A Virtual Microgrid Aggregator Platform for Distributed and Small-Scale RES Prosumers' Management

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***Abstract*— Small or very small energy prosumers who produce renewable energy and sell the energy surplus consumed find it difficult to participate in a liberalized electricity market. This happens due to the fact that the marginal costs of Renewable Energy Sources (RES) production are very low and so are the respective prices in the market. EU co-funded VIMSEN project's premise is that multiple RES prosumers are able to be grouped in virtual associations, which can represent their interests in a liberalized electricity market in a more efficient way. These so called "Virtual MicroGrid (VMG) associations" have greater negotiation power in the market and can even play the role of "price makers". This type of "VMG infrastructure" needs the aid of Information and Communication Technologies (ICT) to be realized. In this paper, we propose a Decision Support System (DSS) to be used by aggregators or Energy Service Companies (ESCOs), which monitors and manages decentralized RES prosumers, via a web-enabled software platform. The platform's implementation is based on virtualization techniques and a wide range of functionalities are described, tested and validated. Over 30 real-life prosumers' profiles are used and results of various decision-making algorithms show that under different formations of prosumers' groups (i.e. "clusterings") can provide remarkable energy savings and monetary profits for the end users.**

Keywords*— Smart Energy Networks; Virtual Microgrids; Decision Support System; Energy Prosumer; Aggregator.

I. INTRODUCTION

Climate change, increased worldwide energy demand with high RES penetration factor, rising fuel costs, outdated electricity grid infrastructure, non-sustainable business models for the electricity market and novel technologies in the converged energy/ICT sector motivates international research and industry partnerships to redesign the existing power infrastructure so that it becomes more efficient and agile [1] , [13]. Renewable Energy Sources (RES) play an increasingly important role in the Smart Grid concept and their integration to the existing infrastructure poses many research challenges. The subsidy feed in tariff (FIT) policy adopted in the past years by many countries for accelerating RES investments, cannot be retained as a sustainable business model for the future smart energy grid. This is mainly because this policy increases the energy cost, especially when the amount of the energy generated by RES is comparable to that generated by traditional ones, as is expected to be the case in the near or long-term future [2].

Nowadays, energy is produced and distributed under a centralized framework, through which different energy producers sell their energy to centralized energy market/system operators or big power suppliers. However, such an approach prevents small electricity producers, which mainly generate energy from RES, from participating in the electricity market, and requires them to be organized in bigger energy associations. Virtual Power Plant (VPP) concept refers to multiple power generators being managed as a single big power unit allowing the utilities to realize OPEX and CAPEX savings [3]. Following up the VPP notion, the effective administration and orchestration of large clusters of small RES prosumers necessitates the exploitation of new technologies in energy and telecommunication sectors, while new, decentralized operational models need to be defined. Toward this direction, EU-funded project called VIMSEN: "Virtual Microgrids for Smart Energy Networks" [4] aims at researching on novel ICT mechanisms that allow multiple individual small electricity prosumers (i.e. producers and consumers) [5], [6] to be represented as a single power unit to the liberalized electricity markets following the EU regulatory framework defined in [7]. A difference between the VPP and the VMG concepts is that the former mainly involves sizeable energy producers that are not based on RES for operational purposes, while the latter involves small and very small RES producers for market negotiation purposes, so that they can be visible and have a more active role in the liberalized electricity market.

In this paper, we present a web-based Decision Support System (DSS), which resides at the Virtual Microgrid Aggregator's (VMGA) side. This ICT platform allows the creation of Virtual Microgrid (VMG) associations or clusters of Distributed Energy Resources (DERs) transforming the current centralized electricity market into a highly distributed one. VMGs are associations of DERs and/or Microgrids (MGs) that are virtually networked with each other and have agreed to operate together on a common basis, mainly so that they can negotiate more efficiently and achieve a better price when selling their produced energy. Each VMG is represented by a VMGA, which is responsible for creating efficient cluster(s) of prosumers in order to achieve its goals (e.g., to procure a certain amount of RES energy, stemming from the requested demands, at the maximum possible benefit for the microgrids or DER associations). With this structure, small-scale RES prosumers are allowed to participate in the liberalized electricity market, since the VMGA acts as a middleware between the market/energy system operators and the small energy prosumers [8], [9].

This paper is structured as follows: in Section II we outline the economic rationale behind creating dynamic VMG infrastructures and thus the motivation for the proposed DSS toolkit. In Section III, we present an overview of the proposed VIMSEN architecture and the system operations. In Section IV, we describe the VMGA Decision Support System extensively. We then describe the web platform functionalities in Section V. Finally in Section VI, we conclude this paper and present some future research insights regarding our platform's academic and commercial exploitation opportunities.

II. Economic Reasons For VMGs

Small RES prosumers who sell their surplus energy (after subtracting the energy they consume) find it difficult to participate in a liberalized electricity market. This is because RES production marginal costs are very low (in contrast to startup and average production costs that are high) and so are the respective prices that small RES producers would get in the market if acting on their own, in which case, being small and many, they would have to be "price takers". For this reason, FIT policy and its variants are used by many countries to make RES investments sustainable and meet the objectives for a "cleaner" electricity grid. The FIT policy has had a noticeable success in the last past years in promoting RES investments, but experiences some significant problems such as that: a) it cannot support a large-scale RES penetration, b) it increases the electricity costs as FIT rates are much higher than market rates, c) energy is always sold at a fixed rate regardless of the actual demand, thus operating outside of the market, and creating inefficiencies and potential bureaucracies.

On the other hand, in an open electricity market model where FIT is removed, many small uncoordinated RES producers will generally have to be "price takers" with minimal negotiating power against big power utilities and suppliers. A "price taker", by definition, has to accept a price equal to its marginal cost, which may be much smaller than its average production cost (which includes the depreciation of the initial investment and a small gain). If the price achieved by RES producers remains below their average production cost, such producers will never recover their initial investments costs, and there will be no incentive for new investments in RES production. This would of course have long term dire consequences for the climate and the economy.

The VMG concept's premise is that multiple prosumers (producers/consumers) can be grouped in virtual associations, in order to represent their collective interests in a liberalized electricity market in a more efficient and beneficial to them way. Each VMG association can negotiate as a single entity, having greater negotiating power in the market, thus becoming "price maker" or competitive monopoly. A competitive monopoly in economic terms is not really a monopoly, but a producer of a significantly diversified product (namely RES) that competes against other products (namely fossil produced energy of various types) in an open market.

III. Overall Vimsen Architecture And System Operation

The DSS platform is responsible for aggregating the prosumers, called VIMSEN Prosumers (VPs), of the system into VMGs through the application of appropriate clustering algorithms. In addition, the DSS component will be responsible for visualizing prosumption data from the individual prosumers, to negotiate with the market on behalf of the prosumers with an aim to maximize profits from the produced energy, and at the same time limiting the costs for the consumed energy, while maintaining the levels of energy security of supply. Finally, DSS is responsible for monitoring and enforcing that the production and the consumption are in accordance to the market contracts or else Service Level Agreements (SLAs), through the application of novel aggregated demand response actions [11]. Finally, novel algorithms regarding the VMG groups' formation, their dynamic adaptation, and the VMG profiles' management based on static and dynamic criteria are being designed and integrated in the DSS platform/toolkit (the algorithms themselves are out of the scope of the current paper and the reader could refer to a number of publications residing at [4]). As described in Fig. 1, the overall VIMSEN architecture comprises of five main S/W components: a) the VIMSEN Gateway (VGW), which resides at the VP side and provide the required data acquisition, communication, and facility automation capabilities, b) the Energy Data Management

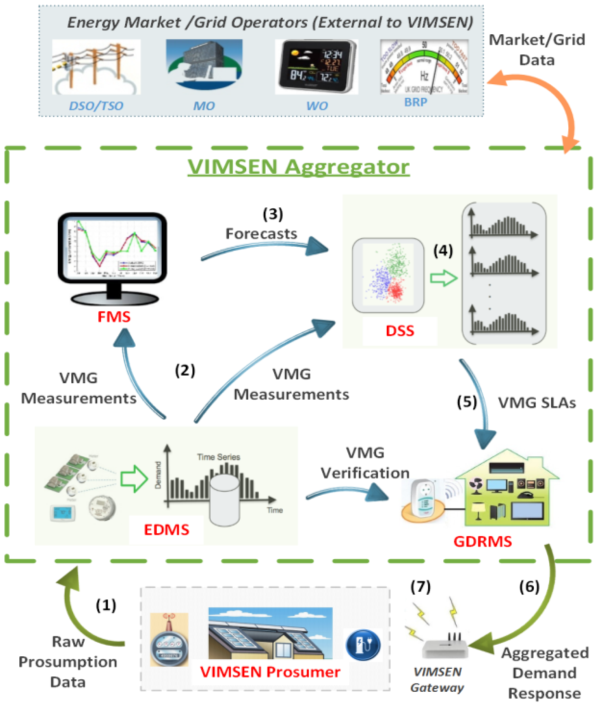

Fig. 1. The VIMSEN Architecture

System (EDMS), which acts as the system's single-point repository and provides both real measurements and short-term forecasts, c) the Forecasting and Modelling System (FMS) that provides the accurate VMG modelling and long-term forecasts, d) the Decision Support System (DSS), and e) Global Demand Response System (GDRMS), which provides aggregated demand response services. More information about each subsystem's functionalities can be found in [12].

IV. Virtual Microgrid Aggregator Decision Support System

In this section, we focus on the DSS, which resides at the VMGA side and its architecture design is depicted in Fig. 2. The DSS gathers prosumption data from each VP in the system, through the interface with the EDMS. The data that is gathered include energy production, energy consumption, the amount of stored energy, the demand response flexibility of each prosumer as well as its reliability factor. DSS receives short-term forecasts from the EDMS, which are used for effectively participating in the electricity markets. The VPs' prosumption profiles are fed into intelligent clustering algorithms, which organize the prosumers into VMGs. After the VMGs have been formed, the DSS negotiates with the electricity market with an aim to maximize the profits from producing energy, and to minimize the cost of consuming energy. DSS gathers forecasts regarding the production and consumption of each prosumer from the EDMS. Based on these forecasts will participate in the day-ahead electricity market on behalf of each VMG. Depending on the level of satisfaction of the day-ahead SLAs, the VPs may be instructed either to reduce their energy supply (e.g. by storing the energy) in case the SLA/contract is over-satisfied, or to scale back their consumption, through the application of demand-response actions, via the GDRMS. A similar procedure is also applicable for the VMGA's participation in other shorter-term electricity markets such as intra-day (interaction with traditional Market Operator - MO), congestion (interaction with Distribution System Operator - DSO) and balancing markets (interaction with Balance Responsible Parties - BRPs). Fig. 2 presents all DSS S/W modules and the technical interfaces between DSS and the other VIMSEN S/W components as well as with the Hybrid Cloud Computing Infrastructure (HCCI), while a brief description of each module's/interface's functionalities is provided below.

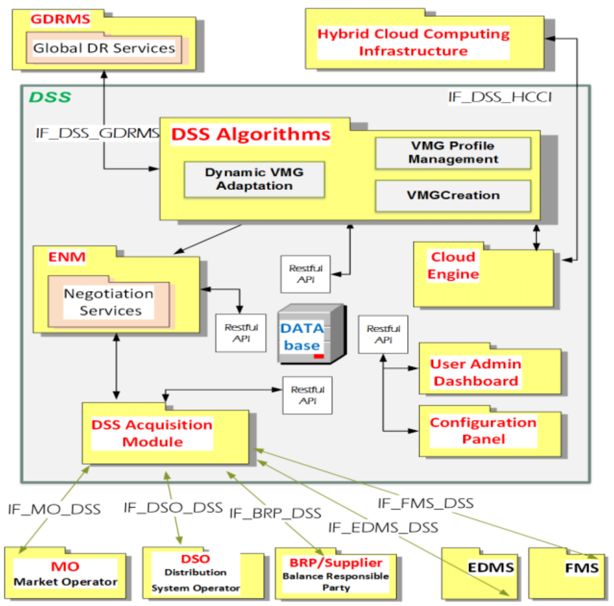

Fig. 2. The VMGA DSS Platform

There are 7 main technical interfaces with other S/W components/sub-systems external to DSS:

- The IF_EDMS_DSS interface is responsible for acquiring prosumption data from the EDMS system. This data is available in different measuring periods (daily, per hour, 15-min, 5-min, etc.). In addition, the EDMS provides short-term forecasts, which are used as inputs for the VMG creation and dynamic adaptation algorithms.
- The IF_FMS_DSS interface is responsible for acquiring data from the Forecasting and Modeling System (FMS). The data that is acquired are long-term forecasts related to the amount of energy that each individual VP is expected to produce, the amount of energy that each prosumer is expected to consume, etc. These forecasts are the basis for the long-term planning of the VMGA's energy needs.
- The IF_DSS_GDRMS interface uses the results/outputs of DSS algorithms (i.e. global DR target, set of flexible VPs to contribute), in order for a given VMG association to fulfill its promised SLAs/contracts. If it is deemed necessary for fulfilling the contracts (including DR contracts with the DSO, BRPs or other actors), DSS will issue DR targets to GDRMS and the latter is responsible for transforming the DR targets into actionable events per participating VP.
- The IF_DSS_HCCI interface facilitates the DSS algorithms' execution in a Hybrid Cloud Computing Infrastructure (HCCI), comprising of both private and public computing resources as well as VGWs' resources.
- The IF_MO_DSS interface is responsible for obtaining the necessary data from the MO that allows VMGA to participate in buying and selling energy transactions. Data sent to the MO consists of the actual bids to the market handed in by the VMGA. The main markets considered are the day-ahead and intra-day markets. The specifics of these markets' operation are subject to the regulatory framework of each MO and may be slightly different in various EU member states.
- The IF_BRP_DSS interface is used for the VMGA's participation in near-real-time balancing markets via the interaction with BRPs. For example, in order for a BRP to maintain its portfolio balanced, it may request VMGA to reduce its consumption, through the issuance of DR events.

- The IF_DSO_DSS interface is used for the VMGA's participation in near-real-time congestion market. For example, in order for a DSO to maintain the stability and proper operation of its grid infrastructure, it may request VMGA to shape its prosumption, through the issuance of DR events referring to specific locations of the grid infrastructure (i.e. local network feeders).

Furthermore, DSS comprises of 7 S/W modules, namely:

- The DSS database (DB) stores all data that is essential for the operation of the DSS algorithms, including historical data related to the prosumption profile of each VP, pricing data from the market, forecasts from the EDMS/FMS, etc., as well as the system state. Furthermore, the DSS DB stores information related to the received DR signals, as well as the corresponding performance metrics, and also market-related data, such as the bids that are submitted and the SLAs that are agreed with the market/energy grid-related actors.
- The DSS Acquisition Module (DAM) is responsible for obtaining data from external (to the DSS) sources. Data acquisition is performed either periodically, or on-demand, as required by the DSS algorithms.
- The energy negotiation module (ENM) is responsible for negotiating on behalf of the VMGs in the VIMSEN liberalized electricity market. This module uses input data from EDMS and FMS as well as market data (acquired from the MO). The ENM module implements novel dynamic pricing algorithms that decide the participation in the market, in a way that allows for the maximization of the profits and the minimization of the costs for each VP.
- The User Admin Dashboard (UAD) is the interface that the system administrators use for administering the DSS operation. A Graphical User Interface (GUI) is implemented, that allows for setting up the details of each VP, as well as the parameters that allow for the configuration of the various algorithms that are integrated in the DSS platform.
- Apart from the administration interface, another GUI is implemented for the users of the system to configure their participation. Each DSS user is allowed to view and change configuration parameters for his own VPs, as well as configure other parameters, such as the frequency and types of notifications that the user wishes to receive, or the types of DR actions that each VP is willing to take in order to optimize the energy costs. Configuration Panel (CP) incorporates all data visualization capabilities that the DSS users may have on the DSS platform/toolkit.
- The DSS algorithms module is responsible for executing the algorithms implementing the automatic operations of DSS, including clustering algorithms for the organization of the VPs into VMGs, scheduling algorithms to determine the optimal timing periods for buying and selling energy in the market, optimization algorithms to determine what is the appropriate quantity and price to participate in the market, in a way that maximizes the revenue from producing RES, while at the same time maintaining energy security of supply. The DSS algorithms module are capable of executing the intelligent algorithms locally, or depending on the local server load, may communicate with the HCCI to offload "heavy" processing tasks.
- Cloud Engine (CE) module is able to manage the HCCI by allocating "heavy" computational tasks incurred by DSS algorithms to the private cloud resources, the public/community cloud resources and/or to the available VGWs' resources. The CE has been designed to be modular in order to support multiple cloud platforms with minimum effort and changes. In addition, CE supports a number of configuration parameters that can be used to define the cloud computing services and their detailed characteristics that will be utilized for the algorithms' execution. Hence, the CE can be configured to use either one or a combination of the supported cloud platforms.

V. WEB PLATFORM FUNCTIONALITIES

This section showcases four basic functionalities of the VMGA DSS platform, namely: a) visualization of aggregated historical and real-time data for multiple VPs, b) visualization of forecast vs. real data for multiple VPs, c) visualization of open energy data published by the MO and monitoring of an SLA's ongoing progress, and d) creation and adaptation of a VMG association to accomplish a given goal (i.e. target aggregated prosumption profile). In the following, a brief description of DSS functionality is given, accompanied by respective illustrations.

A. *Visualization of aggregated historical and real-time data for multiple VPs*

Upon a DSS user's request, historical data is acquired from the DB via a RESTful API. In case real-time data is requested, DAM uses a web API to retrieve the appropriate data from EDMS. Then, DAM stores the data to DB and figures are visualized in CP via a RESTful API. The user can select among various choices to visualize consumption and/or production/storage data in timeframe he/she wants (5-min, 15-min, hour, day, week, month, year etc.).

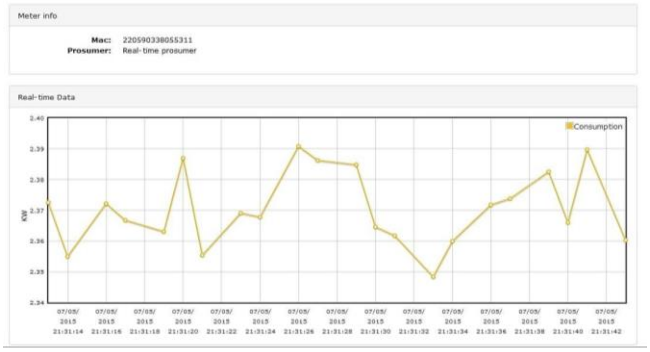

Fig. 3. The real-time data interface for an individual VP

Visualization of historical data is available to users, for multiple VPs and aggregated profiles of specific groups of VPs. As shown in Fig. 3, real-time data can be streamlined for a specific time period in order for the end user to be able to continuously monitor the real-time operation of an individual VP.

B. Visualizing forecast vs. real data for multiple VPs

DSS user is able to request day-ahead forecasts from EDMS regarding a single VP or a group (cluster) of VPs. These forecasts are then used as baseline prosumption profiles by DSS to make its bids/offers in the day-ahead market based on the pricing signals generated by the MO. DAM acquires this data and stores it in the DB. In the automated case, forecast prosumption profiles are used by DSS algorithms for the creation of a VMG infrastructure (cf. section IV.D). The result is that aggregation of VPs can considerably reduce the deviations between forecasts and real-life measurements and thus respective SLAs agreed with the MO can be better met (a similar process is followed for near-real-time events for the interaction with DSO and BRPs). The DSS user can visualize the monetary profits that the aggregation of VPs can provide to individual prosumers as a result of their participation in VMG associations. Furthermore, DSS user is able to request short-term forecasts from EDMS. The timeframe of these forecasts may vary from 15 minutes to several hours enabling the DSS user to manually adapt the VMGs dynamically in order for VPs to be able to participate in the various variants of the intra-day market (e.g., the Italian MO with which our tool currently interacts, realizes five different types of intra-day markets [10]). In Fig. 4, all profiles of individual VPs (both forecast and real) are illustrated accompanied by aggregated profiles for the randomly selected group of VPs. The test sites include 33 real prosumers and are located in Sardinia (Italy) and Athens (Greece). They were chosen because of their locations and facilities benefits for the project.

C. Visualization of open energy data published by MO and monitoring of an SLA's ongoing progress

Regarding market-related data, this is retrieved from the DAM in case of historical data and directly from MO (or an energy system/ grid operator) upon the receipt of a new electricity market event (e.g. DR signal, day-ahead, intra-day, congestion/balancing market bid etc.). Data is stored in DB and is mainly used as input for many DSS algorithms. Upon a

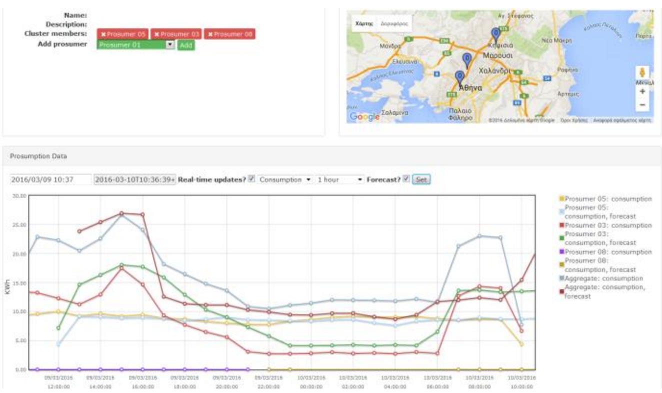

Fig. 4. Real vs. forecast aggregated data

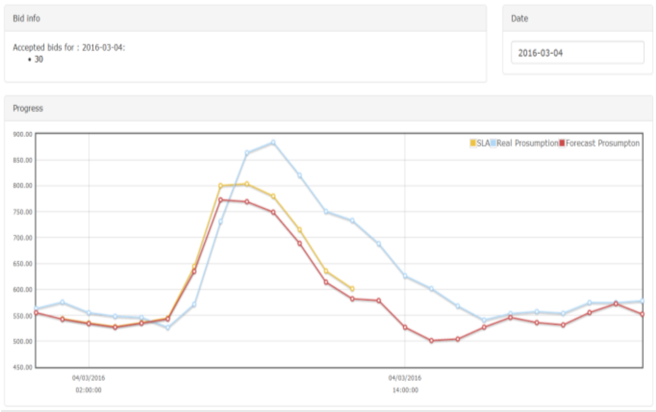

Fig. 5. Open data acquisition from a Market Operator and monitoring of an SLA's ongoing progress

market-related event published by MO, DSS platform should be able to respond accordingly by providing RES offers via the aggregation of individual VPs in the residential sector. The DAM is acquiring the notification from the MO and a message is also displayed at DSS user's side (CP). The day-ahead SLA should be accomplished by VMGA during the next day. In Fig. 5, day-ahead and intra-day curves present the forecasted prosumption, real prosumption and the given SLA. Optimization clustering algorithms are executed to dynamically group the VPs, in order to conform to the agreed contracts through reclustering and/or demand response techniques.

D. Creation / adaptation of a VMG

DSS user can create a VMG group by selecting and configuring a plethora of parameters via the Configuration Panel (CP). The creation of a VMG association may be subject to a regulatory constraint (e.g., the "entry barrier" constraint is used in many countries where a minimum amount of energy is required for a single prosumer/VMG to enter the market). The user can visualize the results of different VMG selection scenarios and compare them to find the most efficient one for each type of event. This can be done manually but also automatically with the aid of a respective DSS algorithm. Finally, as shown in Fig. 6, DSS user is able to "edit" an existing VIMSEN association (add/remove a VP or adapt some VMG configuration parameters).

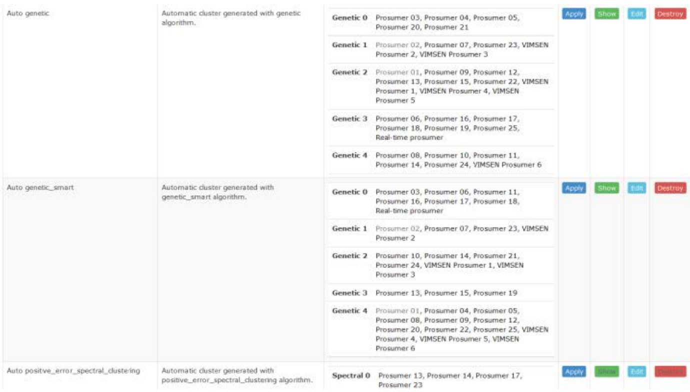

Fig. 6. List of various "clusterings" (i.e. VMG) variants

VI. Conclusion and Future Research Directions

DSS platform is currently under development within the VIMSEN project's context [4]. The next steps include the integration of even more DSS algorithms to perform automatic decision-making about the prosumers' participation in the liberalized electricity market. This section provides an overview of these DSS algorithms and several opportunities for the platform's long-term exploitation.

A. DSS Algorithms

The dynamic/automatic functionalities of the DSS platform (instead of the manual ones described in section IV) are realized via the "DSS algorithms" module. Example categories of DSS algorithms that have been so far implemented and integrated in the DSS platform are: a) clustering algorithms for VMG creation and dynamic adaptation, b) RES scheduling algorithms for VMG profile management, c) aggregated DR and virtual storage asset management algorithms, d) auctioning algorithms for RES assets' negotiation with the market, e) energy prediction and forecasting algorithms, etc. VIMSEN proof-of-concept results are focused on showing that the scenario where multiple VPs are aggregated together to achieve a common objective can outperform the scenario in which each individual VP tries to optimize its own energy prosumption assets.

B. VMGA DSS Platform Exploitation

The exploitation opportunities in the future with respect to the platform's innovation potential are briefly described below:

1) Research E-Infrastructure

DSS platform can be used as an e-infrastructure for research purposes to experiment on novel market mechanisms for distributed RES. In particular, a researcher may connect to the platform, set his/her own scenario and run his/her experiments. Furthermore, he/she can develop novel DSS-related algorithms to compare their performance to that of already deployed open-source algorithms such as those developed within the VIMSEN project's context [4].

2) Energy Services Company (ESCO)

An Energy Services Company (ESCO) or power aggregator can take advantage of the proposed platform's concepts in order to be able to provide innovative services to its customers. For example, the hybrid CC-based deployment of the platform will provide business logic hints about cloud-based converged energy-ICT services that could be offered to both system operators and VPs realizing new revenue streams.

3) Policy Maker

DSS platform could provide authorized access to users from MO and regulator's side offering thus "book-keeping" services. These users should be able to login to the DSS via UAD and request for historical data regarding past energy trading contracts and SLAs. Hence, policy makers will be able to use DSS functionalities for electricity market planning purposes per geographical region and adjust their regulatory policies in a more efficient way.

4) Communities

Finally, non-profit based public organizations or public-private-partnership (PPP) initiatives acting on the interests of their associated members (e.g. a municipality) can use the platform's functionalities for managing blocks of buildings more efficiently. Actually, Sedini municipality located in Sardinia of Italy aims to be an official user of the platform within the VIMSEN project's context. In this case, the municipality's public buildings are equipped with appropriate H/W installations in order to be able to better manage their energy prosumption assets.

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