A holistic flexibility management framework for energy aggregators

Mr. Konstantinos TSATSAKIS

R&D Manager

Mr. Alexandros TSITSANIS

R&D Manager

Contact details of corresponding author

Tel: + 357 2535 5585

E-mail: kostas@suite5.eu

Address: Alexandreias 2, Bridge Tower 3013, Limassol, Cyprus

ABSTRACT

Since 2014, the strategy of the European Union has been clear: “we need to drive a clean, secure and efficient energy transition to face climate and energy challenges”. This strategy has been reinforced by the strong commitment of the European Union towards the signature of the landmark 2015 Paris Agreement as well as the ambitious “Clean Energy for All Europeans” package (EC, 2019). In addition, the EU is now in the process of updating its energy policy framework in a way that will facilitate the clean energy transition and make it fit for the 21st century. The new policy framework brings regulatory certainty and empowers European consumers to become fully active players in the energy transition and fixes two new targets for the EU for 2030: a **binding renewable energy target of at least 32% and an energy efficiency target of at least 32.5% -** with a possible upward revision with the new EU Green Deal (EC, 2021)

In the context of these key targets for the year 2030, the increasing share of Distributed Renewable Energy Sources has **become key to improve the carbon footprint of the European electricity system and achieve energy and climate change policy goals.** While these distributed ecosystems are posing serious challenges to the stability and security of the European grids, there are at the same time new opportunities for new types of power assets such as batteries, power to heat/cold solutions, vehicle to grid services etc. offering a large flexibility potential. There is an evident need for a set of efficient, cost-effective, integrated solutions, to facilitate the optimum combination of decentralised flexibility assets, both on the generation (DER -Distributed Energy Resources) side and on the demand side (V2G - Vehicle to Grid, power-to-heat/cold/gas, batteries, demand response), enabling all parties, including final prosumers, to offer their flexibility in the recently established markets creating benefits in the smart grid value chain. Towards this direction, a tool for flexibility managers is designed and developed to: (a) provide analysis and forecasting of flexibility potential from different energy sources with focus on Power-to-X (P2X) solutions incorporated in the electricity grid, (b) segmentation, classification and clustering of flexibility sources based on their location, response time, flexibility capacity and suitability to offer different types of services (c) Dynamic Virtual Power Plant (VPP) creation tools for the deployment of distribution grid optimization strategies (e.g. peak demand reduction/ increase of RES penetration/ ancillary services based on DSOs/TSOs (Distribution/Transmission System Operators), (d) Dynamic Configuration of flexibility-based VPPs (execution of what-if scenarios and selection of optimal VPPs to increase the profits obtained by means of new market options and mechanisms). In section 2 of the paper, an overview of the holistic approach along with the modeling details for the P2X framework are provided. In section 3, the business layer of the proposed framework is specified. In section 4, some words about the demonstration activities for the innovative framework are reported along with the conclusions and key remarks.

Keywords: Flexibility management, Aggregators, P2X solutions, Self-consumption, flexibility marketplace

A HOLISTIC FLEXIBILITY MANAGEMENT FRAMEWORK FOR ENERGY AGGREGATORS

Up to now, most of the research activities and commercial solutions in the area of DER flexibility management have focused mostly on specific energy sources, technologies and actors, considering only a very limited and isolated part of the whole network, missing the vast flexibility opportunities that a holistic, integrated approach to the overall energy value chain can bring. In this context, we propose a framework that aim to create and integrate synergies across all energy flexibility sources and technologies, to create the optimal combination of decentralized flexibility assets located along the whole energy value chain, providing benefits to all the actors of the smart grid, energy retail and wholesale market, offering an all-win scenario.

At first, the details of the innovative flexibility management framework which brings together a wide range of DER types and technologies and integrates them in a holistic framework are presented in the following figure.

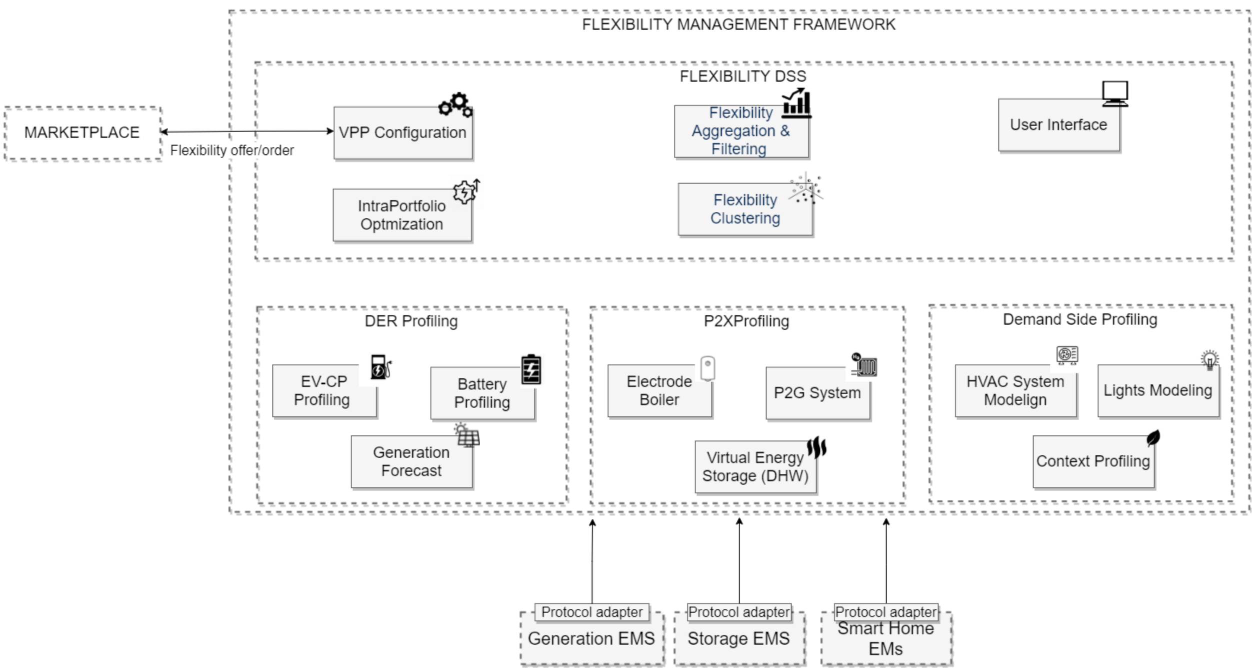

Figure 1 Conceptual architecture for the holistic flexibility management framework

The different layers that comprise the integrated framework are briefly described below.

The **Application layer** represents the point of analysis of raw data coming from the different DERs in order to further model and forecast the operation of these DERs towards the extraction of the available flexibility. The different modeling approaches are incorporated into software bundles, setting that way the different microservices for the management of the different flexible assets' technologies in place, namely:

- DER profiling layer covering generation, battery and EV charging point assets
- P2X profiling layer covering P2G and P2H solutions
- Demand Side Flexibility profiling layer covering demand side assets

In association with the different micro-modules, a unified common semantic layer is defined to ensure that the output of each modeling approach can be easily integrated into the proposed framework. On top of this layer is the (business) flexibility aggregation & clustering component responsible to aggregate the available flexibility from the different flexible sources, further making it available to the Aggregator or 3rd party business entities (marketplace). This layer is split into different functions namely:

- Flexibility Aggregation & Filtering analytics layer where the focus is at providing simple analytics over flexibility timeseries
- Flexibility Clustering layer where the focus is at providing more complex analytics over flexibility timeseries
- A flexibility management component responsible to optimize the utilization of the different flexible sources taking into account the business and operational requirements and constrains
- The User Interface provided as the front end of the application, on the way to provide an intuitive visualization for the system stakeholders, the aggregators.

As stated at the introduction, a main innovation of the proposed framework is the incorporation of a P2X framework for the exploitation of the available flexibility. More specifically, this task aims at properly modelling P2G (power-to-gas) systems (electrolysers together with hydrogen storage in fuel cells) as well as different types (both at industrial and residential level) of boilers as P2H solutions. Regarding the Power-to-Gas, the concept uses renewable or excess electricity to produce hydrogen (Power-to-Hydrogen) via water electrolysis (Wulf C. et al., 2018). By using a P2G system the sur-plus electricity production from the local generation system is used to generate and store gas. The stored gas can be exploited afterwards in a variety of applications such as power generation, chemical industry, district heating, transportation and gas storage (Xing X. et al., 2018). The above-mentioned characteristics make P2G systems able to be coupled with multi-energy systems adding also more flexibility to the electrical system. For these reasons P2G is considered as a key technology that may enable the realization of large-scale integration of renewable energy. In the concept considered, we envision the exploitation through fuel cells in order to generate electricity when needed. Regarding the modelling of the electrolyser several models are available in the literature. In (Mazza E., Bompard G., 2018; Schiebahn S., et al., 2015) the authors used a model to estimate the hydrogen production rate of a Unipolar Stuart cell by assuming 100% current efficiency. Empirical models have also been developed using experimental data to describe the current-voltage characteristics of the electrolyser. The experimental measurements show that the I-V characteristics are mainly depend on the temperature and pressure. There are empirical models that use the “log” term to describe the non-linearities between the volt-age and the current and others that use the “ln” term.

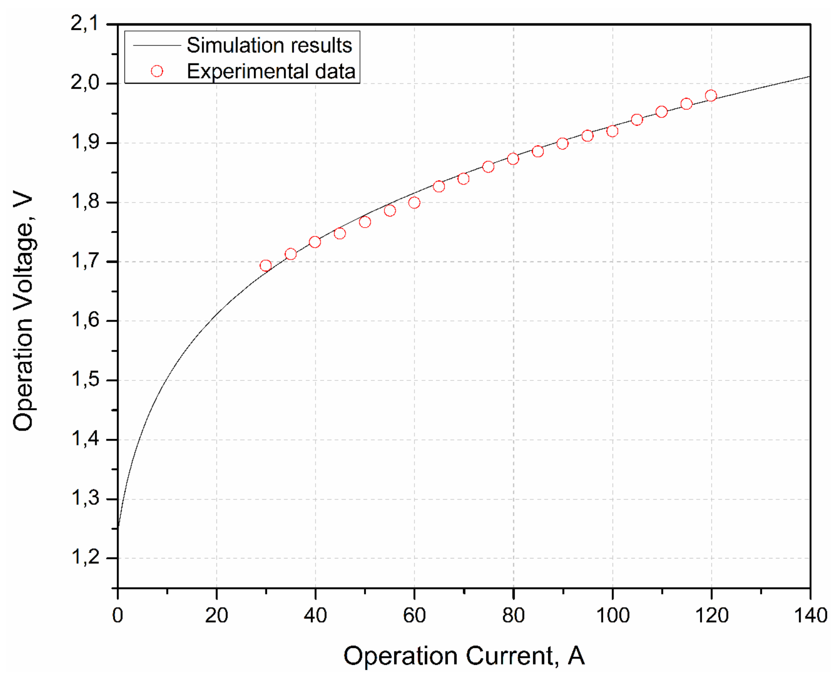

Figure 2 Operation curve of electrolyser

Regarding the fuel cell modelling, polarization curve fitting equations can be found in the [7](Priya K. et al., 2018; Laurencelle F. et al., 2001) to express the relation between the cell voltage and the current density. These equations model the I-V characteristics of the fuel cell and are a good indicator of the performance of the fuel cell stack A typical polarization curve of a PEM fuel cell is characterized by three distinct regions (Barbir F., Gomez T., 1997; Kim J. et al., 1995; Liangyu M. et al., 2018), namely: activation polarization, ohmic polarization, and concentration polarization. The activation polarization region is represented by the first part of the curve which is strongly non-linear and steep indicating the nature of the reactions. The ohmic polarization region corresponds to the second part of the curve where the ohmic losses caused by the membrane electrical and contact resistance are depicted. Concentration polarization is reflected in the last section of the curve indicating the concentration gradient caused by electrochemical reaction.

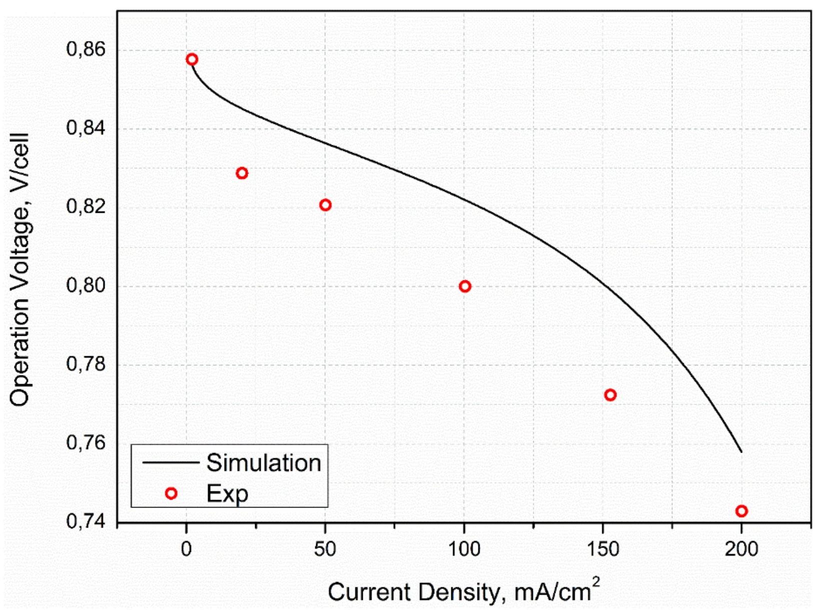

Figure 3 Operation curve of fuel cell

On the other hand, the P2H technology (Bloess A. et al., 2018) is also examined with focus on boiler systems, both industrial and residential. Starting with industrial applications, electrode boiler is a type of boiler that uses electricity flowing through streams of water to create steam or hot water. Circulating water is injected into the outer bucket by the feedwater pump, while the variable frequency pump (inner circulating pump) injects the circulating water into the inner bucket (mounted on ceramic insulators which in turn are attached to the outer vessel) to adjust the water level. Three electrodes are symmetrically arranged on the top of electric boiler, which are directly pulled into the inner bucket and are immersed in the circulating water. The electrodes and the circulating water of inner bucket form a closed loop to transform electrical energy (coming in between 1-35 kV) into heat or hot water when the electric boiler is working, making molecules of circulating in boiler's upper part water move faster. The steam or hot water is sent to the heat exchanger through pipe and exchanges the heat with heat users, then the main steam or water is cooled down to cooling water. After removing salt in desalting device, the circulating water is sent back to the outer bucket again.

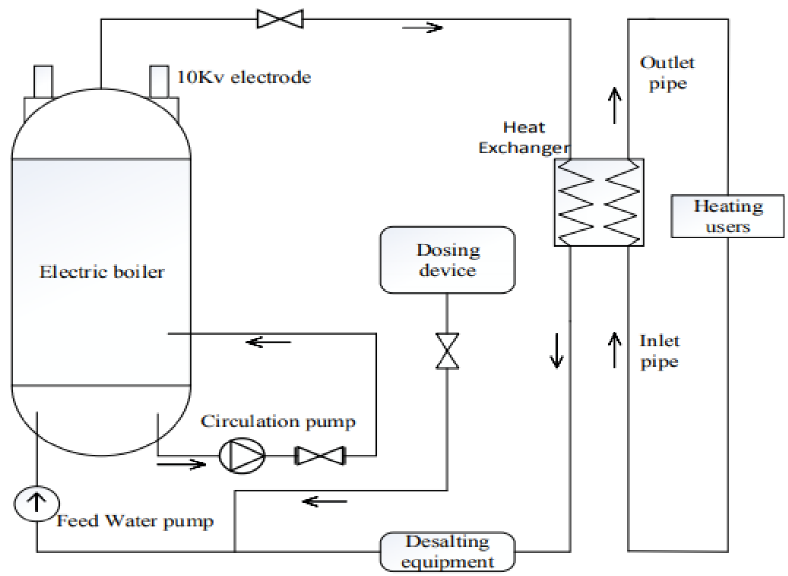

Figure 4 Technical characteristics of electrode boiler

Water conductivity and temperature are the non controllable parameters that affect the operation of the system. Therefore, as part of the modeling work, the appropriate fitting curve must apply in order to extract the operational curve that fit to the nominal curve of the electrode boiler system (Francois B. et al., 2005; Zhi X. et al., 2017).

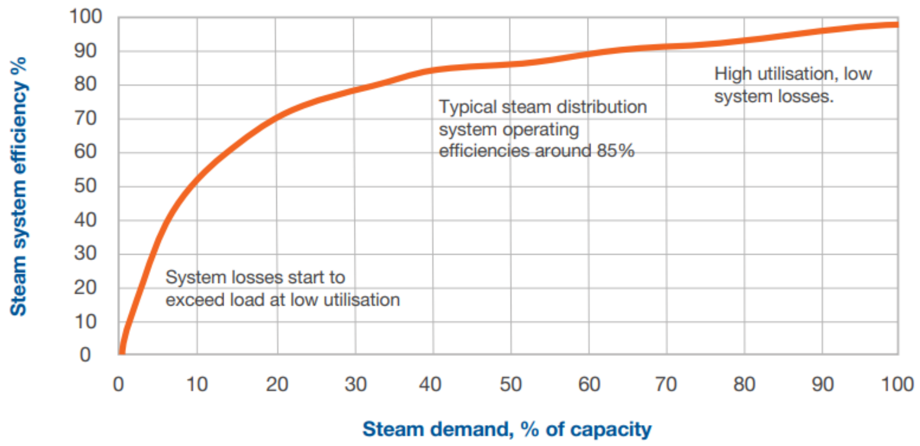

Figure 5 Operation curve of electrode boiler

A similar approach is adopted for residential boiler systems. The main differentiation is that there is no SCADA system available for monitoring the operational parameters and thus context-based models have to be considered. The same physics principles are considered for the residential level boiler systems and the monitored parameters are: water and air temperature, water flow in and out along with the operational status considering also hot water demand as presented in the following schema (Vanthournout K. et al., 2012; D'hulst R. Et al, 2015).

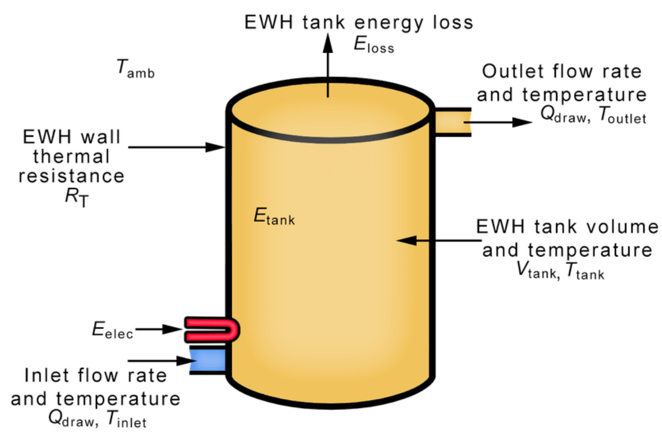

Figure 6 Operation curve of a domestic hot water boiler

A one-node lumped-parameter model is selected for the closed-loop DHW model operation. The equation that expresses the operation of the DHW is presented:

$$E_{tank}(t) = P_{elec(t)} - P_{draw(t)} - P_{loss(t)} \quad (1)$$

Where at each given state t:

- $E_{tank}(t)$ is the thermal energy of the water inside the DHW at each state (t)
- $P_{elec(t)}$ is the power input delivered to the heating element at each state (t)
- $P_{draw(t)}$ is the power output due to hot water draw (hot water leaving the DHW and being replaced by cold water) at each state (t)
- $P_{loss(t)}$ is the power output due to thermal losses to the environment at each state (t)

The details of each of the aforementioned parameter is provided as part of the modeling work. Starting with power input modeling, the heating element is either OFF or ON, which means that the power input $P_{elec(t)}$ delivered by the element is either zero or its rated power P_{rate}. This operation is evident from the load curve of the DHW system.

The power output due to hot water draw $P_{draw(t)}$ is given by the following equation:

$$P\_draw(t) = \rho * Qdraw(t) * [\, h\_outlet(t) - h\_inlet(t)] \quad (2)$$

Where:

- ρ is the density of the water,
- $Qdraw(t)$ is the hot water outlet volumetric flow rate
- and $h\_inlet(t)$ $h\_outlet(t)$, are the specific enthalpy entering and leaving the water heater, respectively.

Under conditions of constant pressure and constant specific heat capacity, this can be approximated by the following:

$$P\_draw(t) = cp * Qdraw(t) * [T\_outlet(t) - T\_inlet(t)] \quad (3)$$

Where:

- cp is the constant pressure-specific heat capacity of the water
- $T\_outlet(t)$ is the hot water outlet temperature
- $T\_inlet(t)$] is the cold-water inlet temperature.

Last but not least, the power output due to hot water losses is expressed by the following equation:

$$\mathrm{P\_loss(t)} = \frac{1}{R_{TH}}[\mathrm{Ttank(t)} - \mathrm{Tamb(t)}] \qquad (4)$$

Where:

- RTH is the thermal resistance (1/conductance) of the DHW wall,
- $\mathrm{Ttank(t)}$ is the water temperature inside the DHW,
- $\mathrm{Tamb(t)}$ is the ambient temperature.

Overall, the modelling approach for the DHW (Brattle, 2015) (Somer et al., 2017) takes into account the operational characteristics of the device, the water and air temperature conditions as well as the water flow from the system to the actual use.

We presented above the modeling details for the P2X technologies examined in the proposed framework. In the next section, the technical details about the integration of the different models into the holistic flexibility management framework are provided.

FLEXIBILITY FORECASTING & MANAGEMENT LAYER DETAILED SPECIFICATIONS

In this section, the detailed specifications of the business layer of the proposed framework responsible for Flexibility Forecasting, Clustering and Management are provided. As presented above, the analysis is split into two key components that consist of the overall layer.

The Flexibility Aggregation & Clustering Component is the component in charge of facilitating aggregators to get an overview picture and management of their portfolio assets flexibility potential (e.g., duration of flexibility, flexibility amount that can be provided, response time for flexibility activation, location of flexibility etc), in order to be able to deliver the available flexibility to 3rd party entities (e.g. flexibility marketplace). The detailed overview of the Flexibility Aggregation & Clustering component is presented. Starting with the flexibility aggregation & filtering functionality, a multi-dimensional characterization of the flexible. Each flexible asset is characterized by its metadata (both technical and business-related aspects of the asset), namely:

- Device Class: generation, storage, demand
- Device Type: HVAC, Lights, etc…
- Device Category: Inflexible, Shiftable, Storage, Adjustable / Shift, Shed, Shimmy
- Device Location: the spatial characteristics of the portfolio (or network location related characteristics)
- Device Nominal Power and Energy statistics
- Device Flexibility Potential (over time) as derived from the flexibility profiling agents
- Device Business Parameters taking into account market flexibility services (asset ownership, time to response, how often to call etc…)

By applying the respective filters, a look up on the database is performed to extract the assets with the search characteristics as defined by the user. Then, the user is prompted to store the configuration parameters for further use.

On the other hand, the details of the flexibility clustering component are considered. The potential list of input data of the Flexibility Clustering component is the same as to the filtering component. The main differentiation is the algorithmic process applied to extract clusters with common characteristics. ML clustering techniques (k-means) apply to serve the business needs of the stakeholders. Therefore, the output of the analytics process will extract, DER clusters that best fit to:

- Different flexibility markets that emerge in the electricity value chain
- Timeframes for the provision of flexibility
- Location based parameters that affect the usability of the available flexibility

Apart from the Flexibility Aggregation & Clustering functionality as presented in previous section, an optimization layer is incorporated in the proposed framework in order to enable the active participation of the flexible DERs at different business objectives. Overall, there are two different business processes examined as part of the proposed approach:

- The objective of the 1st case is the exploitation of the available flexibility by 3rd party entities when required. Upon request from the grid or the market and by taking into account the results from flexibility sources clustering, the system/platform should be able to trigger commands to the flexibility assets. The role of this use case is to incorporate the logic/functionality in order to assure optimization of flexible sources at local level taking into ac-count the requests from the external business/grid environment.
- An intra portfolio optimization process is incorporated in order to maximize the profit of the entities at district/region/portfolio level. By combining RES profiling, the analysis of the storage entities (Batteries, P2H/P2G, EVs), and load flexibility profiling, the aim is to establish a coordinated flexibility management framework for balancing of generation/ flex consumption/ storage based on internal (e.g., excess of RES and requirement to ensure maximum self-consumption, retailer prices) parameters.

By taking into account the aforementioned business objectives, the details of the algorithmic process are provided. Starting with VPP formation to serve 3rd party needs, the main objective is to ensure maximum flexibility offering by aggregating the flexibility available from different flexible sources (and considering the demonstration scenarios at the different demo sites that pose limitations on the use of flexible assets). Criteria for the selection of the assets are the contractual terms (specifying financial and non-financial – level of controllability, duration of controllability, reliability level- in the proposed framework).

On the other hand, intra-portfolio management focus on baseline profile optimization (through demand and generation shifting) by exploiting the available flexibility of the different flexible sources. A modular approach is adopted in order to ensure the incorporation of different business objectives (self-consumption maximization vs price-based optimization) or types of assets available in each demonstration scenario. The main differentiation from VPP is that while the timeframe for VPP is short term (2 -3 hours ahead), this is not the case for intra-portfolio where optimization is performed at a continuous manner (and with a long day ahead horizon).

We presented above the design details of the business analytics layer of the proposed framework tool. As stated above, a UI is considered as part of the tool to facilitate the business actors on decision making. The details of this feature are out of the scope of this paper.

DEMONSTRATION ACTIVITIES & PERFORMANCE ASSESMENT

The overall solution is about to be tested for a long period of time (18 months) in real conditions in 4 pilot sites in 3 EU Member states (Bulgaria, Slovenia and Greece), with different needs and socioeconomic and technological boundaries, involving multiple existing flexibility assets (batteries, power to heat/cold, vehicle to grid and other storage solutions) and all complementary actors of the energy network (DSO, microgrid operator, utilities, flexibility providers, local communities).

In the following figure, the key assets at the different demo sites are presented. Special focus at the integration of P2X technologies and further incorporation in the proposed innovative management framework

Figure 7 Demonstration Assets for framework evaluation

With this global and holistic approach, the proposed framework aims to demonstrate the technological, economic and social benefits generated by the flexible sources in existing energy systems, ensuring major impact and replicability, as well as the exploitation potential of the project solutions. In all these demo sites different types of services will be tested taking into account the data gathered from the installations in premises. More specifically, the different demonstration cases are presented:

- Demo Case 1: Local/Demo site optimization ensuring maximum self-consumption. In this case, the focus of the local system operator is to optimize the operation of the local DERs in order to ensure maximum level of self-consumption and thus reduce the dependency from the upstream network.
- Demo Case 2: Participation in energy markets (DA, ID, ancillary services) by fully exploiting the flexibility potential. In this case, the focus of the local system operator is to optimize the operation of the local DERs in the existing energy markets, considering also the role of the emerging marketplaces

- Demo Case 3: Provision of the services to the DSOs, considering different types of ancillary services required by the local system operator through the innovative market schemas and local size marketplaces.
- Demo Case 4: Grid resilience against extreme weather event. In this case, if severe weather conditions are predicted to hit a line of the local network, flexibility from assets may be asked in order to support the feeding of this loads (incl. reduction of the load injection of RES energy to the network etc).

The demonstration activities should be accompanied by the performance assessment of the different use cases as the main interest for the consumers and business stakeholders in order to ensure tangible profit along with any other social impact. A non exhaustive list of KPIs is defined for the proposed framework and are briefly presented in the following table:

Table 1 Performance Assessment Indicators

Category	KPI Name	Description
TECH	Self-sufficiency ratio	The ratio between on-site production and consumption of all loads.
TECH	Active power deviation from flexible units	The divergence of the active power flows of each flexible unit from their realized average values over a comparable time period. The aim is to analyse each flexible unit separately and to verify whether their activation follows a stable pattern over the time or whether DSM actions affect their use.
TECH	Flexibility availability forecasting accuracy	The accuracy of the forecast of flexibility modelled
TECH	Amount of flexibility	The ratio of capacity that can be managed with flexibility over the total installed capacity in the pilot site.
TECH	Dispatchability	The system capability for providing power when required by 3rd party entities
TECH	Generation forecast accuracy	The accuracy of the forecast of electricity generation from RES modelled
TECH	Consumption forecast accuracy	The accuracy of the forecast of electricity consumption in the network
TECH	Pilot site model accuracy	The global accuracy of each pilot site by measuring the deviation between forecasted and measured flexibility availability, RES generation and electricity consumption.

TECH	EV demand flexibility availability	The amount of energy that the smart charging strategies in EVs enable to shift compared to the total amount of power required for charging.
TECH	Peak-to-average ratio improvement	The peak-to-average ratio provides information regarding the shape of the load curve indicating how extreme the peak consumption is relative to the consumption at off-peak hours.
TECH	Amount of reduced or shifted load	The amount of load shift or the reduction from one time period to another. The aim is to evaluate the effectiveness of DSM actions.
ENV	Change in GHG emissions	Greenhouse gas (GHG) emissions are reduced by means of increasing the penetration of local renewable production and/or load shifting to the hours with higher production from renewables.
ENV	Change in total cumulative energy demand	Total (including fossil, renewable and other sources) cumulative energy demand of the pilot site or at a certain UC of the pilot site in comparison to a reference case.
ENV	Change in total renewable cumulated energy demand	Renewable cumulated energy demand of the site pilot site or a certain UC of the pilot site in comparison to a reference case.
SOC	User satisfaction	Overall user satisfaction regarding the proposed framework
SOC	Ease of use of tools	Ease of use of the tools that are defined in the proposed framework
SOC	Economic Benefit for Aggregators	The economic profit for aggregators as derived through participation in innovative business schemas
SOC	Economic Benefit for Asset Owners	The economic profit for asset owners as derived through the enrolment of their assets in innovative flexibility strategies

All in all, a holistic assessment process applies in order to ensure that economical and non-economical parameters are considered at the decision-making process and assessment of the flexibility management framework.

CONCLUSIONS & SUMMARY

Up to now, projects and research activities in this area of DER flexibility have focused mostly on specific energy sources, technologies and actors, considering only a very limited and isolated part of the whole network, missing the vast flexibility opportunities that a holistic, integrated approach to the overall energy value chain can bring. In this context, we propose an innovative framework to facilitate the optimum combination of decentralised flexibility assets, both on the generation (DER) side and on the demand side (V2G, power-to-heat/cold/gas, batteries, demand response), enabling all parties, including final prosumers, to offer their flexibility in the market creating benefits to all the actors in the smart grid value chain. The proposed approach is unique in its multi-technology, multi-actor approach which, in an increasingly RES-powered grid, will ensure security, resilience and stability for all, even under grid-stressing scenarios such as extreme climate events, offering an all-win scenario.

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ABBREVIATIONS

V2G	Vehicle to Grid
EU	European Union
P2X	Power-to-X
P2G	Power-to-Gas
P2H	Power-to-Heat
VPP	Virtual Power Plant
RES	Renewable Energy Source
DHW	Domestic Hot Water
DSM	Demand Side Management
PEM	Polymer Electrolyte Membrane
SCADA	Supervisory Control and Data Acquisition
UI	User Interface
HVAC	heating Ventilation Air Condition
DSO	Distribution System Operator

DA	Day Ahead
ID	Intra Day
GHG	Greenhouse gas
UC	Use Case
DER	Distributed Energy Resources
EVs	Electric Vehicles
KPIs	Key Performance Indicators

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