An innovative flexibility management and optimization framework for demand side aggregators

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ABSTRACT

The new geopolitical conditions at EC level (backed by the very recent REPowerEU [1] regulation) as well as the vast spread of Renewable Energy Sources (RES) [2] pose new, major challenges for the electricity networks in Europe. Solutions for the optimization of local energy systems are required, enabling direct integration with distributed generation and demand, enabling enhancement and optimal coordination of local flexibility resources. Such integrated solutions shall optimally combine distributed generation, demand, storage, electric vehicles and interconnections with heterogeneous local energy networks and introduce them into holistic optimization strategies to ensure operational and economic optimization of local energy systems. Optimal coordination of local energy sources is directly linked to maximum utilization of the flexibility [3] they can offer to support the operational stability of the grid and reinforce the economics of local energy systems through the avoidance of RES curtailment and the establishment of local flexibility markets.

Taking into account the emerging need for coordinated optimization of the flexibility potential of the different types of controllable assets available in the electricity network, we propose a state-of-the-art methodology and a framework for the optimal utilization of flexibility on the basis of:

- Accurate extraction of the flexibility potential of the different types of flexible assets by applying data driven techniques that take into consideration the actual status of the flexible devices.
- Fine-grained intra-portfolio orchestration of local generation output, demand and storage (including novel solutions for P2G systems), to facilitate maximum RES integration into the grid, avoidance of curtailment as well as self-consumption optimization at regional/community level.
- State of the art flexibility source optimization towards offering aggregate flexibility service offerings via local flexibility markets to address the balancing and ancillary grid needs for the operational optimization of local, regional and national networks.

The main innovation of the proposed approach is the incorporation of actual and in real time data as retrieved from the physical assets as well as the application of state of the art, ML based optimization techniques for intra-portfolio optimization as well as participation in local flexibility markets. The proposed framework has been developed and deployed and now is under extensive testing at a first of a kind, mid-scale demo site in Xanthi, Greece. The preliminary results from the evaluation of the proposed framework will be presented in this paper.

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

A DATA DRIVEN FLEXIBILITY PROFILING FRAMEWORK FOR ENERGY ASSETS

In order to support the provision of a fine-grained tool for flexibility management and aggregation, the conceptual architecture of the ICT solution is presented in Figure 1.

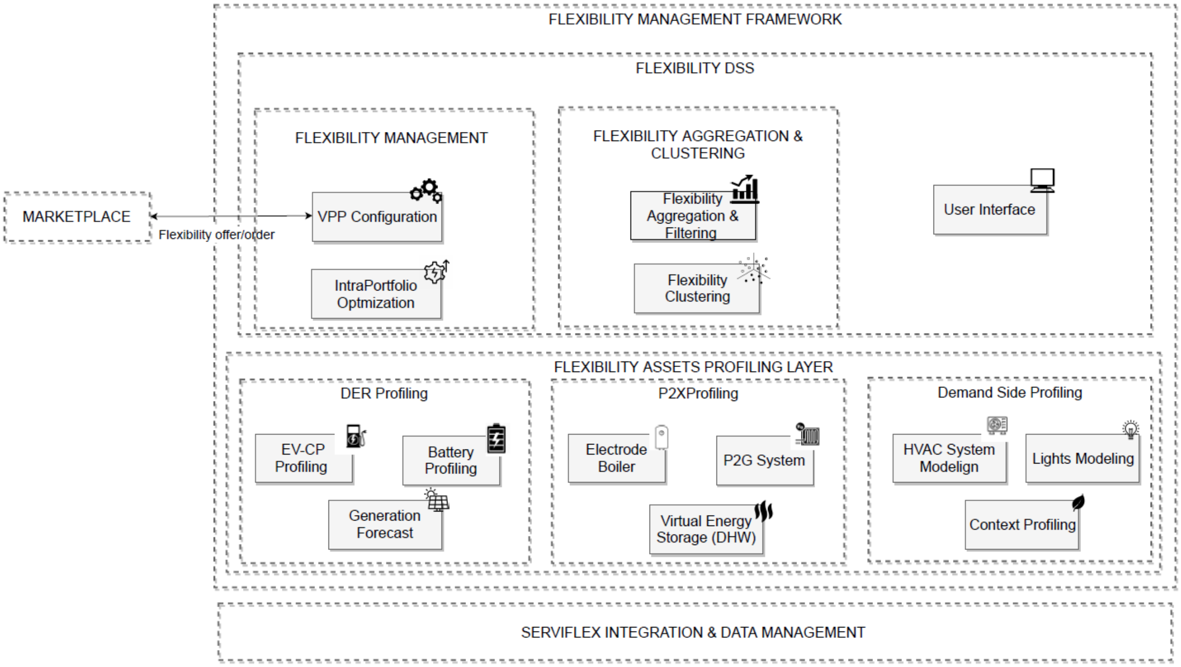


Figure 1: Flexibility Management Tool Conceptual Architecture

At the heart of the system, is the flexibility profiling layer responsible to incorporate the heterogeneous modelling approaches as different 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 this section, the high-level modelling details for the key controllable assets examined are presented, namely demand side management assets, battery solutions, P2G systems modelling.

In the field of demand side, the modelling is focusing on DHW and HVAC systems as the heavy controllable loads within the building environment. The modelling details for the DHW systems are presented in [3]. In brief, the modelling framework is dependent on the hot/cold water temperature conditions, the power consumption and the water flow (as the representation of the demand for hot water).

In addition, a detailed model for air-to-air HVAC systems is defined as part of the demand side flexibility framework. The model principles of a grey-box 1-order RC model is considered in order to capture the evolution of indoor temperature of building, supposing the thermal capacity C, and the equivalent thermal resistance R as physical related parameters of the models. Starting from heat balance modelling, we need to correlate the impact of the HVAC system and heat losses to indoor temperature conditions, as expressed in the following equation:

$$\frac{dTin}{dt} = f(\dot{Q}in - Qo\dot{u}t) \qquad (1)$$

Where:

- $\frac{dTin}{dt}$, is the temperature different at each time step
- $\dot{Q}in,$ is the thermal heat flow from the heat source (HVAC system)
- $Qo\dot{u}t,$ the heat loss in the building environment

Considering physics law dynamics, the variation of the indoor temperature is characterized by the difference between the variation of heat flow from electric heater and heat loss multiplied by the reference C factor.

$$\frac{dTin}{dt} = \frac{1}{C}(\dot{Q}in - Qo\dot{u}t) \qquad (2)$$

On the other hand, $\dot{Q}in$ is defined by taking into account the COP of the heating/cooling system and the power characteristics, while the heat losses equivalent as the difference between the indoor and the outdoor temperature, divided by the equivalent thermal resistance of the building (R) as depicted in the following:

$$\dot{Q}out = \frac{Tin - Tout}{R} \quad (3)$$

Considering the discretization of the variation of the indoor temperature, the equation of the thermal building model is presented:

$$\frac{dTin}{dt} = \frac{1}{C}\dot{Q}in(t) - \frac{1}{C}\left(\frac{T\imath n(t) - \dot{T}out(t)}{R}\right) \qquad (4)$$

$$Tin\ (t+1) = Tin(t) + \frac{1}{C}\dot{Q}in(t)dt - \frac{1}{C}\left(\frac{T\imath n(t) - \dot{T}out(t)}{R}\right)dt \qquad (5)$$

Overall, the RC modelling equation consists of the definition of the relationship between indoor, outdoor temperature conditions and the operation of the HVAC system. In order to extract the R, C parameters, a simple statistical method applies (fitting regression approach) is considered. In Figure 2, the raw data about indoor/outdoor conditions and the impact of HVAC operation is provided.

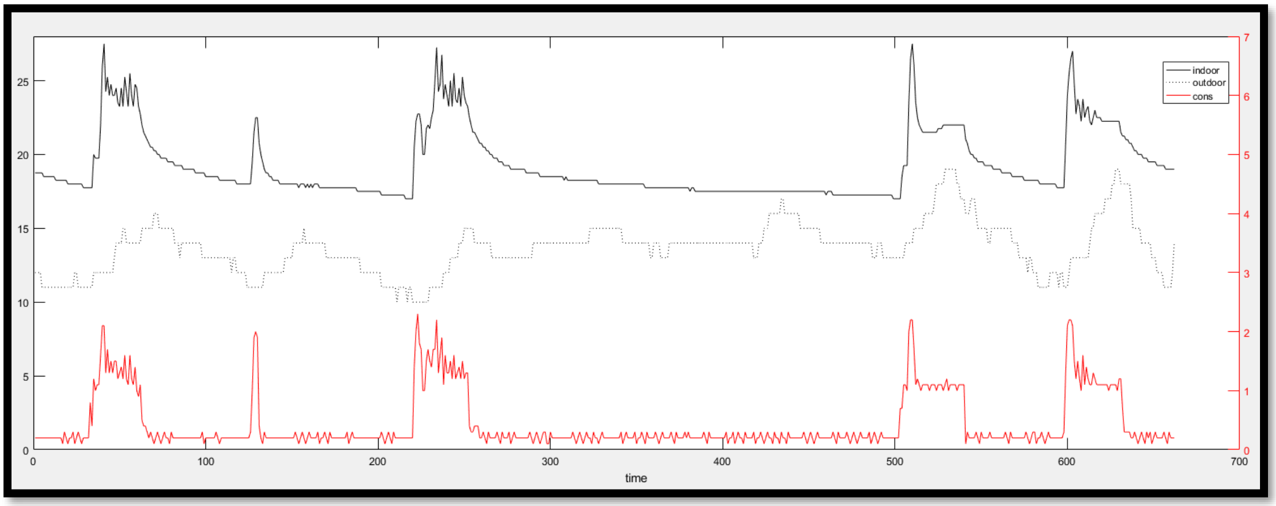


Figure 2: HVAC operational conditions

In Figure 3, the model vs actual conditions of the HVAC system are presented over the time (3-week period).

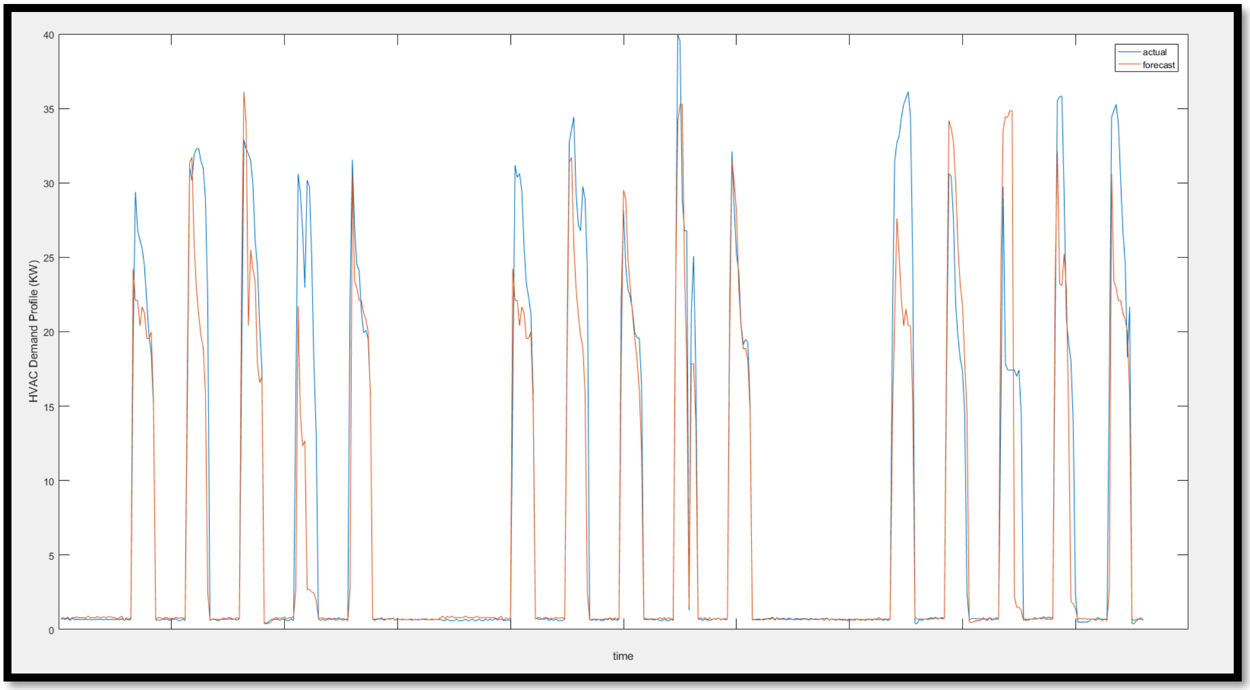


Figure 3: HVAC Energy Consumption Modelling

The battery system is modelled using Kinetic Battery Model which is an intuitive battery model originally developed to model the chemical processes of large lead-acid batteries by a kinetic process [4]. The main equations of the KiBaM are presented below:

$$q_1 = q_{1,0} \cdot e^{-k \cdot t} + \frac{(q_0 \cdot k \cdot c - I) \cdot (1 - e^{-k \cdot t})}{k} - \frac{I \cdot c \cdot (k \cdot t - 1 + e^{-k \cdot t})}{k} \quad (6)$$

$$q_2 = q_{2,0} \cdot e^{-k \cdot t} + q_0 \cdot (1 - c) \cdot (1 - e^{-k \cdot t}) - \frac{I \cdot c \cdot (k \cdot t - 1 + e^{-k \cdot t})}{k} \quad (7)$$

Where q_1 is the “directly available capacity”, q_2 is the “temporary capacity” of the battery, c is the fraction of the capacity stored in the available charge tank, k is the rate constant, I is the current and t is the time.

A comparison between simulated and experimental results is presented in Figure 4.

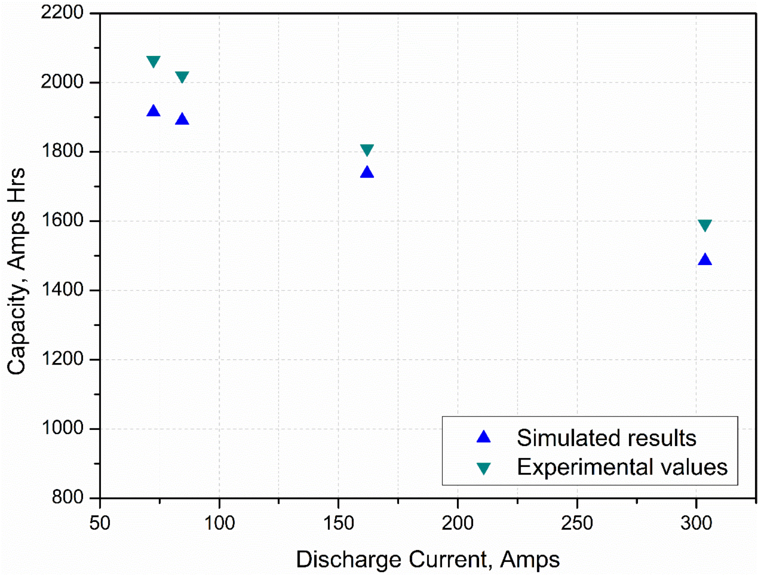


Figure 4: Comparison between simulation results and experimental data for the Sunlight battery system

Regarding the P2G system empirical models have been adopted for both the electrolyzer and the fuel cell. The respective equations are presented below.

Current-voltage characteristic of the electrolyzer [5]:

$$U = U_{rev} + \frac{r_1 + r_2 \cdot T}{A} \cdot I + (s_1 + s_2 \cdot T + s_3 \cdot T^2) \cdot \log\left(\frac{t_1 + t_2/T + t_3/T^2}{A} \cdot I + 1\right) \quad (8)$$

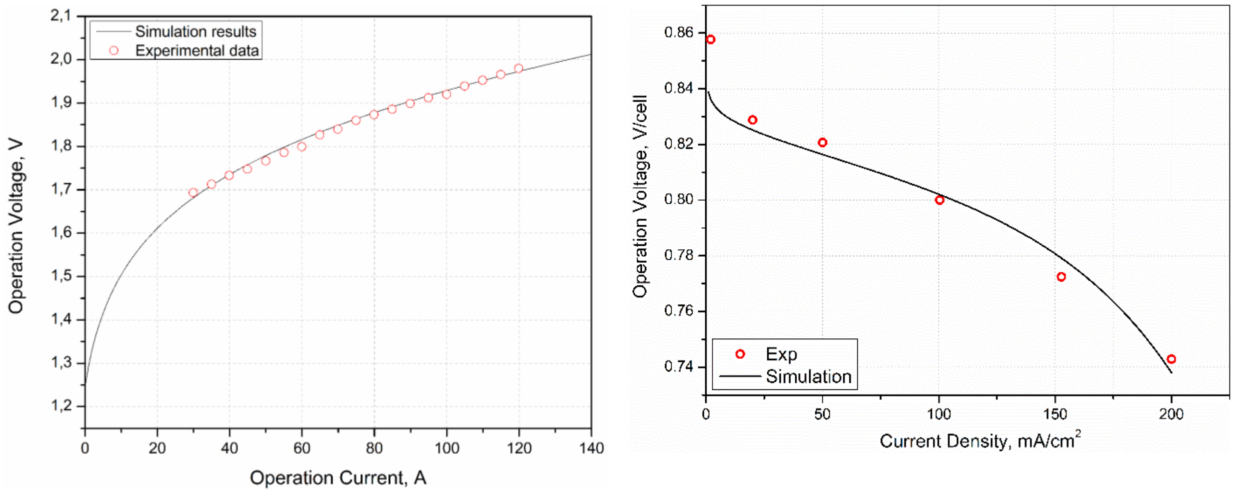
Where U_{rev} is the reversible cell voltage, r_i (i=1…2) are parameters for ohmic resistance of electrolyte, s_i, t_i (i=1…3) are parameters for overvoltage on electrodes, A is the area of the electrode and T_{el} is the temperature of electrolyte.

Current-voltage characteristic of the fuel cell [6]:

$$U = U_0 - b \cdot \log(i) - R \cdot i - m \cdot \exp(d \cdot i) \quad (9)$$

Where U_0 is the open circuit voltage of the fuel cell, b is the Tafel slope of the fuel cell, R is the resistance of the fuel cell, m and d are the parameters for overpotential due to mass-transport limitation.

In Figure 5, a comparison between experimental and simulated results is presented.



(a) (b)

Figure 5: Comparison between simulated and experimental values for the P2G system, (a) electrolyzer, (b) fuel cell

FLEXIBILITY MANAGEMENT AND OPTIMIZATION FRAMEWORK

On top of the flexibility profiling layer presented in previous section, a state-of-the-art analytics layer is incorporated in the ICT solution to enable the provision of fine-grained services to the business actors. There are four different types of analytics features supported by the application, namely:

- Flexibility Aggregation & Filtering Module to enable search over the flexible assets available at the portfolio of the aggregator and further aggregation of flexibility profiling data (from the flexibility sources) in order to address the business needs of the aggregator.
- Flexibility Clustering module to provide fine grained analytics techniques for the management of the flexibility sources available in the portfolio of the aggregator.
- VPP Configuration module to facilitate the optimal placement of the flexibility sources to 3rd party business campaigns. These business campaigns are triggered by the market as the innovative flexibility marketplaces are evolving now in Europe.
- Intra portfolio optimization module to facilitate the optimal management of the flexibility sources within the portfolio of the business stakeholder of the tool.

The first layer is the Flexibility Aggregation & Filtering module is providing the functionality of searching over the portfolio of the aggregator and filtering with specific criteria in order to set groups of flexibility assets with similar characteristics. There are different parameters (both technical and business) that characterize the flexibility assets and on the basis of these parameters appropriate segments may be defined in order to set groups of flexible assets which are of interest for the business stakeholder (Aggregator). On top of this filtering functionality, an aggregation functionality is incorporated in order to aggregate energy and flexibility related profiling information, which is again of interest for the business processes of the business stakeholder. Filtering functionality over the data streams is also incorporated in order to enable search over a selected period of time.

The flexibility clustering module is responsible for the execution of simple and advanced analytics processes over the flexibility data streams. More specifically, the module complements the filtering functionality as presented above and support the quick access to the filtered data, as well as the execution of the respective analytics services: generic statistics algorithms (i.e. aggregations, KPI calculations etc…) as well as advanced models (i.e. ML-based algorithms such as classification, clustering, regression, etc. targeting the energy domain applications) are incorporated in the module in order to serve the clustering scenarios of interest for the business actors.

While the filtering and clustering analysis is focusing mainly at the provision of insights for the business actors, there are different optimization strategies and scenarios incorporated in the ICT tool to serve the business needs for flexibility exploitation. At first, the VPP Configuration Layer module is responsible for the execution of the optimization of the portfolio flexible assets taking into account 3rd party requests triggered by the flexibility markets. There are different approaches adopted in the market, with the most common approach to be defined by USEF as the state-of-the-art implementation for flexibility exchange through a market-based framework. Under this concept, the overall management of flexibility is performed taking into account:

- The flexibility potential at portfolio (aggregation) level as well as the flexibility request that has been made available from the flexibility markets via a bid that has been triggered to the tool. The bid contains information about the amount of flexibility to be served over a specific timestep.
- The pricing/market details about the usage of the different flexibility sources that are part of the portfolio. We have to point out that these market details are incorporated in a flexibility registry in order to promptly remunerate the different flexibility sources for the provision of the associated flexibility
- The level of reliability of each flexible source that is part of the portfolio of the Aggregator.

Then, a linear optimization process applies in order to formulate the subset of the aggregator portfolio that will execute the demand response signal. The details of this optimization process are provided below:

$$\min \sum_{i=1}^{n} S(flex_i), \qquad (10)$$

$$S(flex_i) = f(price, reliability) \cdot |flex_i|$$

$$\left|\sum_{i=1}^{n} flex_i\right| = |FlexOrder|$$

$$|flex_i| \leq |FlexOffer_i|, i = 1, .., n$$

$$|S\_n(flex_i)| \leq |S\_n\_limit_i|, i = 1, .., n$$

Where:

- $flex_i$ is the flexibility utilisation of each flexible asset that is part of the portfolio of the aggregator
- $f(price, reliability)$ as the cost incurred to the aggregator for utilizing the flexibility unit of the asset. As reported above, the cost is defined as a synthesis of financial and performance related parameters. In the context of experimentation, we consider a linear proportional

correlation of the price with the cost and a negative slope for reliability level in order to quantify the penalization for non-reliability at flexib8ility provision.

- $FlexOrder$ as the total flexibility requested by external markets. This is the typical case of DSO requests for flexibility in order to address grid needs.
- $FlexOffer_i$ as the maximum amount of flexibility estimated to be available by each flexibility asset.
- $S\_n(flex_i)$ any other limitation imposed at the provision of flexibility. For example, it may be the case that the total amount of flexibility to be offered by an asset should not exceed a specific amount over a period of time (these are typical contractual limitations that are defined in bilateral contracts between aggregators and flexibility asset owners).

In parallel to the formulation of the portfolio for DR activation, a backup list is formulated with the remaining flexibility resources and amounts that are available for the same interval but are excluded from initial enrolment. In case, there is no fulfilment of activation from the main pool, the procedure of VPP restructuring is performed in order to reset the portfolio for activation. The output format (for asset flexibility activation) is following the USEF/UFTP principles (a simplified approach incorporating only the mandatory fields), providing the details about the activation of each asset for each time interval.

Following the execution of any DR campaign, the VPP Configuration module is responsible for the calculation of the flexibility related KPIs; results intended to be available to the business stakeholder through a dedicated UI.

Complementary to the VPP Configuration module, the intra-portfolio optimization module is responsible for the execution of the optimization of the portfolio assets taking into account intra -portfolio business objectives (thus not participating in flexibility related markets). More specifically, this module incorporates the optimization algorithms for assets management addressing both cost minimization as well as self-consumption optimization use cases. The details of the optimization process are presented below.

$$\min/\max \underset{,Self-Consumption}{OperationalCost} \qquad (11)$$

$$Energy\ Balance\ Equation$$

$$|SoC, \min| < |SoC_i| < |SoC, max|, i = 1, .., n$$

$$|Pi| < |P, max|, i = 1, .., n$$

$$|flex_i| \leq |flexOffer|, i = 1, .., n$$

The details of the different methods (11) are then provided; at first the functional objective details are specified. As stated in the intro section, there are 2 core business objectives for the flexible asset manager: to minimize operational/energy costs or to maximize the level of self-consumption |(thus minimizing the dependence on the upstream network:

$$OperationalCost\colon \min \sum_{n=1}^{N} \sum_{t=1}^{T} (E_{n,t} * s_{n,t}),$$

- $E_{n,t}$: *energy from n source at time t*
- $s_{n,t}$: *energy cost of n source at time t. The cost data refer to the cost for energy generation from the different DERs or the price of the market for injection of energy from the grid.*

$$Self-Consumption\colon \min \sum_{t=1}^{T} \mathrm{E_{grid}}$$

- E_{grid}: *energy from the grid at time t*

Apart from the core business objectives, the constraints of the optimization process are defined. At first the E*nergy Balance Equation*, express the equilibrium between generation and consumption at local level (also the energy balance from/to the storage systems available at the demo site), considering the different types of assets (generation, storage, demand) available at the demo site ($\mathrm{E_{demand} = E_{localgen} + E_{storage}} +$ E_grid).

In addition to the energy equilibrium, constrains at asset level are also considered in the analysis and more specifically:

- SoC, the state of charge level of the different storage systems available on site should be within the operational limits of the storage system,
- P, the power charge/discharge potential of the different systems available on site should be within the operational limits. This is again very important for the battery systems where operational limits apply
- $flex,$ is the flexibility utilisation for each flexible asset.

Based on the optimization result, the control strategies to be performed in order to achieve the goal objective are formulated. These are expressed either as flexibility schedules for the flexible assets (demand side) or as power schedules for the storage related assets. In addition, the module is responsible for the calculation of the intra -portfolio performance KPIs; similar to the VPP Configuration module presented above.

We presented above in brief the technical details about the different analytics processes that are executed at the DSS layer of the tool. This is a mixture of data analytics techniques incorporated in order to provide a fine-grained analysis of the flexibility potential and optimization processes in order to maximize the level of exploitation of the different flexible sources that are part of the portfolio of the aggregator.

FLEXIBILITY ASSESSMENT DEMONSTRATION ACTIVITIES AT THE GREEK DEMO SITE

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 this section, the focus is at the presentation of the results from the early demonstration activities at a Greek site in Xanthi region. A whole set up has been established with the integration of local generation, flexible demand, battery systems and P2G technologies. In the following figure, the schematic of the demo site is presented.

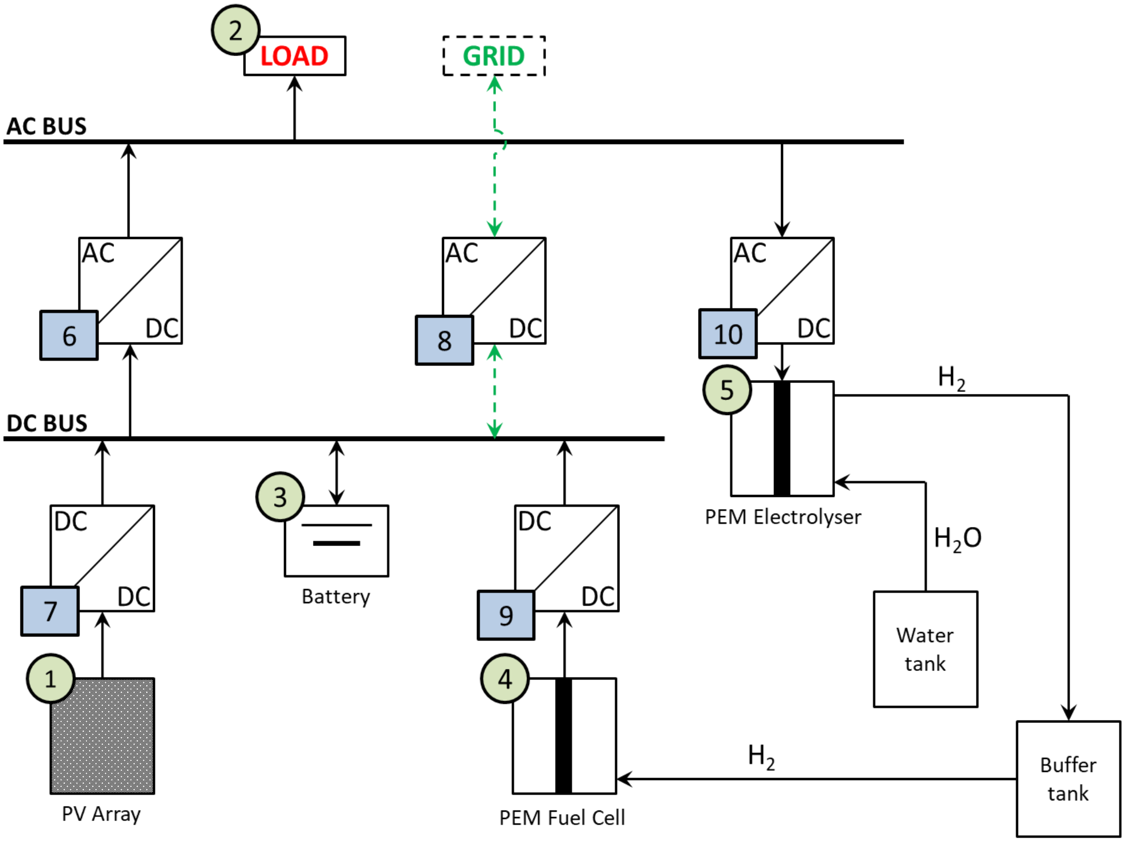


Figure 6: Microgrid set up in Greece

The focus of the optimization is the maximization of self-consumption. The base curves for local generation are presented. Then, by taking into account the flexible profile as well as the capacity of the storage systems in place, the optimization process applies.

In the following figure, we present the aggregate daily data of the different sources over a short period of time (2-week period). It is worth referring to the dynamic operation of the storage systems as they can charge and discharge based on generation and demand data.

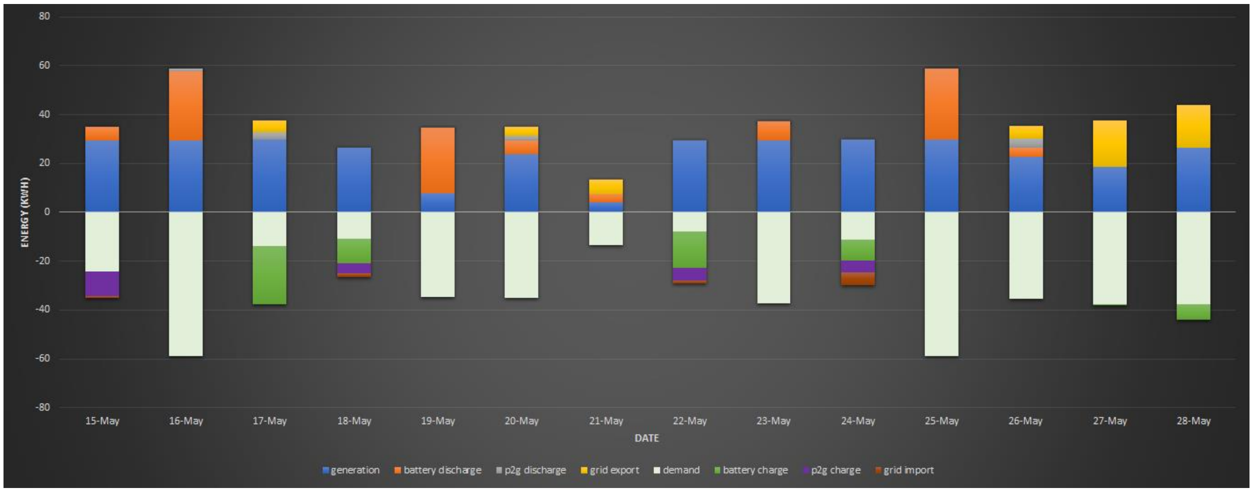


Figure 7: Self consumption optimization over a 2-week period

A snapshot of the operation of a single day is presented in the following figure.

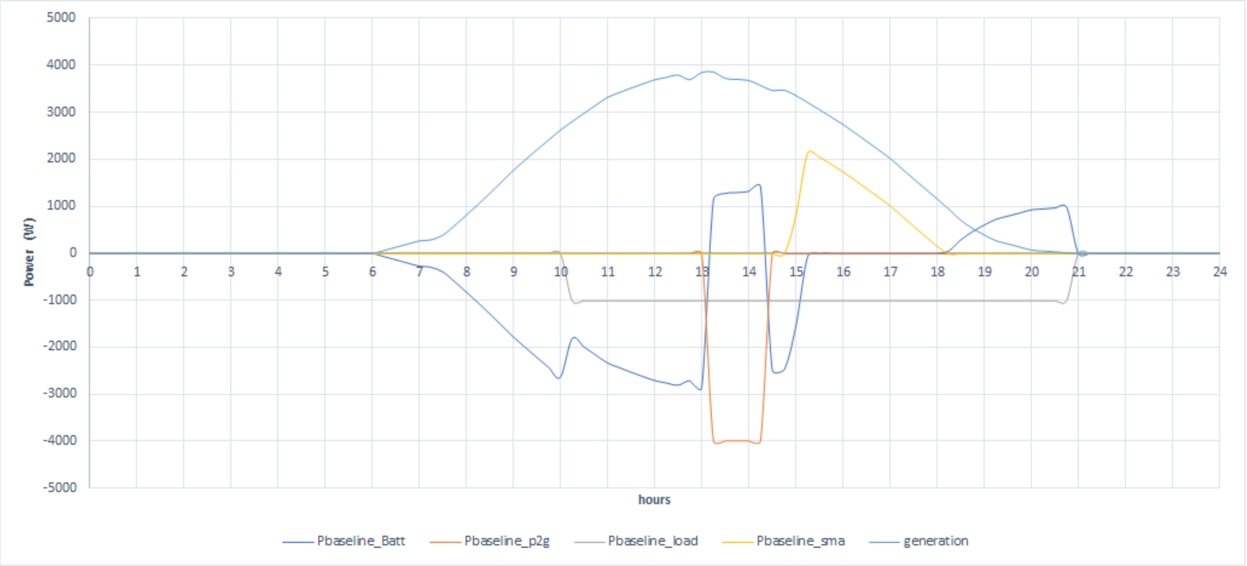


Figure 8: Self consumption optimization over a typical day

From the analysis it is evident the sequential operation of the different systems. First charging the battery system (in case generation> demand), then charge of the P2G system (by utilizing also load from battery in order to address the technical limitations of the electrolyzer) and then the rest of excess is exported to the grid.

CONCLUSIONS & SUMMARY

The main objective of this document is to specify the modelling details of an innovative ICT tool that will facilitate the management of local flexibility profiles in order to forecast and decide upon optimal flexibility utilization strategies, while satisfying the goal of reduced complexity that comes from organising profiles into clusters of homogeneous behaviour. The tool embeds all functionalities pertaining to the tool chain for collecting local flexibility profiles, managing them in order to establish optimal VPP composition for the delivery of flexibility services to network operators or the market. An extensive testing has already been performed in the Xanthi demo site and this will continue together with the replication of the demonstration activities in 2 other demo areas of Europe.

ACKNOWLEDGMENT

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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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