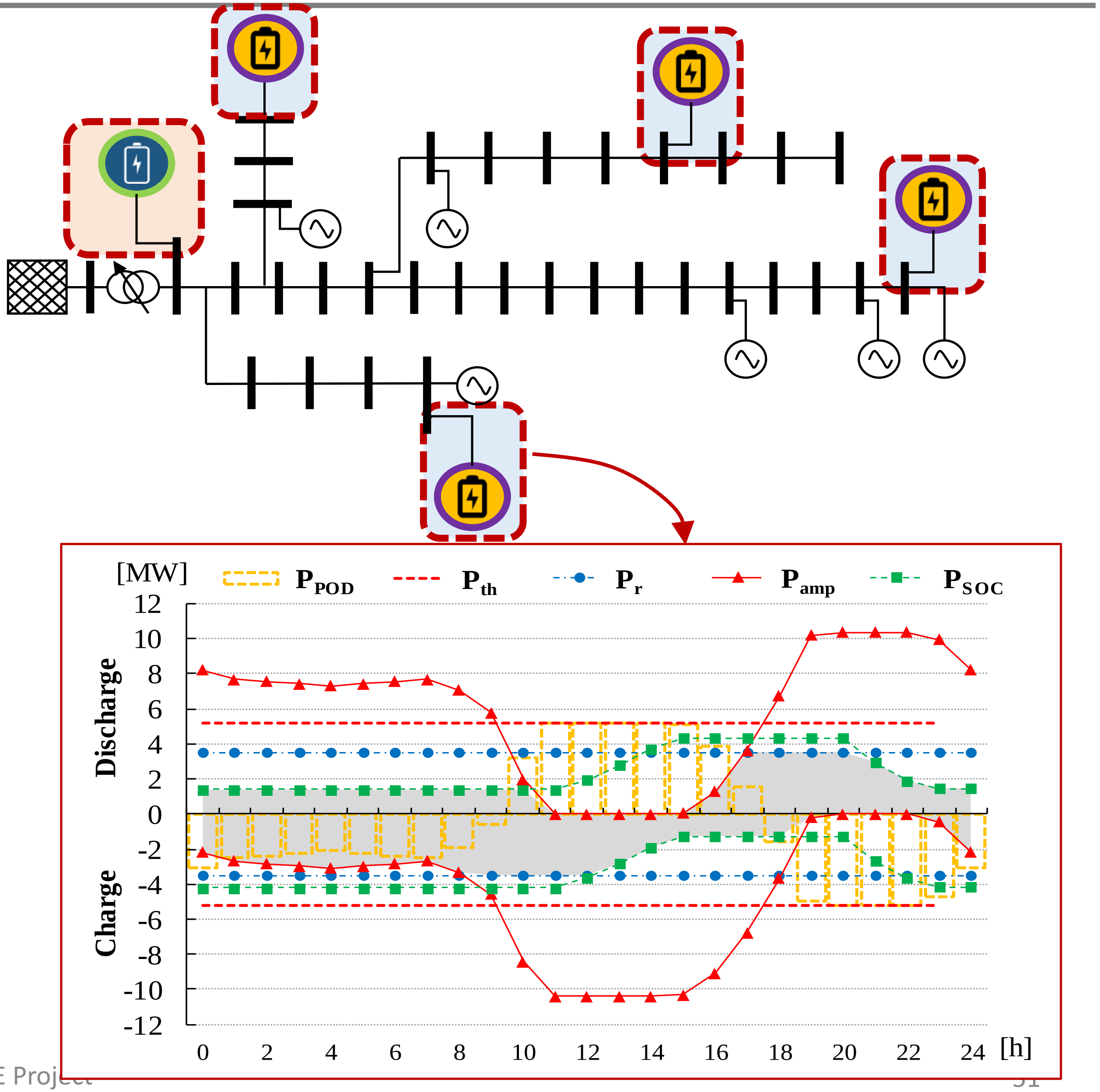
Example of TSO/DSO coordination: MM3 application

Advanced scenario:

optimal dispatching of distribution network with distributed units

Distributed Energy Storage units dispatched by the DSO on the basis of **technical constraints** on:

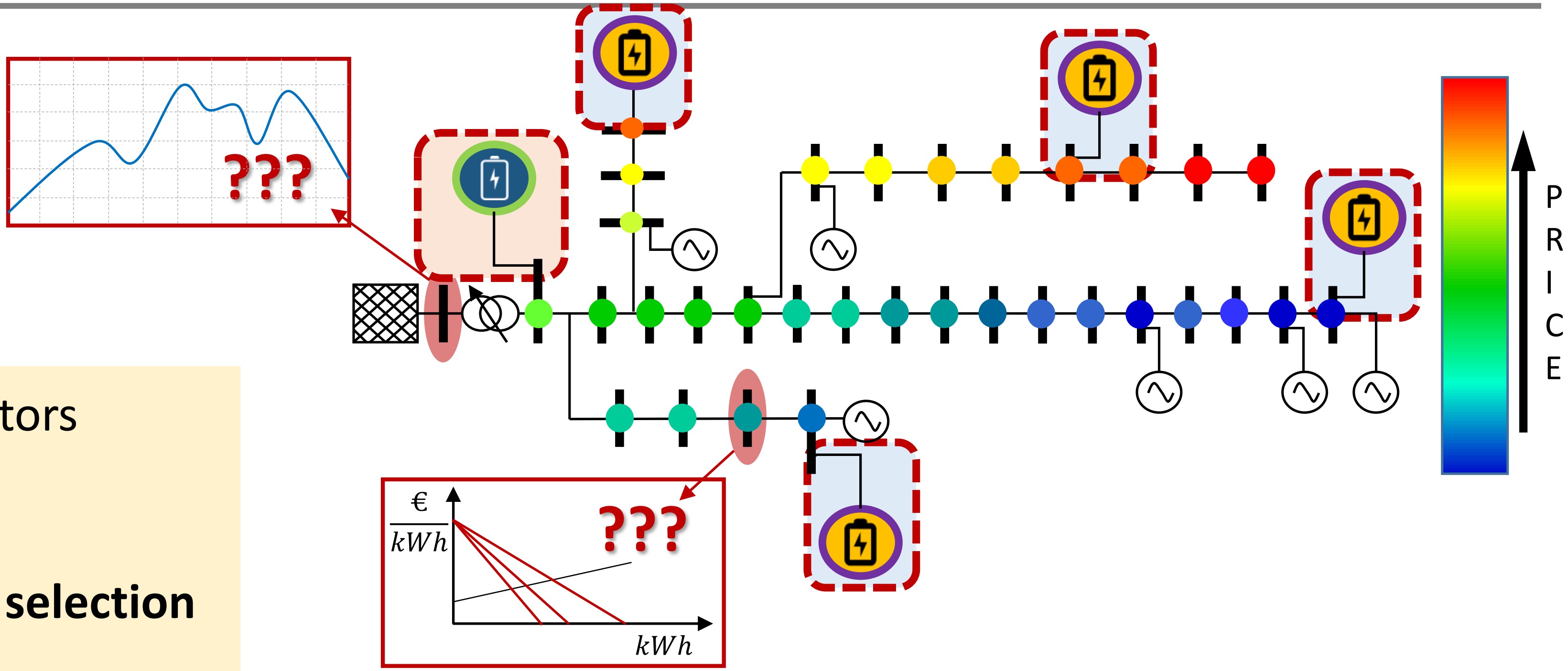
- ❑ The network: lines ampacity, voltage …
- ❑ The storage: SOC max/min, discharging cicle



Example of TSO/DSO coordination: MM3 application

Full smart grid scenario:

application of spot prices



Competition among end-users/aggregators enabled by **nodal price signals**

The end-users dispatching relies on the **selection of offers by the DSO** in a local market

Prices summarize information on network constraints, included those set by the DSO for dispatching

Open questions:

1. How to evaluate end-users **price elasticity**?
2. How to generate the interface power profile? (**energy+services trading?**)
3. Are the requirements by TSO and DSO in **agreement**?

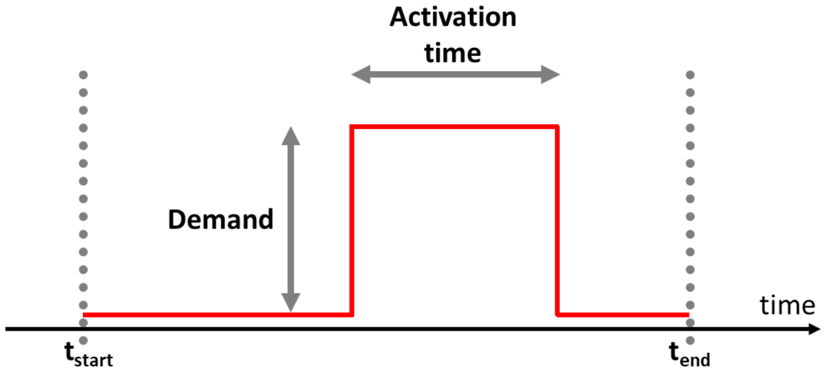
Demand Response and time-based services

- ☐ Medium Voltage (MV) network **Optimal Distribution Management System** modelling for Local Market implementation
- ☐ Modelling the behaviour of responsive users according to the **nodal prices** and **specific technology**
- ☐ **Macroscopic standpoint** (aggregated set of customers or large-scale units)
- ☐ The approach should allow to consider **time-related constraints**

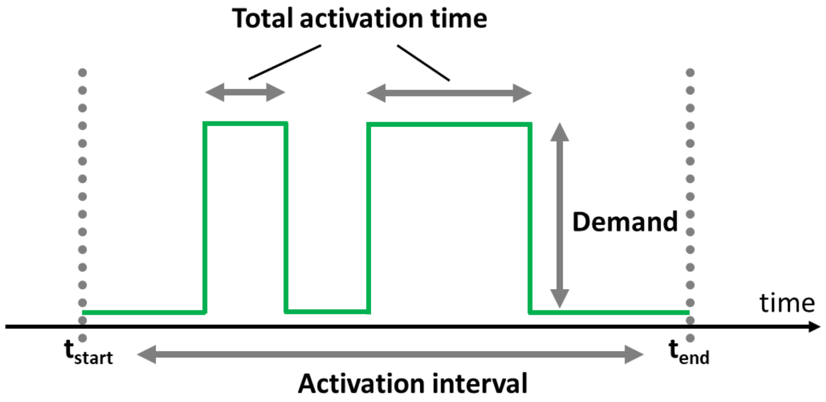
Demand Response and time-based services

Typical behaviours of responsive users:

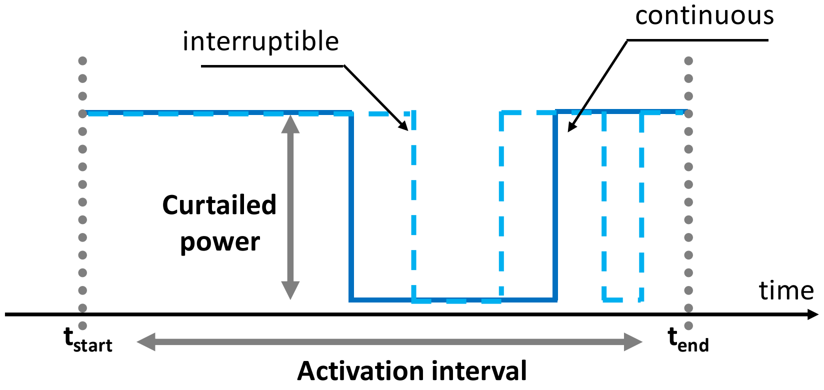
- ❑ **DR-A: Shiftable loads :**



- ❑ **DR-C: Intermittent shiftable loads**

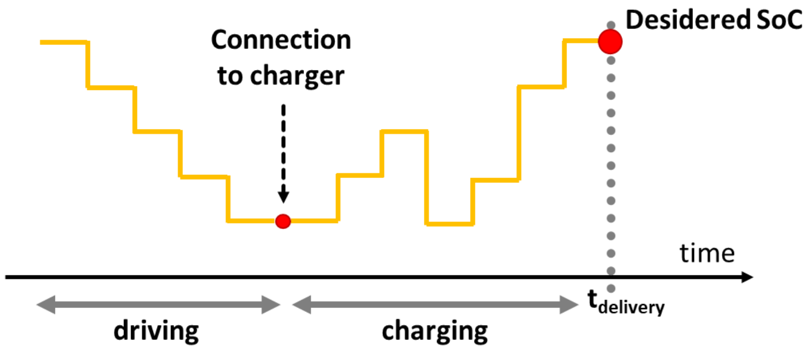


- ❑ **DR-B: Nonpreemptive loads**

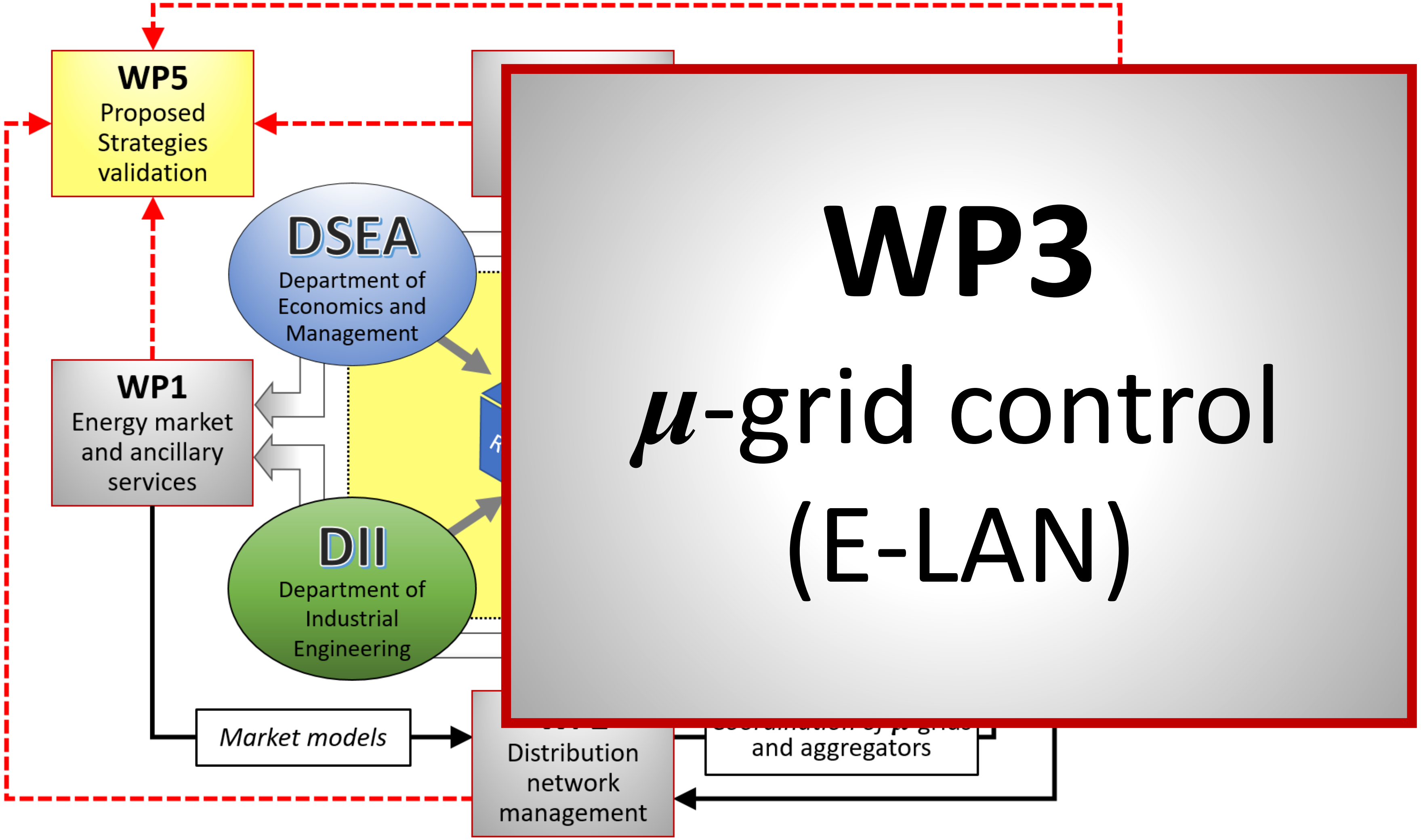


- ❑ **Mixed approaches:**

  e.g. Electric Vehicles (storage capable loads)



NEBULE Project



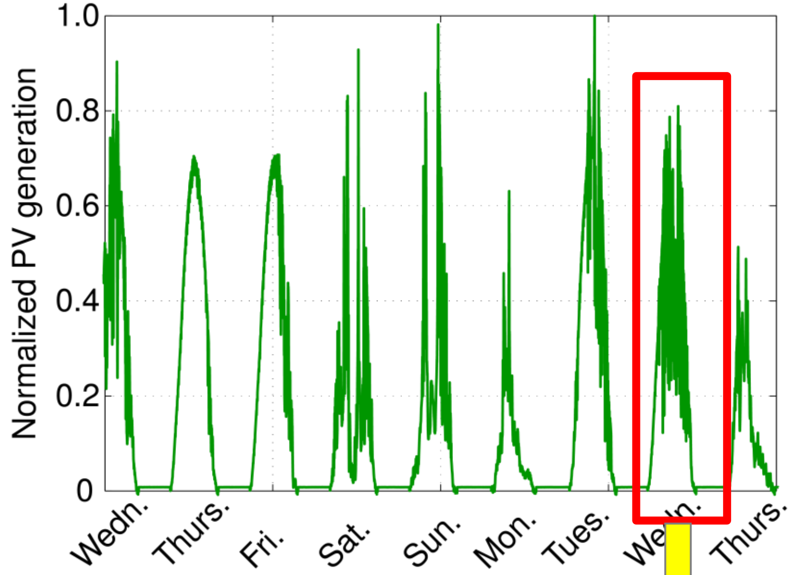
WP3

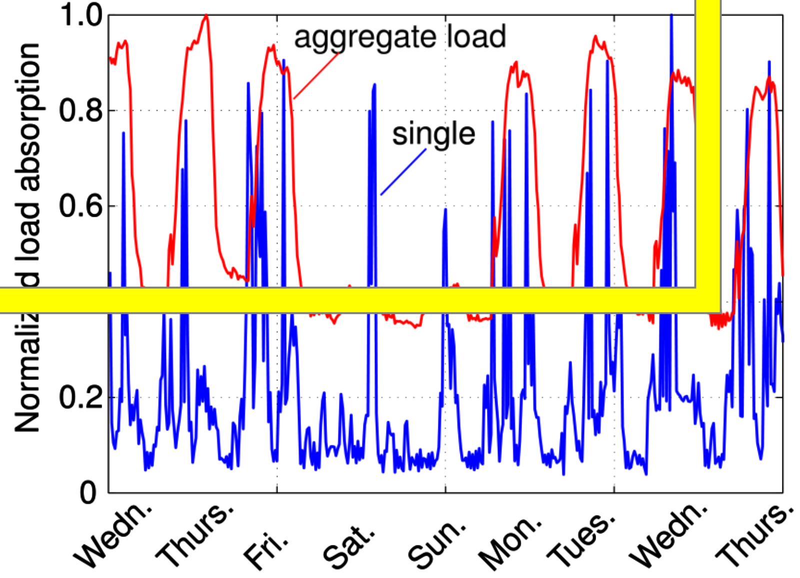
μ-grid control

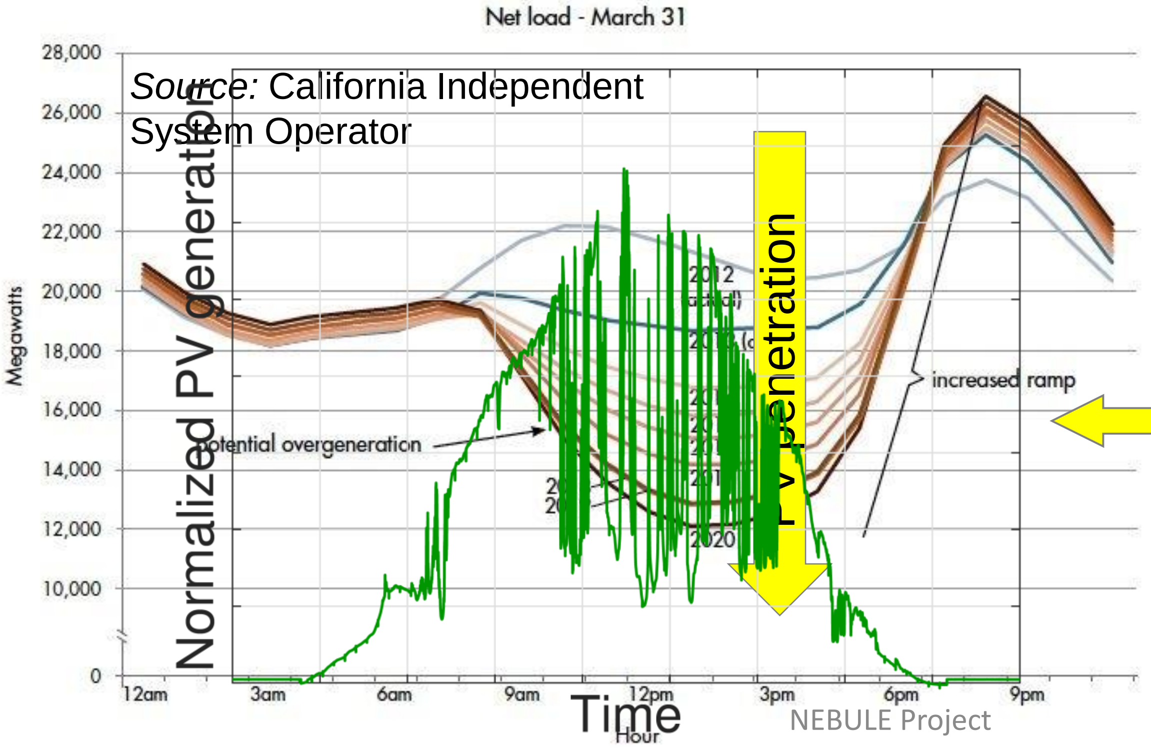
(E-LAN)

❑ Typical Features of Renewables and Loads Behaviors

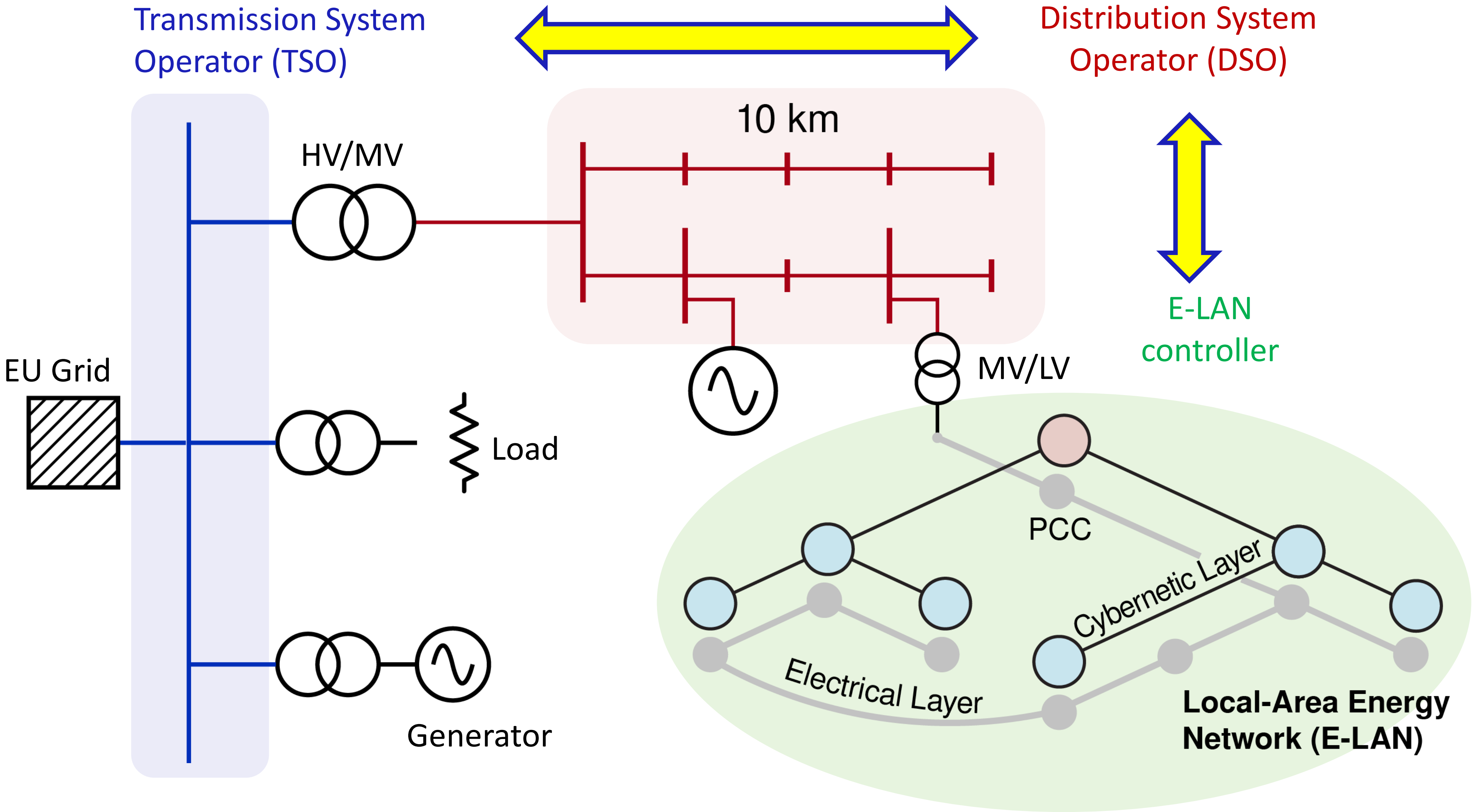
- Energy from renewables may be predicted. Generated power is intermittent.
- Aggregate loads are smoother and more predictable.
- *Remark:* generation and absorption may unfavorably combine.






Source: California Independent System Operator

❑ Considered Scenario

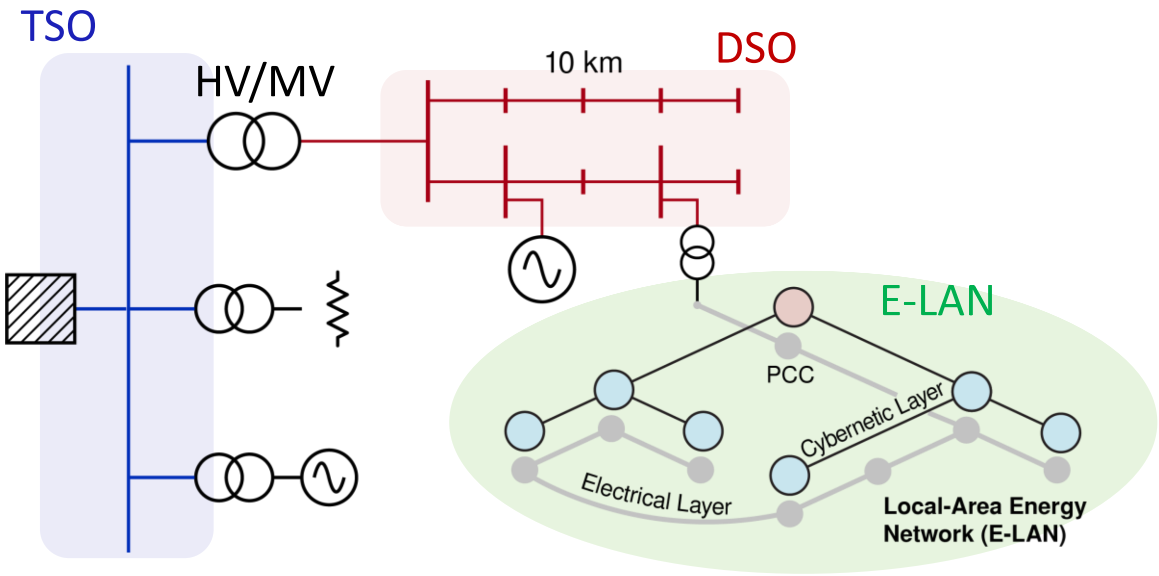


❑ Proposed Control Principle

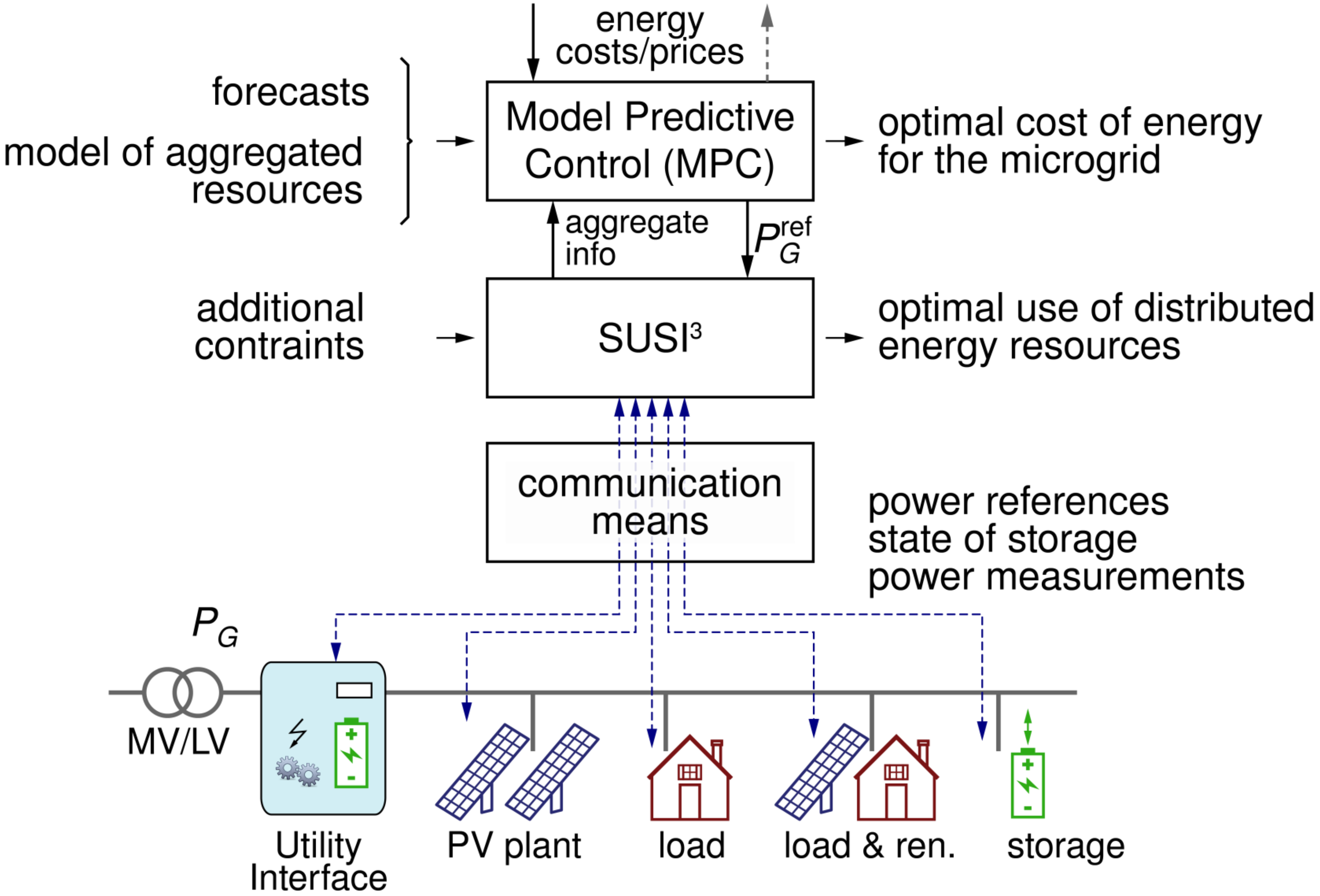
1. **DSO interacts with the TSO** to agree about a power profile at the HV/MV interface.
2. **DSO computes price signals for the E-LAN controller**, to meet commitments with TSO.
3. **E-LAN controller** defines how to use its **aggregate storage** based on the costs communicated by the DSO.
4. **SUSI^3 control optimally shares the control effort** among the distributed resources of the E-LAN.

→ Work presented in [12] and [13], DEI + DTG

→ Work presented in [11] DEI + DTG.

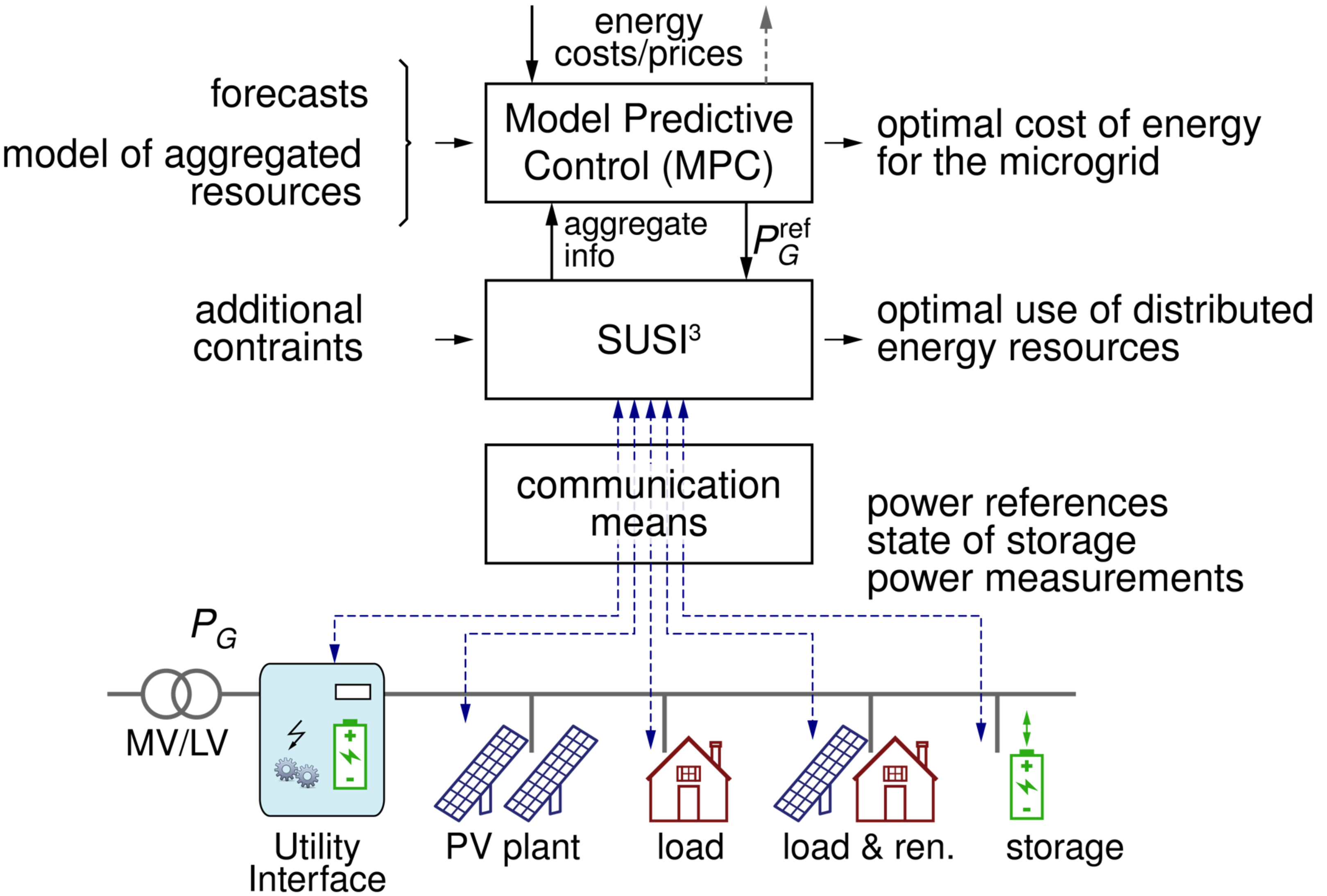


❑ Control Overview from the E-LAN Perspective



- This principle will be tested and validated in the next months.

❑ Control Overview from the E-LAN Perspective



energy costs/prices

forecasts
model of aggregated resources

Model Predictive Control (MPC)

optimal cost of energy for the microgrid

aggregate info

P_G^{ref}

additional contraints

SUSI³

optimal use of distributed energy resources

communication means

power references
state of storage
power measurements

P_G

MV/LV

Utility Interface

PV plant

load

load & ren.

storage

Tertiary control
(DEI + DTG with [12], [13])

Secondary control
(DEI + DTG with [11])

Primary control
(DTG, work in progress)

Zero-level control
(DTG with [8, 9, 12, 18])

- This principle will be tested and validated in the next months.

❑ Control of Distributed Electronic Power Converters

- Crucial aspects for adequate operation with high penetration of renewables:
  - Robust converters control
  - Rejection of grid disturbances
  - Adaptability to dynamic conditions

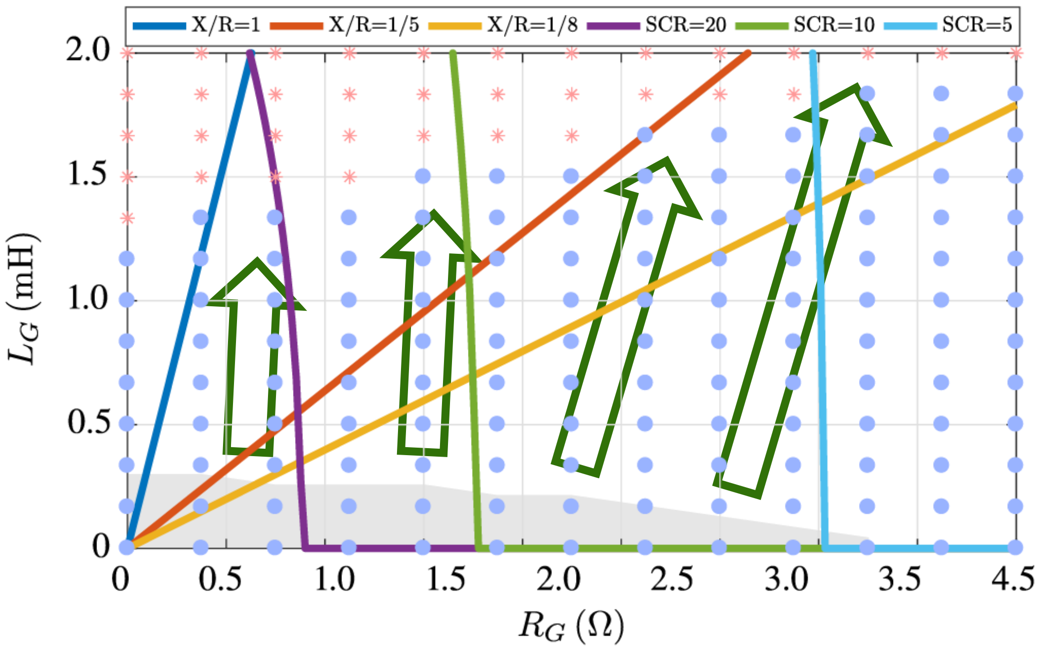
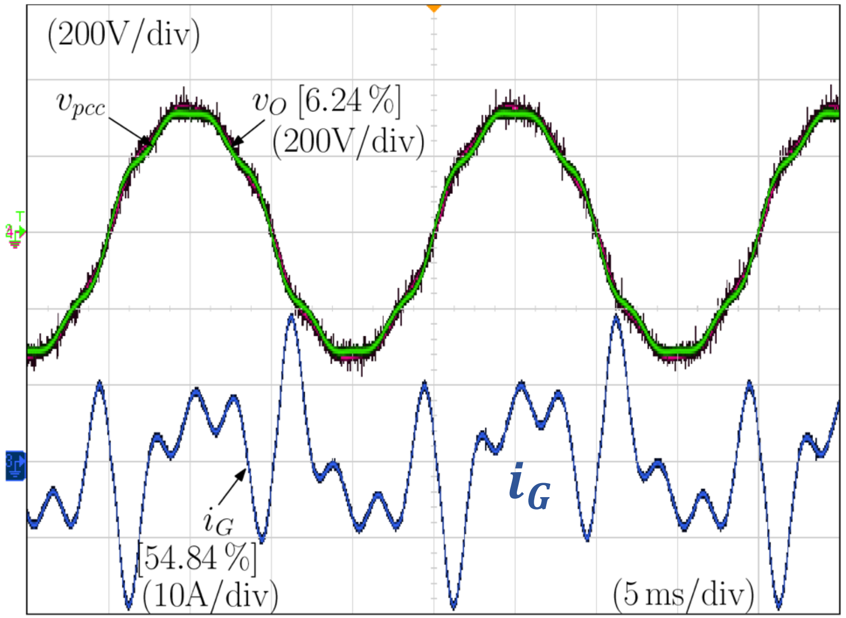


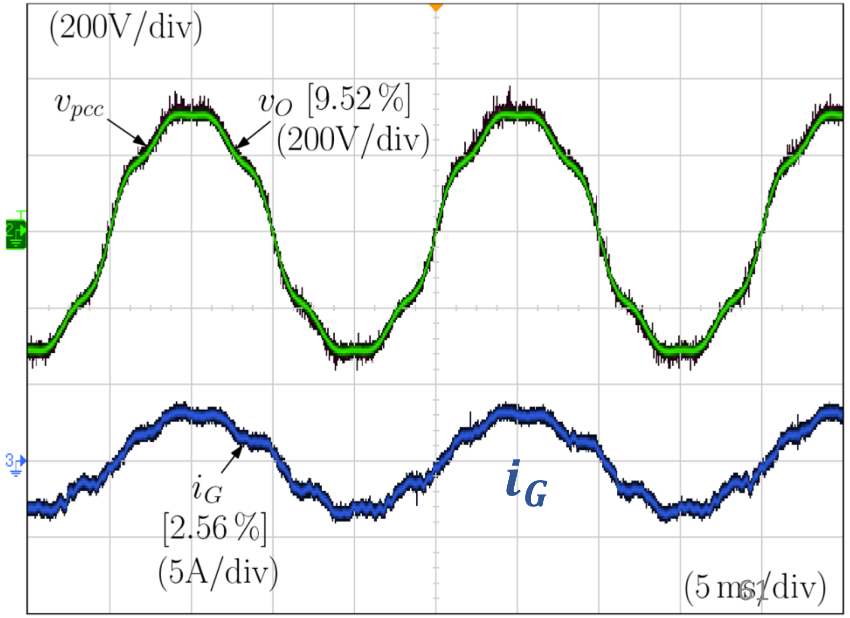
Fig. 9. Region of acceptable performance (blue dots) of the grid current loop (bandwidth ≥ 1 kHz, phase margin $\geq 45°$); red crosses indicate points of lower performance. For comparison, the shaded area is the acceptable performance region of Fig. 3.

Zero-level control

Traditional solution

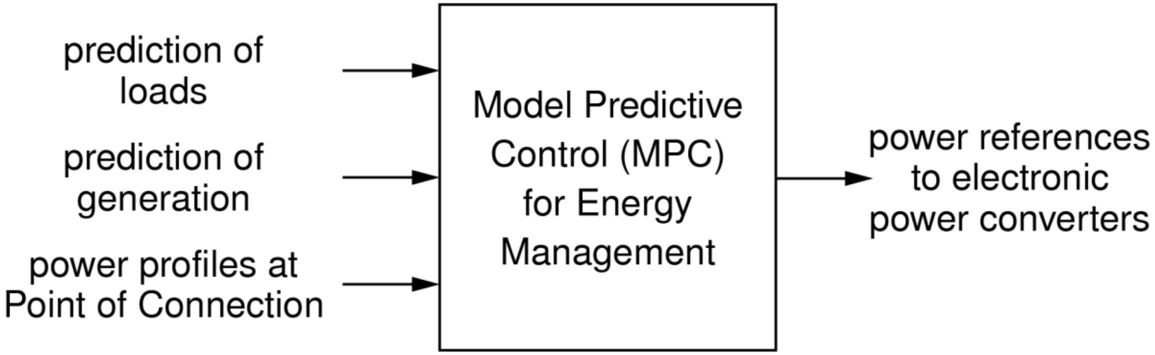
Proposed solution: much improved current i_G





❑ Model Predictive Control (MPC) Approach

- An MPC approach allows an optimal management of resources integrating relevant information on:
  - Plant model
  - Forecasts of generation
  - Forecasts of loads
  - Energy price variabilities

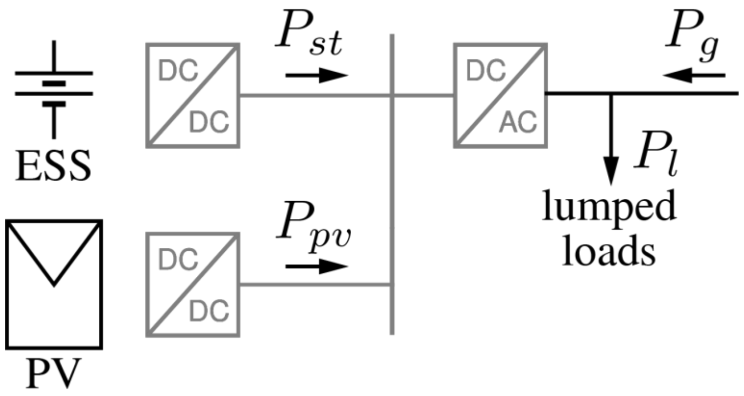

prediction of loads

prediction of generation

power profiles at Point of Connection

Model Predictive Control (MPC) for Energy Management

power references to electronic power converters



In this application: the available information of load absorption & PV generation exploited for the best use of storage, improved behavior seen at the point of connection with the upstream grid, and economic cost minimization.

❑ Example of MPC Application (1)

$$\min_{P_{st},\,P_{pv}} J = \min_{P_{st},\,P_{pv}} \left(\sum_{k=1}^{N_p} c_t \left| P_g(k) - P_g^*(k) \right| + \sum_{k=1}^{N_p} c_{ESS} |P_{st}(k)| + \sum_{k=1}^{N_p} c_{ESS} \left(c_0 + c_1 |P_{st}(k)| + c_2 P_{st}^2(k) \right) \right)$$

$$E_{st}^{+} = E_{st} - \Delta T P_{st} \qquad P_l = P_g + P_{st} + P_{pv}$$

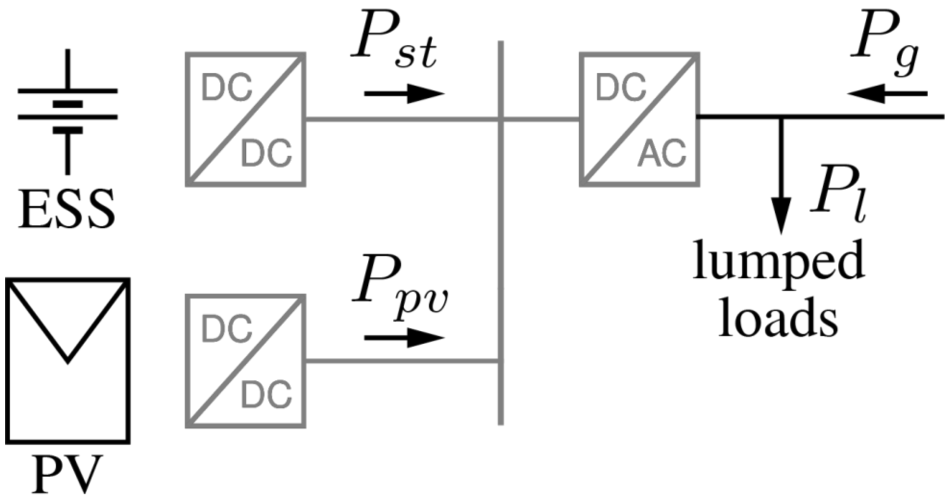
where N_p is the prediction horizon.

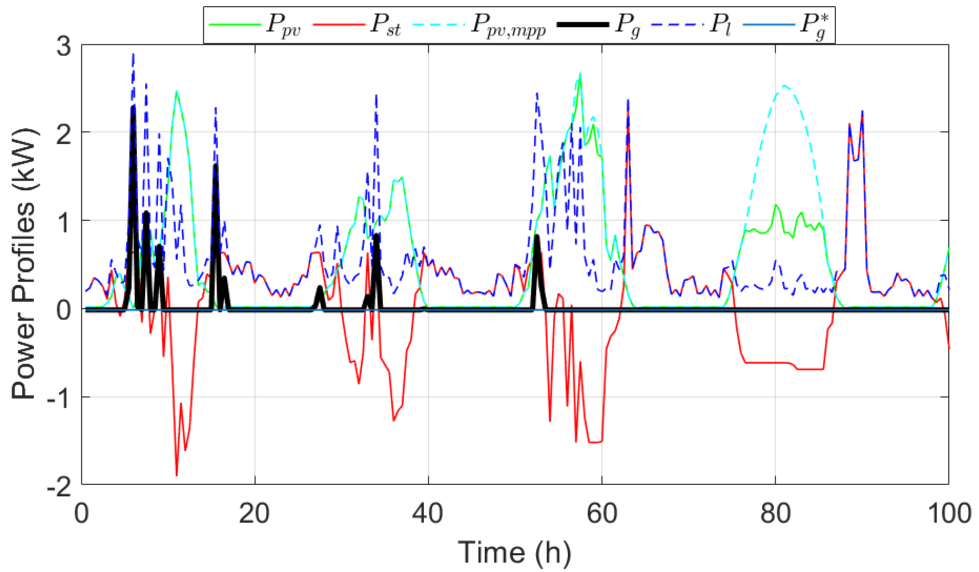
The cost function considers:

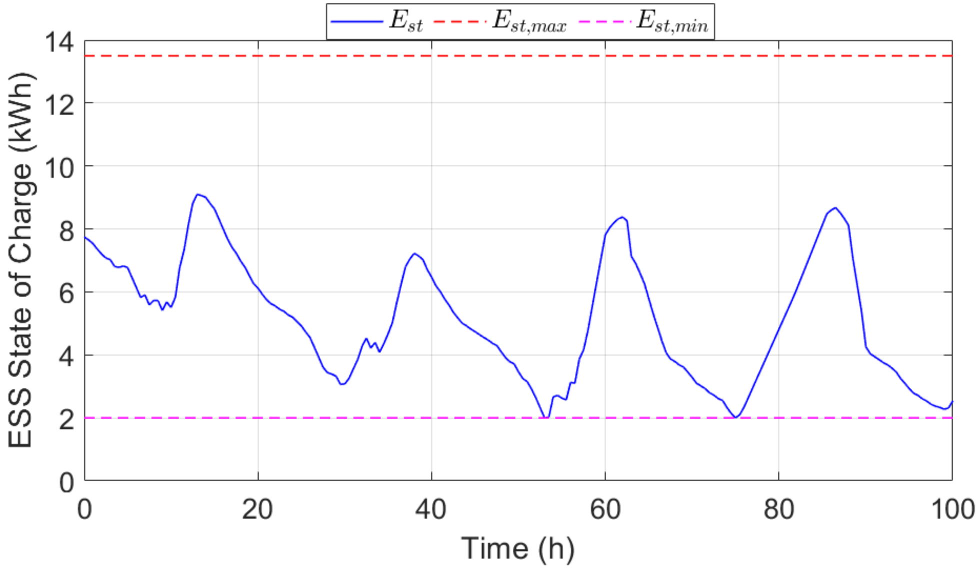
1. the **deviation from the set reference** P_g^*; c_t is the tracking error cost, measured in €/kWh
2. the **wearing of the battery**, on the basis of its economic cost C_{ESS}, the expected cycle lifetime N_{cy}, and the capacity $E_{st,N}$; $c_{ESS} = C_{ESS}/(2N_{cy}\,E_{st,N})$, measured in €/kWh
3. the **power loss of the battery-interface converters**

❑ Example of MPC Application (1)

- The MPC-based approach allows to attain a desirable power exchange at the PoC, which is valuable in microgrids and power systems
- The predictive solution provides limited stress to the battery with respect to standard control approaches







❑ Example of MPC Application (2)

$$\min_{P_{st}} J = \min_{P_{st}} \left(\sum_{k=1}^{N_p} \frac{1}{2} c_a \left(P_g(k) + \left|P_g(k)\right|\right) + \sum_{k=1}^{N_p} \frac{1}{2} c_v \left(P_g(k) - \left|P_g(k)\right|\right) + \sum_{k=1}^{N_p} c_{ESS} |P_{st}(k)| \right)$$

$$E_{st}^{+} = E_{st} - \Delta T P_{st} - \Delta T P_c \qquad\qquad P_l = P_g + P_{st} + P_{pv}$$

where N_p is the prediction horizon. P_c is the power loss of the converters:

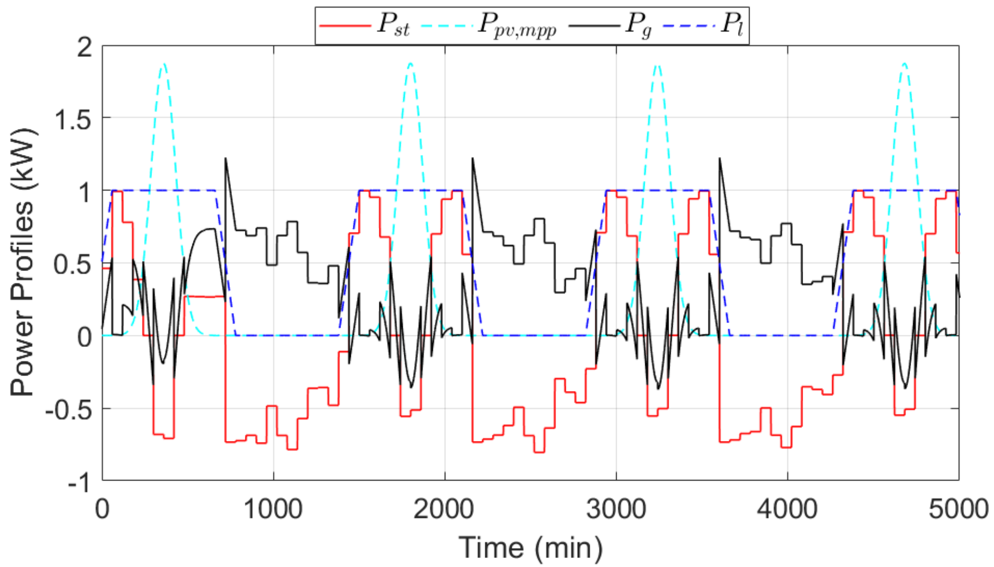
$$P_c = c_2 P_{st}^2 + c_1 |P_{st}| + c_0$$

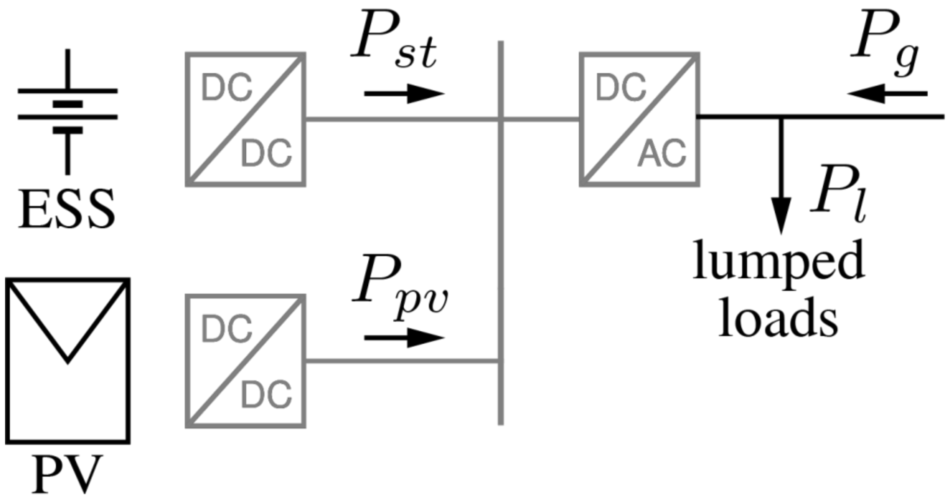
The cost function considers:

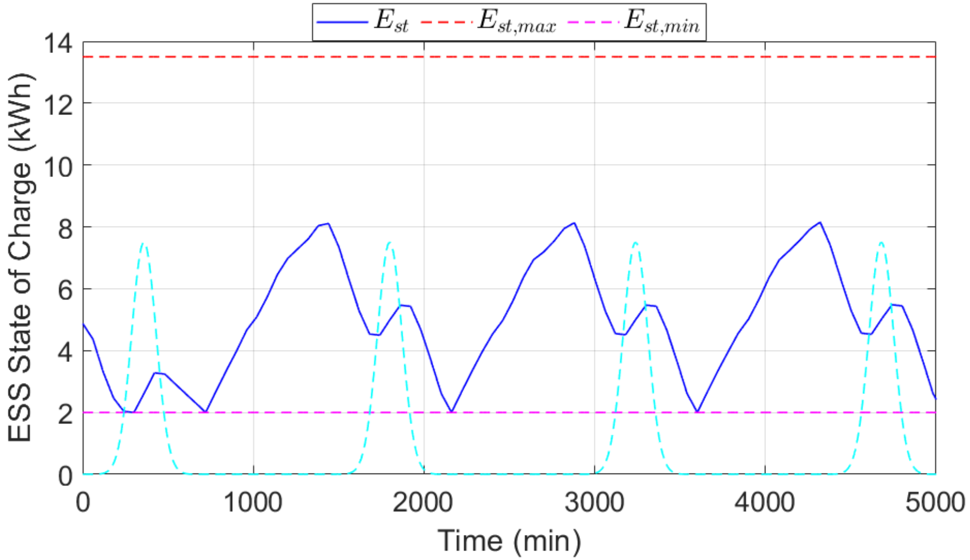
1. the **cost of buying energy**, c_a is the cost coefficient, measured in €/kWh
2. the **profit of selling energy**, c_v is the profit coefficient, measured in €/kWh
3. the **wearing of the battery**, on the basis of the coefficient c_{ESS}, measured in €/kWh

❑ Example of MPC Application (2)

- Cost of energy lower at night
- The MPC exploits the electrical grid during night to charge the storage
- The predictive approach improves the performances in terms of economic cost minimization with time-varying electricity prices



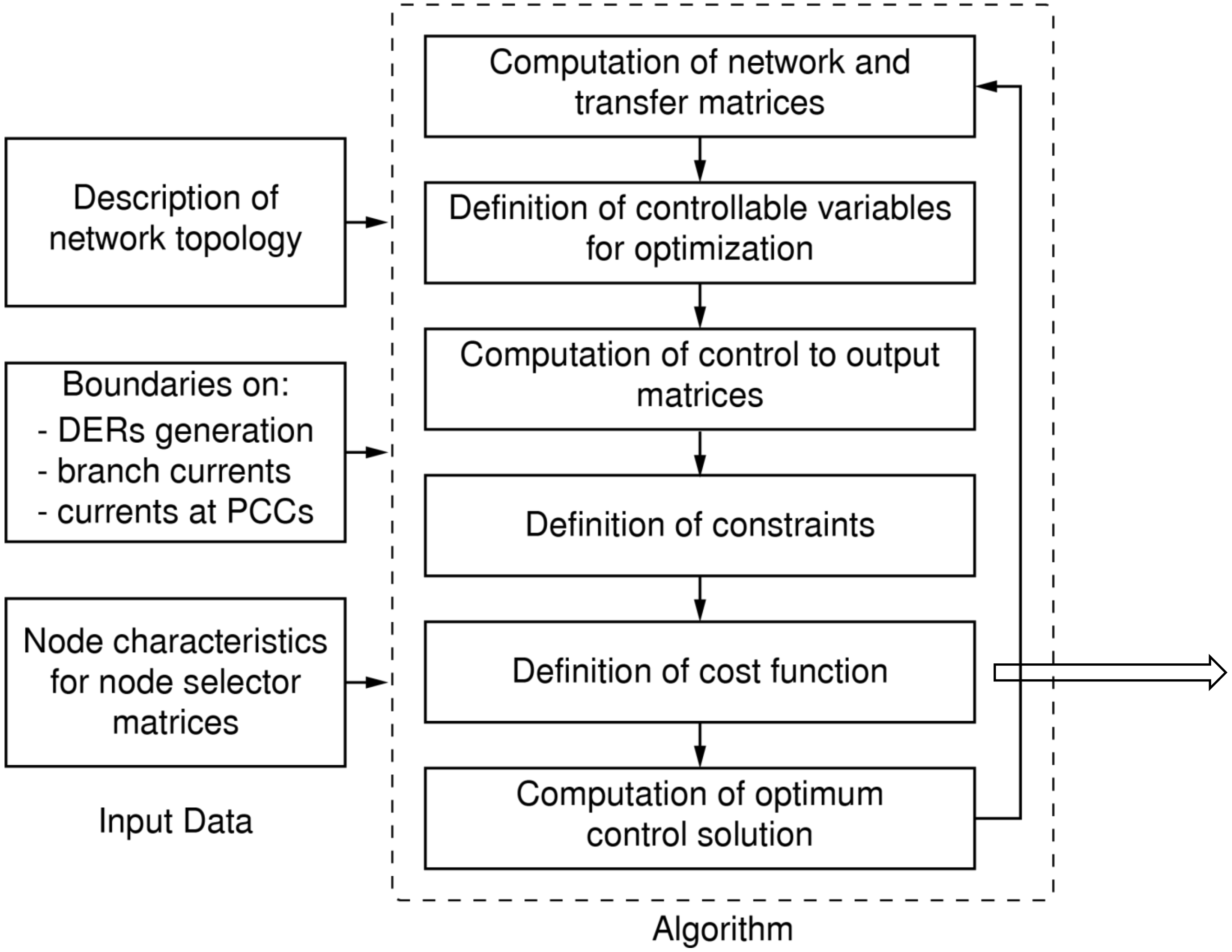




❑ SUSI^3

- SUSI^3 : Smart Users & Sources Integration, Interconnection and Interplay.
- Optimal control considering ***i)* network model**, ***ii)* set of constraints on power flows**, ***iii)* cost function**.
- Allows to:
  - Independent demand-response at multiple points of connection to DSOs (distribution system operators);
  - Active and reactive power steering through specific grid paths;
  - Active compensation of load unbalance;
  - Active clearing of currents for servicing grid lines;
  - Voltage profile regularization;
  - Limitation of stresses in feeders & grid-tied devices.

❑ SUSI^3



Description of network topology

Boundaries on:
- DERs generation
- branch currents
- currents at PCCs

Node characteristics for node selector matrices

Input Data

Computation of network and transfer matrices

Definition of controllable variables for optimization

Computation of control to output matrices

Definition of constraints

Definition of cost function

Computation of optimum control solution

Algorithm

1. RMS voltage deviation at grid nodes.
2. Power loss in sources & distribution feeders.
3. Power stress in sources and grid-tied inverters (including saturation effects).
4. …

Further details in [11].

❑ Example of Results

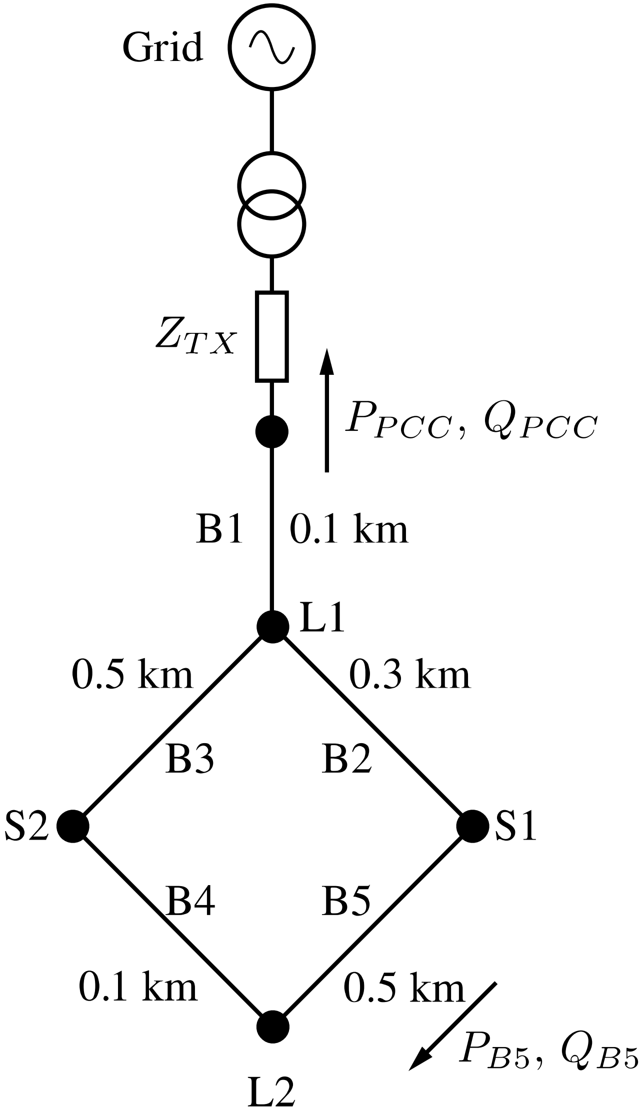
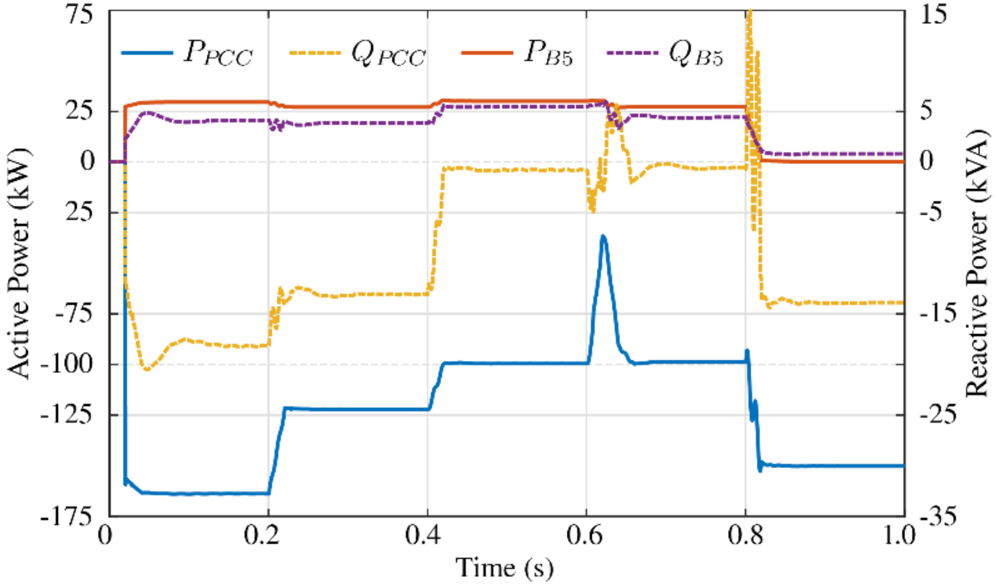


Table 1: Parameters of Application Example #1

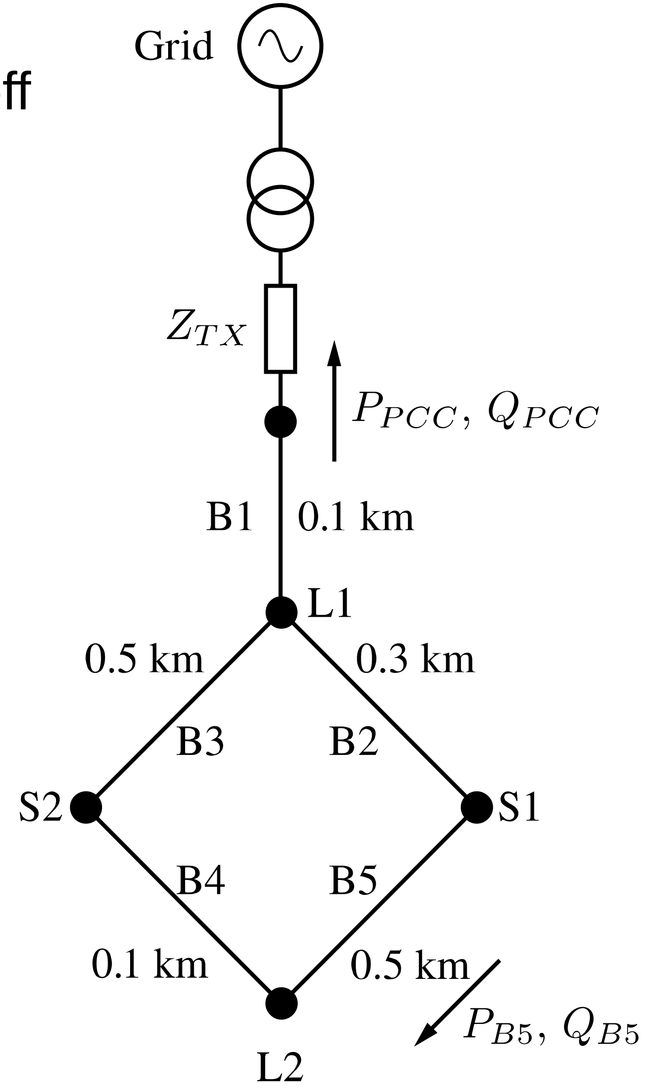
Operating Conditions	
Voltage amplitude	230 V
Grid frequency	50 Hz
Cable Parameters per km	
Phase Cable	0.163 Ω, 0.433 mH
Neutral Cable	0.490 Ω, 0.150 mH
Transformer Parameters	
Turns ration	20 kV - 230 V
Nominal frequency	50 Hz
Short-circuit impedance	$10e^{j\pi/4}$ mΩ
Load Connection and Parameters	
L1:	a-n 40 kW, cos ϕ = 0.97 b-n 20 kW, cos ϕ = 0.97 c-n 10 kW, cos ϕ = 0.97 b-c 20 kW, CF= 3
L2:	constant power load of 90 kW, cos ϕ = 0.99
Source Parameters and Connections	
S1:	three-phase plus neutral connection
S2:	connected between phase b and c
Efficiency	92%

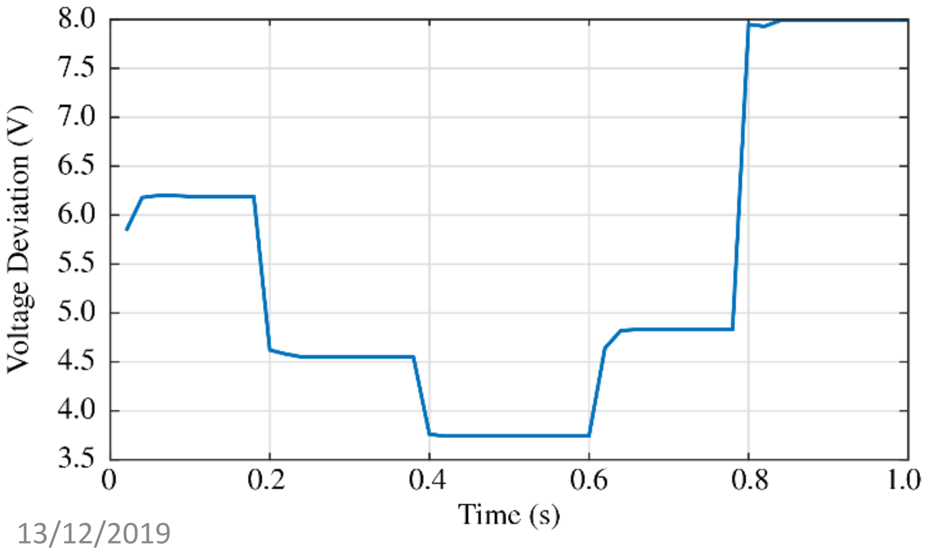
❑ Example of Results

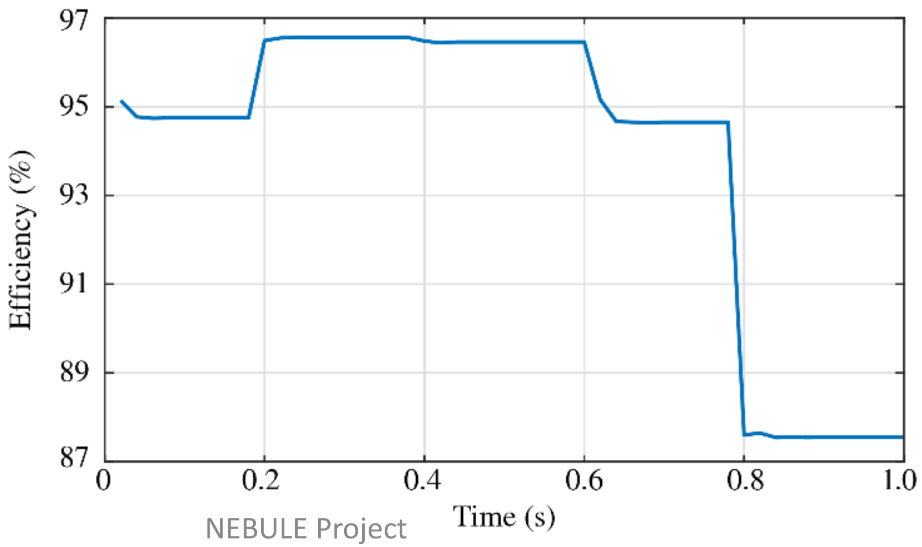


Control settings:

- 0.0 – 0.1 s no control, sources off
- 0.2 – 0.4 s optimal control, no constraints
- 0.4 – 0.8 s demand-response at PCC, 100 kW
- 0.8 – 1.0 s power steering at branch B5, 0 kVA



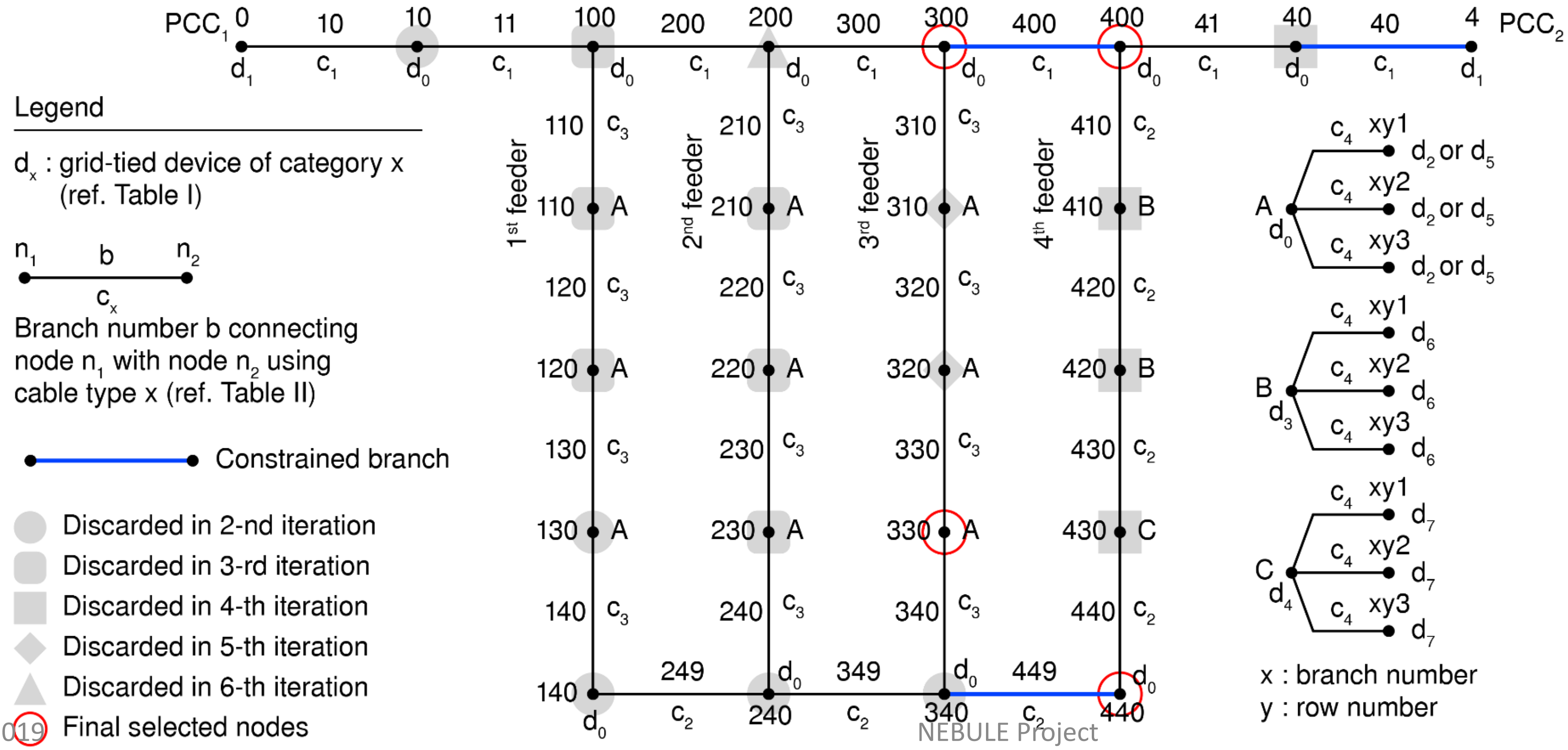




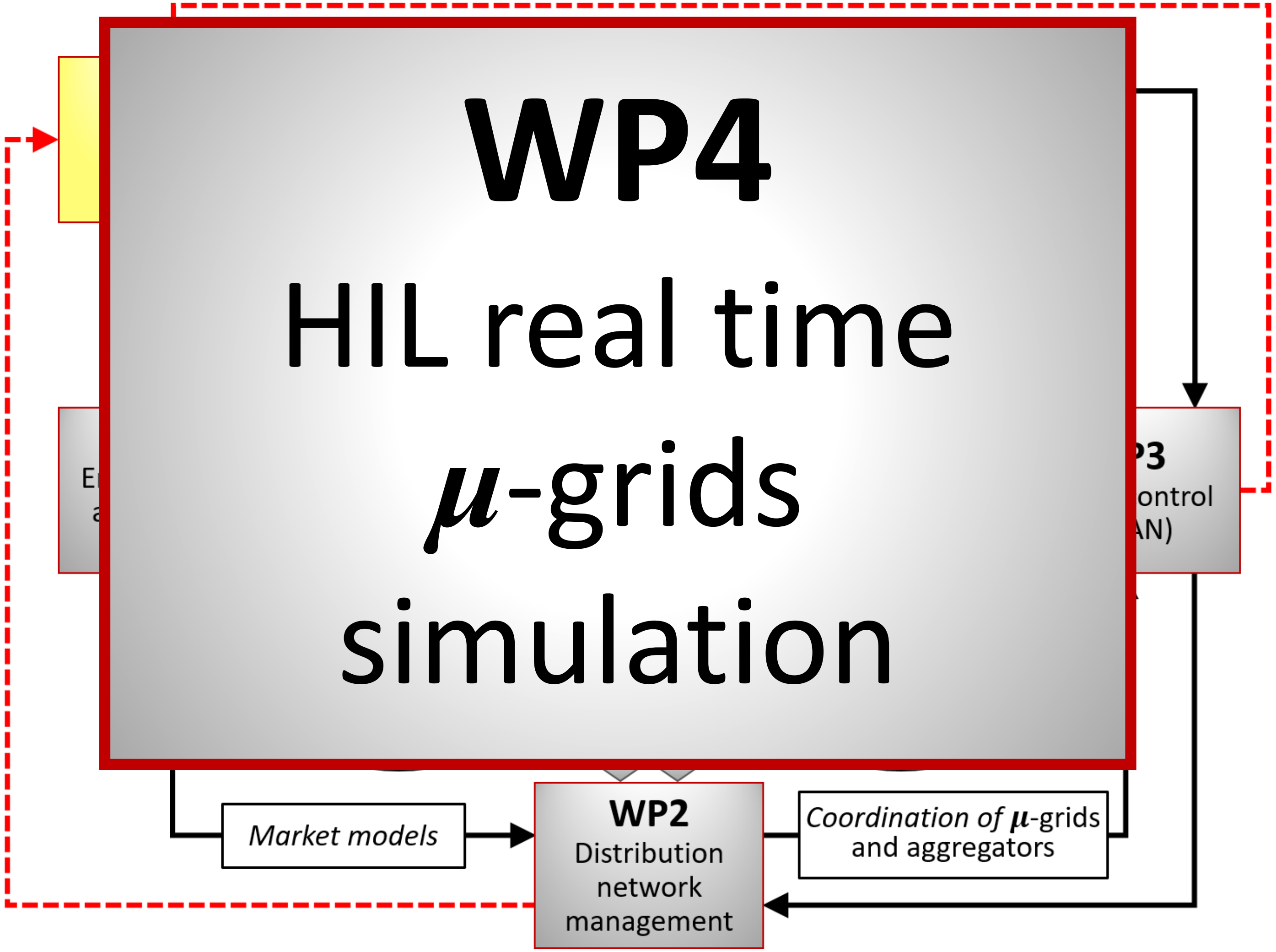
❑ Research Questions & Related Outcome

1. How distributed energy storage should be located & sized to facilitate E-LAN management? ➡ Further details in [7].

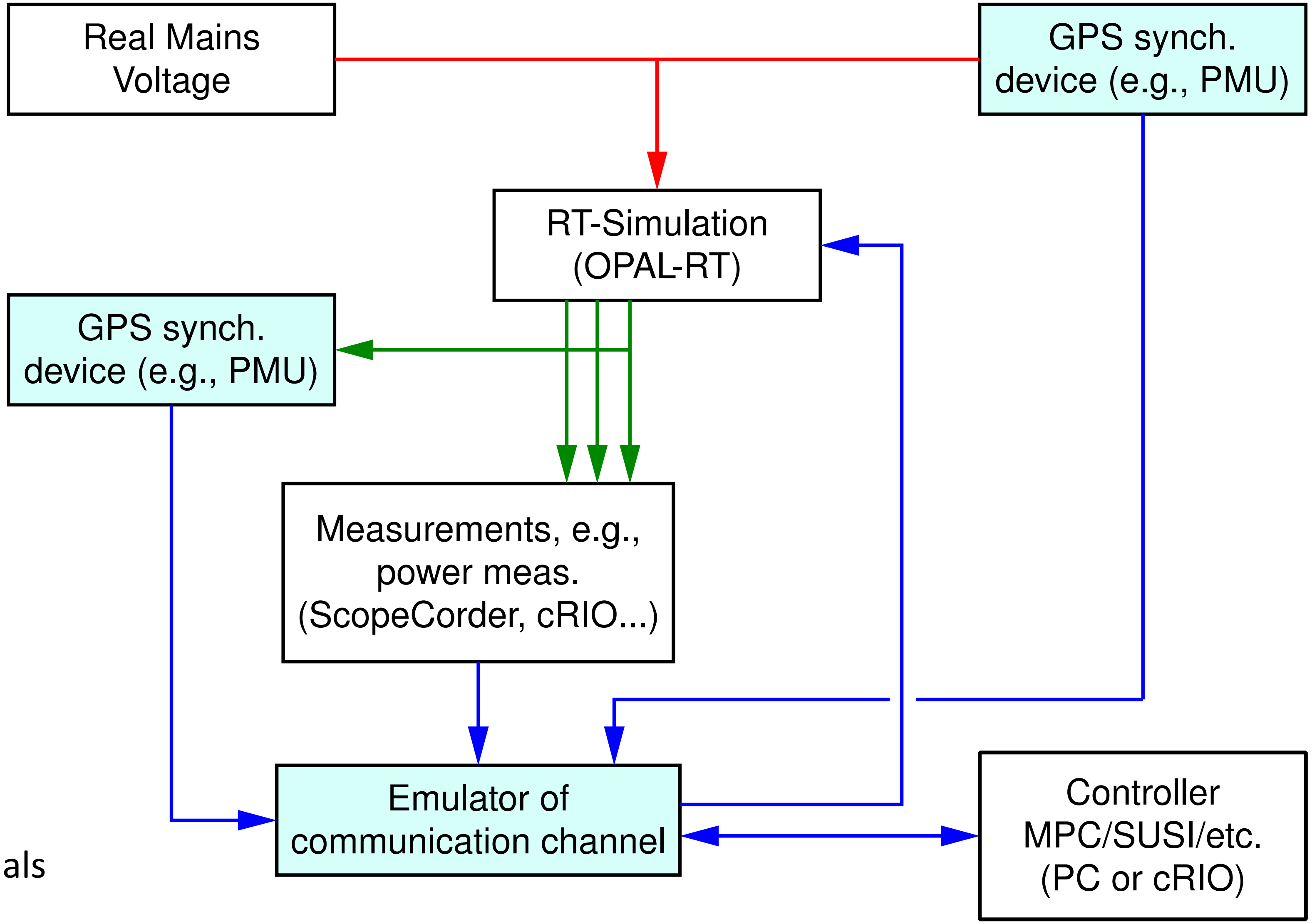
2. Microgrid controller reacting to price signals at the MV bus
   ⇒ interaction with local market?



NEBULE Project



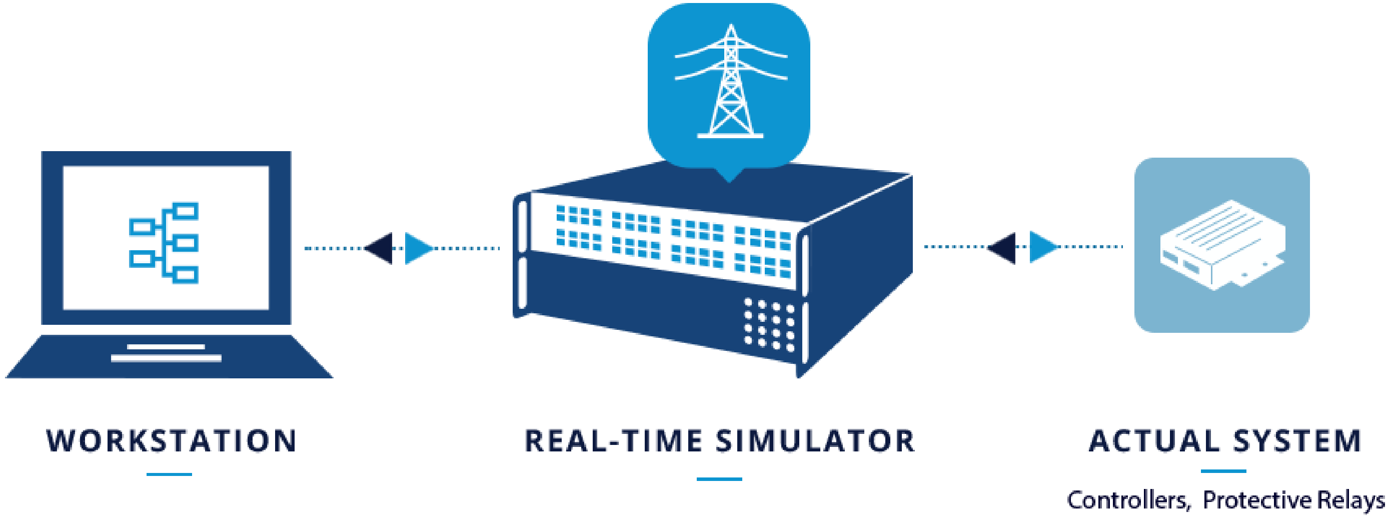
❑ Real-Time Simulation Testbench



- Blue: ethernet
- Red: LV grid
- Green: AO signals

❑ Real-Time Simulation

- RT Simulation: computer simulation running synchronously with the wall-clock-time to allow the interaction with real (non-simulated) elements taking part to the testing.
- Useful to:
  - Consider of the actual behavior of real subsystems.
  - Test final controllers implementations by interfacing them to an emulated version of the plant.



❑ Synchronization

- Synchronization is required for a coordinate operation of converters at the system's frequency and phase.
- Synchronization is crucial for:
  - Islanded to grid-connected transition of a microgrid (phase & time).
  - Distributed harmonic compensation.
  - Supporting multi-microgrid operation.
  - Knowing absolute time for economic transactions.
- Goal: Analyze the performance achievable by standard commercial synchronization units.

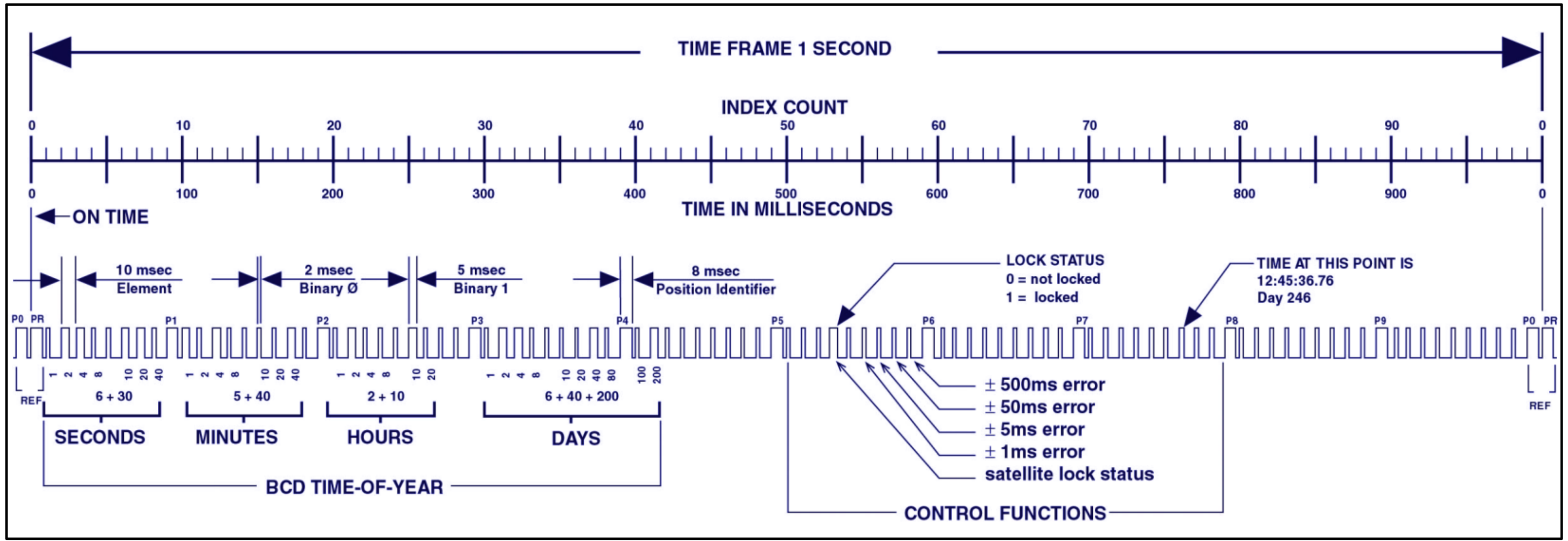
❑ Synchronization

SEL-2401

Satellite-Synchronized Clock

Compact, precision-time device for limited space and high-accuracy timing to ±100 nanoseconds.

Typically Ships in 5 Days



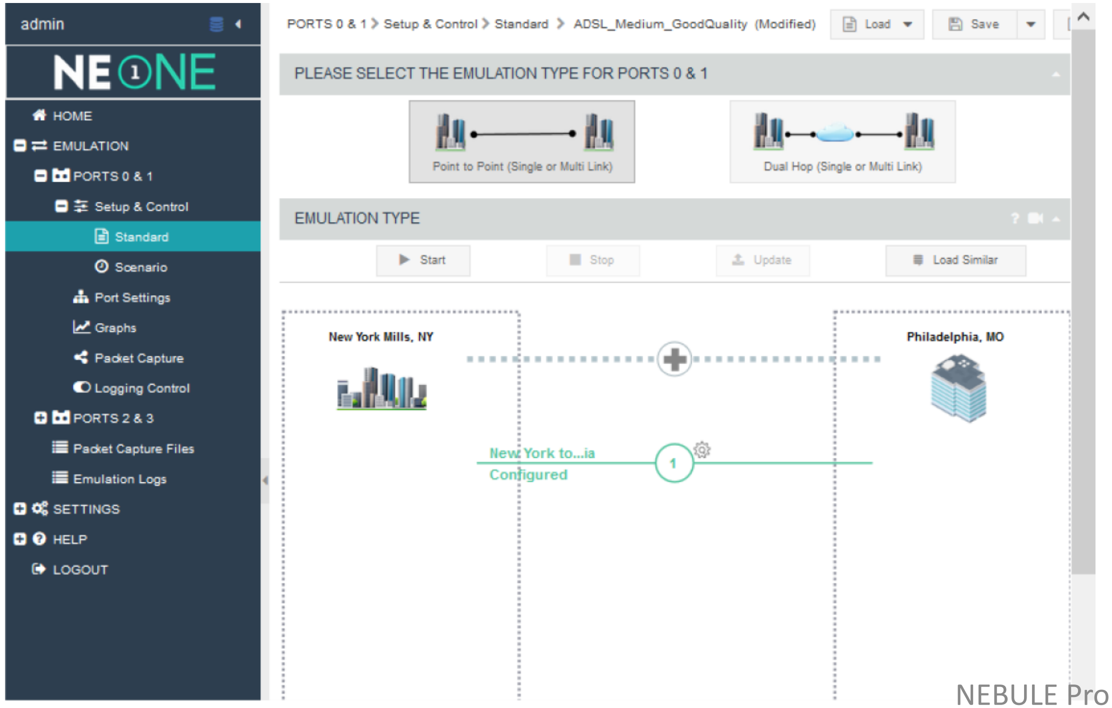
❑ Communication

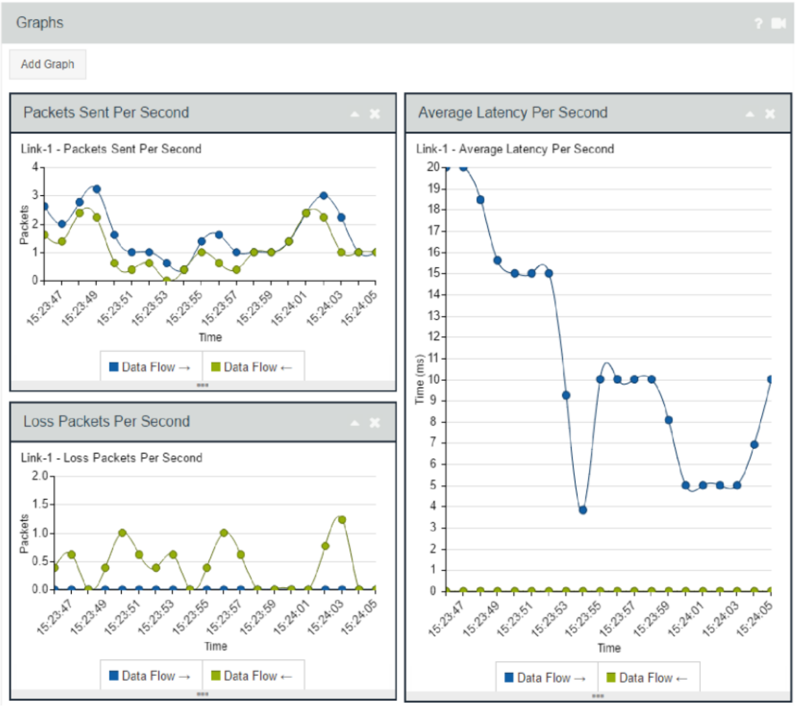
- Communication is generally required for centralized and distributed control.
- Microgrid control requires communication to:
  - acquire data from distributed resources.
  - send control signals to distributed resources.
- But communication issues exist, like, delays, packet loss, corruption, duplication, reordering, rate limits.
- Are our control algorithms robust against such real-world issues

Network Emulator

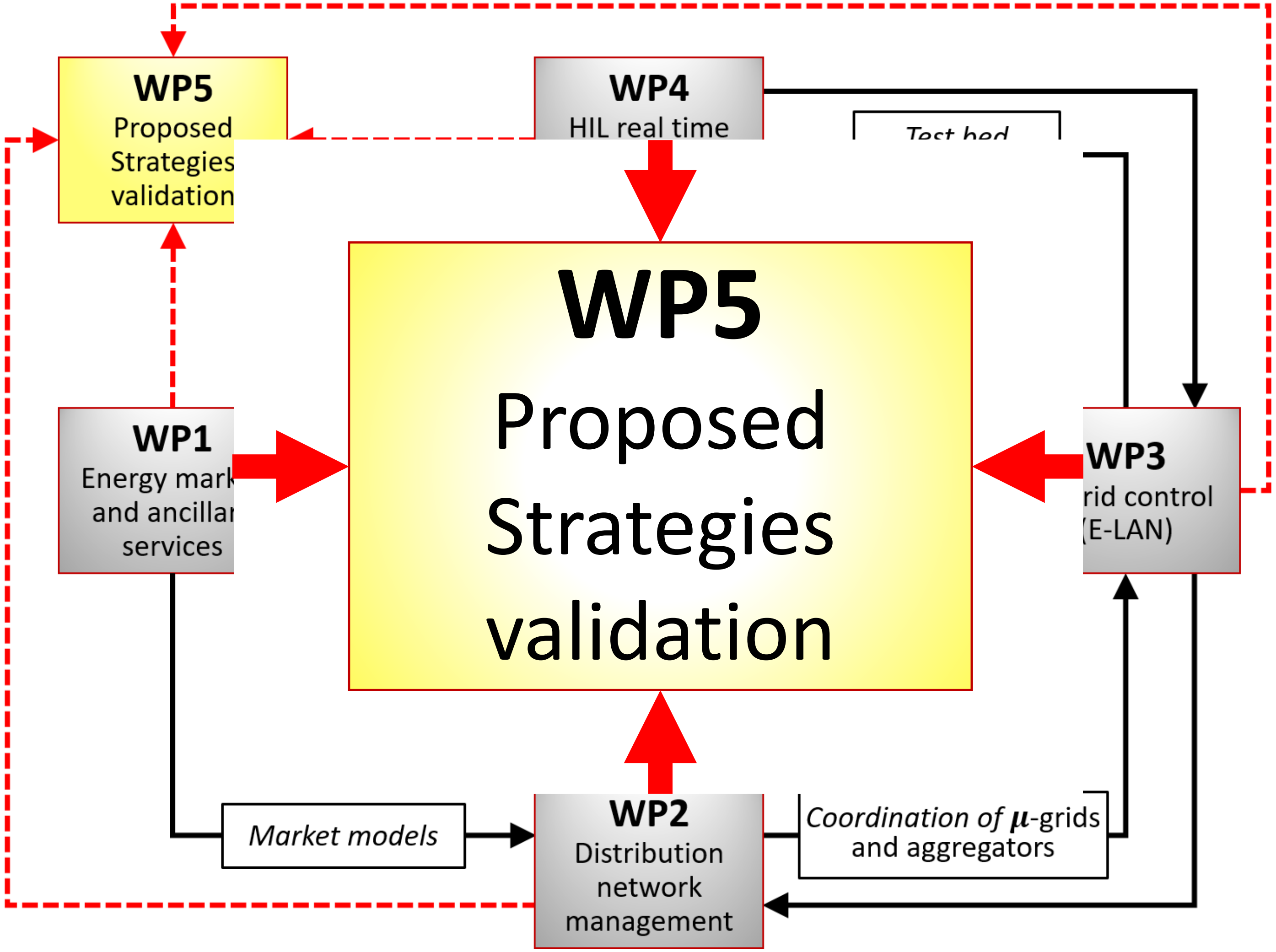
- Emulates real communication links by including delays and other characteristics to packets going through the device.
- Emulates dynamical changes in the communication link quality.
- Collects statistics about channel use.

NE-ONE Model 10





NEBULE Project: future work



WP5
Proposed
Strategies
validation

WP4
HIL real time

Test bed

WP5
Proposed
Strategies
validation

WP1
Energy mark
and ancillar
services

WP3
rid control
(E-LAN)

Market models

WP2
Distribution
network
management

Coordination of μ-grids
and aggregators

Project dissemination (Journal papers)

[1] Blasi, S., and Sedita, S.R. "The diffusion of a policy innovation in the energy sector: evidence from the collective switching case in Europe." Industry and Innovation (2019): 1-25.

[2] Blasi, S. Brigato, L., and Sedita S. R. "Eco-friendliness and fashion perceptual attributes of fashion brands: an analysis of consumers’ perceptions based on Twitter data mining." Journal of Cleaner Production (2019): 118701.

[3] Marina Bertolini, Marco Buso, Luciano Greco, “Competition in Smart Distribution Grids”, submitted for publication to Energy Policy

[4] M. Agostini, F. Bignucolo, M. Coppo, R. Turri, “Partecipazione della generazione distribuita nel controllo integrato delle reti MT e BT”, in L’Energia Elettrica, 2019

[5] M. Coppo, F. Bignucolo, R. Turri, “Sliding time windows assessment of storage systems capability for providing ancillary services to transmission and distribution grids”, submitted for publication to Applied Energy

[6] J.M. Schwidtal, M. Agostini, F. Bignucolo, A. Lorenzoni, “Flexibility from Distributed Energy Resources: a critical review of the innovative Italian UVAM project”, submitted for publication to Energy Policy

[7] P. Tenti and T. Caldognetto, "A General Approach to Select Location and Ratings of Energy Storage Systems in Local Area Energy Networks" in IEEE Transactions on Industry Applications. doi: 10.1109/TIA.2019.2932679

[8] Q. Liu, T. Caldognetto and S. Buso, "Stability Analysis and Auto-Tuning of Interlinking Converters Connected to Weak Grids" in IEEE Transactions on Power Electronics, vol. 34, no. 10, pp. 9435-9446, Oct. 2019. doi: 10.1109/TPEL.2019.2899191

[9] S. Buso, T. Caldognetto and Q. Liu, "Analysis and Experimental Characterization of a Large-Bandwidth Triple-Loop Controller for Grid-Tied Inverters" in IEEE Transactions on Power Electronics, vol. 34, no. 2, pp. 1936-1949, Feb. 2019. doi: 10.1109/TPEL.2018.2835158

[10] Guido Cavraro, Tommaso Caldognetto, Ruggero Carli, and Paolo Tenti, "A Master/Slave Approach to Power Flow and Overvoltage Control in Low-Voltage Microgrids" Energies 2019, 12(14), 2760; https://doi.org/10.3390/en12142760

[11] P. Tenti and T. Caldognetto, "On Microgrid Evolution to Local Area Energy Network (E-LAN)," in IEEE Transactions on Smart Grid, vol. 10, no. 2, pp. 1567-1576, March 2019.

[12] Q. Liu, T. Caldognetto and S. Buso, "Review and Comparison of Grid-Tied Inverter Controllers in Microgrids," in IEEE Transactions on Power Electronics. doi: 10.1109/TPEL.2019.2957975

Project dissemination (Peer-reviewed conference papers)

[13] Enrico Mion, Tommaso Caldognetto, Francesco Simmini, Mattia Bruschetta, Ruggero Carli, "Model-Predictive Control of Electrical Energy Storage Systems for Microgrids-Integrated Smart Buildings", The Eleventh IEEE Annual Energy Conversion Congress and Exposition, Baltimore, MD, USA, sept.-oct. 2019.

[14] Tommaso Caldognetto, Mattia Bruschetta, Ruggero Carli, Enrico Mion, Francesco Simmini, Paolo Tenti, "A model Predictive Approach for Energy management in Smart Buildings", 21st IEEE European Conference on Power Electronics and Applications, Genova, Italy, sept. 2019.

[15] M. Agostini, F. Bignucolo, M. Coppo, J.M. Schwidtal, R. Turri, “Concurrent control of MV and LV networks for ancillary services provision”, in 2019 1st International Conference on Energy Transition in the Mediterranean Area (SyNERGY MED), Cagliari, 28-30 May, 2019

[16] M. Agostini, F. Bignucolo, M. Coppo, J.M. Schwidtal, R. Turri, “Ancillary services provision by aggregators and impact on distribution network operation”, in 2019 54th International Universities Power Engineering Conference (UPEC), Bucharest, 3-6 Sept., 2019

[17] F. Bignucolo, A. Lorenzoni, J.M. Schwidtal, “End users aggregation: a review of key elements for future applications”, in 2019 16th European Energy Market Conference (EEM 2019), Ljubljana, 18-20 Sept., 2019

[18] H. Abdollahi, A. Khodamoradi, E. Santi, P. Mattavelli, "Online Bus Impedance Estimation and Stabilization of DC Power Distribution Systems: A Method Based on Source Converter Loop-Gain Measurement", Applied Power Electronics Conference and Exposition, March, 2020.

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Question time