Generalized Microgrid-to-Smart Grid Interface Models for Vehicle-to-Grid

Claudia Battistelli, *Member, IEEE*

***Abstract*— This work presents a systemic method to address the integration of electric vehicle (EV) services in electricity distribution areas. Unidirectional vehicle-to-grid (V2G) is considered as the first feasible step in exploiting the EVs potential to provide energy services for the grid, because it necessitates of fewer infrastructures and gives lower stress to EV batteries. The implementation of unidirectional V2G requires the application of smart grid (SG) features in distribution networks with local micro-generation units, which involves dealing with the microgrid (MG) concept. In this respect, a generalized model is proposed to facilitate the definition of the possible modes of V2G interaction with both the other domains of the MG and the SG interface. An application of the methodology is proposed for the energy trading in short-time markets. In this case, the participation of V2G is addressed via optimization-based modeling where the different EV service attributes are considered by indices.**

***Index Terms*—Energy trading, Microgrid, Smart Grid, Smart User Grid, Vehicle-to-Grid.**

I. INTRODUCTION

A. Background

Vehicle-to-grid (V2G), the provision of energy or ancillary services from a fleet of EVs to the grid, can bring about new mechanisms and modes for participation in the deregulated electricity market [1, 2]. Through V2G it is possible to strongly characterize microgrid (MG) features such as consumers' jurisdiction, self- and distributed generation, flexible distributed energy resources (DERs), energy storage systems (ESSs), and overall the possibility of participation in energy trading through the future standard of two-way communication with the smart grid (SG) [3].

The feasibility domain and the economic potential of both revenues and collective benefits of the integration of V2G in electricity users' areas (EUAs) are definitely huge, but for a concretization of targets in reasonable times the internal development of these areas from now on has to be driven by proper and systemic approaches that should be easily customized to specific applications within the smart technological environment. Such approaches should be robust and flexible, in order to address either already existing structured electricity service areas or new large-scale implementation cases. For this purpose, an extension of the application of MG paradigms sounds promising in the roadmap toward the development of SG interfaces [4]. Such extension represents the core of the generalized model of MG-to-SG interface proposed in this paper to address the integration of V2G in the electricity distribution systems.

B. Purpose and Contributions

A methodology based on the use of MG concepts is proposed to investigate and discuss how the SG paradigms could be customized to the V2G implementation. In this respect, the paper gives two main contributions –first, it proposes a new paradigm, the *smart user grid (SUG)*, for systematizing the concepts, and second, it develops an advanced and generalized model based on this new paradigm for the study of EUAs provided with EV services.

The proposed modeling approach, for its evident methodological features, is flexible and therefore suitable for different applications. In this paper, we consider the market context to show how SUG approach and related models should be used for studying the energy trading in local short-term markets where also V2G participates. Tools and models needed for this study are described. Since the problem of energy trading can be formulated as an optimization problem, a general formulation of this problem is derived based on models already presented in literature. However, some developments of these models are proposed in order to include in the formulation the different V2G attributes via indices. The case study of a SUG representing a load serving entity that provides unidirectional V2G service is addressed.

II. METHODOLOGY DESCRIPTION

A. The "Smart User Grid" Paradigm

Any EUA provided with micro-generation (and hence "active") can be viewed and represented as a general structure made of several domains of major functionalities (generators, flexible/non-flexible loads, EESs, transformers, etc.) having different features, uses, behaviors and requirements. Each domain is reserved for different tasks performed by individual agents that can have interoperations with each other [3]. This structure, given the clear connection with MG and SG concepts, will be referred to as "smart user grid" (SUG).

From a market perspective, the SUG can be seen as an EUA operator (e.g. a pool delegate energy manager) integrating two main components:

- *Supply point:* it is the front-end of the SUG interfacing with the SG. This point represents a physical and intelligent power section capable to: a) exchange energy with the SG; b) control the state of connection between SUG and SG; c) act as the SUG participants' representative.

Claudia Battistelli is with the Department of Electrical and Electronic Engineering, Imperial College, London, UK (email: claudia.battistelli@hotmail.it)

- *Sub-SUGs:* representative of the individual domains/functionalities; aggregated via a proper architecture that mixes hierarchical and peer-to-peer relations managed by multi-agent system (MAS) procedures [3].

The SUG can be virtually represented as an aggregator of all the functionalities within the EUA that also acts as a mediator for the participation in the energy market. Any component of the SUG - being it a MG, a multi-MG, or an individual energy entity - can be conceived as a sub-SUG. Fig. 1 shows a possible evolutionary implementation of SUG concepts. A SUG can coordinate and represent various combinations of MGs and multi-MGs, including different operators organized according to similar operation and technological platforms. As further described, also EV services aggregators can be recognized as operators, concretizing the possibility to extend the MAS paradigm for realizing modes of distributed or mobile operation for the V2G. Note from this figure that also the EV aggregators can be seen from the SG interface as individual agents (sub-SUGs) representing the first level in the hierarchy of the two-way communication with the SG.

B. *Approach to Microgrid Modeling*

Within the SUG paradigm, a correct roadmap should be defined to best exploiting the potential of the MG paradigms. For this purpose, a systemic approach has to be recommended in order to safely and effectively address the incorporation of different MG features into more or less complex EUAs.

The approach to EUAs modeling requires a preliminary phase aimed at setting up the MG's architecture. The first step of this preliminary phase considers two aspects: 1) MG's structure and organization must fit in with the operational needs of the individual electric facilities within the EUA; 2) electricity is an essential internal service that can contribute to the unitary value of the consumers' economic activity and can be a commodity, but first it has to comply with the aforesaid operational needs of the electric facilities. Therefore, the systemic approach has to be supported by service-oriented analytic procedures enabling the *customization* of the MG applications to the service areas' characteristics.

The customization envisages decomposing the organizational EUA's structure into individual physical sections and defining the technical and service requirements specifications, which makes possible to identify what MG features could be implemented in any specific case. The expected outcome of this step is the definition of agents, internal rules, formal constraints derived from peer-to-peer relations and interactions, individual agent's strategies, and then of all the elements that can feature a "customer-driven MG" [5]. This process leads to a definite configuration through the added value given by a *rationalization* of the available DERs, loads and other area components, which can be easily pursued through: a) aggregation of these components; b) definition of the corresponding architecture; c) assignment of preliminary attributes and features to the single entities. The application of service-oriented methods helps mitigate the criticalities associated with both the identification of communication networks and the secure management of data information. The use of systemic procedures can help simplify interrelation and interfacing features and therefore facilitates the design of the logic architecture of the SUG-to-SG model. For example, wide EUAs containing heterogeneous DERs can be horizontally organized in multiple MG cells and vertically layered in levels, as in Fig. 1. Finally, the application of methods such as the Class Diagram techniques can help identify the criteria of aggregation of DERs and loads, the associated interdependencies among components, and the attributes and parameters characterizing the individual functionalities.

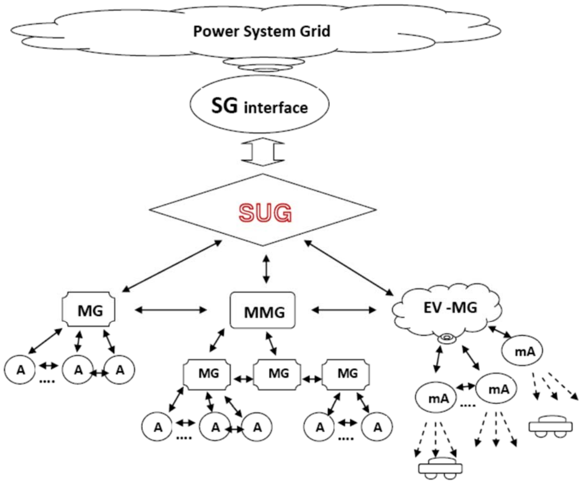

Fig. 1. Evolutionary scheme of SUG

The second step of the MG's architecture set up addresses the detailed model's configuration through a *parametrical analysis* that aims at identifying the most relevant attributes, parameters and variables for the definition of the peculiarities of each agent and, in the whole, of the entire modeling area. At this stage, the physical distribution of functionalities and components within the EUA has to be properly considered, in order to define quantity and quality of the parameters that characterize, on one hand, the generation and load profiles (*parameterization*) and, on the other hand, the different combinations and aggregations of components (*vectorization*). Parameterization and vectorization allow defining the models for the DERs' operation modes and the users' consumption trends.

With specific focus on the V2G agent, the stage of MG modeling should bring to a complete definition of the organizational, operational and economic attributes of the EV services, for both the V2G operator side and the EV customers side.

C. *Approach to Vehicle-to-grid Modeling*

In EUAs providing V2G services, the modeling of the EV aggregator functionalities, either unidirectional or bidirectional, can be efficiently solved via the methodological approach discussed above, and in this respect customization and configuration procedures appear particularly suited to identify the V2G entity.

From an organizational point of view, the characterization of the V2G has to be done taking into account not only the specific EV attributes (e.g., EV type, battery size, driving range, charging/discharging time, price, reliability) and V2G service attributes (type of V2G infrastructure/parking, operational program, trading strategy, costs, customers segmentation) but also the local end-users' demographic and socio-economic attributes, because these characteristics influence EVs penetration and demand rate patterns [6]. All these attributes, properly classified, constitute the basis for the parameterization and vectorization of the EV aggregator.

From a market perspective that particularly regards the type of services the V2G can provide, the characterization mainly depends on the V2G infrastructure being either unidirectional or bidirectional. Unidirectional V2G can sell demand response services by throttling EVs charge rate only, being therefore limited to participation in regulation or spinning reserve market, whereas bidirectional V2G would be able to provide electricity delivery to the grid as an additional service [1]. It must be recalled in this respect that if the implementation of unidirectional V2G sounds feasible and promising, on the other hand the bidirectional solution still appears futuristic because it requires additional hardware not included in the EVs in production and it increases the battery degradation [7, 8].

It has to be considered that an EV service aggregator has several technical and commercial options for differently organizing its services or for differently and independently participating in the market mechanisms. For example, with respect to the market, the aggregator can participate in the energy trading at different levels based on the pursued business strategy - it can operate as an independent agent that represents itself in the bidding; or it can decide to aggregate with another entity (e.g. a MG agent, or a Multi-MG agent) to sell its services.

III. METHODOLOGY IMPLEMENTATION FOR THE MARKET

A. *Vehicle-to-grid Participation in the Energy Trading*

Differently from other types of operators, the EV aggregator is still hardly featured as a participant in the energy market due to the clear difficulty of statically representing the dynamics of the EV services. Moreover, the EV services appear to be affected by a substantial uncertainty that is related to the financial risk the EV aggregator incurs because of the rigidity of the energetic strategy carried out by the SUG agent. These issues could be however overcome considering that until now the V2G provision can be realistically assumed in real-time (balancing) markets only. In these markets, dynamics and uncertainties can be neglected if certain simplifications and assumptions are made for the modeling of the EV aggregator. In this respect, bidirectional EV services could be modeled via load or generation profiles representative of EV charging or discharging services, whereas unidirectional EV services could be modeled as variable load profiles.

Introducing the EV aggregator as an active agent in the energy trading does not change features and mechanisms of the market where the SUG operates. However, combining the V2G service in the energy bidding can impact on the business formula adopted by the SUG, because the EV aggregator represents an “additional economic value” at the interface with the SG and this additional economic value could complicate or slow down the consolidation of the final bid of the SUG. The complexity of the SUG’s configuration is related to the actual contribution of the EV resources to the SUG customers and to the possible presence of multiple MGs with multiple EV agents at the interface with the SUG. In view of the business formula adopted by the SUG and of its complexity, the EV agent will decide its own market participation options based on the peer-to-peer set with the other SUG’s agents (or other Sub-SUGs) and on an evaluation of the tradeoff between the costs and the benefits of participating in the SUG market.

According to the possible aggregations of the SUG components and to the agreements among the Sub-SUG agents, including the EV aggregator for the V2G services, a generalized SUG model can be derived. In the configuration shown in Fig. 1, for example, a common EV-MG agent provides the interface with the SG functioning as an energy service company (ESCO) that manages the sub-SUG security strategy and represents the pool of all the MG agents included in the sub-SUG for their participation in the market. This example makes other so-far-atypical solutions realistic, considering on one hand the intrinsic unsteadiness of the local RESs and DERs and on the other hand the different stability and elasticity of individual offers from SUG participants.

From a market perspective, the multiplicity of different domains within the SUG represents a major variable for the generalized model. Even for MGs operating autonomously, in some cases the association of them for market participation and business purposes could be more profitable for the different MG agents, because of the respective available RESs and DERs and because of the respective internal costs and energy prices elasticity, the latter depending on the whole dealing with the SG interface. A second variable in the modeling within the market is the flexibility of the EV service organization and management, which in general depends on the way of aggregating the local EV parking and charging demands and on the possibility of implementing different V2G services. Other variables can be the EV aggregator (real or virtual parking areas characterized by rated parameters of physical extension, EV parking places, plug-in places, unidirectional/bidirectional service) and some management variables that can be assumed in terms of service timetable, sharing of EV service capacity among internal (inside parking area), public and resident customers, etc.

The EV-SUG agent has to be designed based on: a) the SUG’s configuration; b) the EV aggregator’s configuration; c) the service features to rely on. For this purpose, a systemic optimization study should be carried out in order to find a business formula for the EV aggregator that at a first level is compatible with its presence within the SUG and its coexistence with the other agents, and at a second level is optimal for its active participation in the market. In the following, this optimization study is further explored with specific reference to unidirectional V2G, and mathematical models for the EV aggregator and the analysis of the optimal trading strategy of the SUG-EV agent are presented.

B. *Aggregator Model*

The proposed aggregator formulation builds on the conceptual framework associated to plug-in EVs. The concreteness of the model makes it a valuable support tool for the implementation of V2G into real-world.

At least two aspects should be considered to model an EV aggregator. First, since the principal utility of vehicles lies in their availability to provide transportation to its owners, the EVs may not always be plugged into the grid. Second, the energy stored in the EVs plugged into the aggregator and available for the EV service provision is variable and depends on the distance travelled during the day. These aspects should be properly represented in the aggregator model. Moreover, since the power the EV aggregator can provide for unidirectional service depends on factors such as type of batteries, size, number and type of vehicles, EV state (driving pattern), charge/discharge rate of the battery [9], the definition of these is also necessary for the modeling. All these factors are affected by uncertainty (e.g., the EV state, which depends on the driving pattern) or by variability (e.g., the type of vehicle, which could be "non plug-in", or "plug-in charge-only", or "plug-in charge/discharge").

Based on the above, the mathematical model of the power $P_{EV-Ag}(t)$ that each EV aggregator provides within the SUG for unidirectional V2G services can take the following formulation, as detailed in [9]:

$$P_{EV-Ag}(t) = r_c(t) \cdot N_{EV,c}(t) - r_{sd}(t) \cdot N_{EV,i}(t) \qquad (1)$$

In (1): $r_c(t)$ and $r_{sd}(t)$ respectively are rates of charge and self-discharge at time *t*, whereas $N_{EV,c}(t)$ and $N_{EV,i}(t)$ denote, respectively, number of charging EVs and inactive (that is, connected but not charging) EVs at time *t*. $N_{EV,c}(t)$ and $N_{EV,i}(t)$ are stochastic variables that could be modeled via time-series techniques, whereas the uncertainty associated with $r_c(t)$ and $r_{sd}(t)$ could be taken into account via ranges of variation.

Note that the aggregator is modeled in (1) only with respect to technical and technological parameters. The economic parameters needed to complete the representation of the aggregator for the energy trading problem should rather be considered in the formulation of the optimization model for the trading, as shown in the next subsection.

C. *Generalized Optimization Model for Combining Unidirectional V2G with SUG Services in the Energy Trading*

A mathematical formulation is given here for the problem of trading in the short-term energy market for a SUG that owns thermal and renewable power plants as well as a unidirectional V2G infrastructure, hence serving a load which tends to be perceived by the grid as an equivalent customer with significant EVs penetration. This formulation is a generalization of that presented in [2], and can be applied to any particular configuration of SUG, included those with unidirectional V2G.

The problem can be expressed as an optimization algorithm where the objective is maximizing the expected profits of the SUG under certain imbalance, operating and EV charging constraints. The objective function should take into consideration the contribution of all the domains (sub-SUGs) of the SUG, as follows:

$$\begin{aligned}&Maximize\\ &PROFIT_{SUG} = \textstyle\sum_s \pi_s \cdot (PFT_s + PFR_s + PFD_s + PFI_s)\end{aligned} \qquad (2)$$

where: 1) PFT_s is the per-scenario (*s*) profit from thermal generation, which is a function of thermal energy revenues, thermal production costs and start up cost, per time period and generating unit; 2) PFR_s is the per-scenario profit from RESs, which depends on RES revenues and on production, operation and maintenance costs; 3) PFD_s is the profit from both traditional (non-EV) and EV load serving; 4) PFI_s is an imbalance term that takes into account additional profit or penalties due to renewable power, load imbalances, or other factors that are not necessarily electrical but can affect the service operation. The parameter π_s takes into account the probability of realization of a scenario *s*.

Note that the unidirectional V2G is modeled in the objective function by means of the load profit term, PFD_s, which consists of two terms – the first is the SUG's revenues paid by the loads, EVs included, the second term is the cost of the scheduled energy to be purchased by the energy market:

$$PFD_s = R_s \cdot \left(L_{ac,s} + EV_{ac,s}\right) - \rho_s \cdot \left(L_{sch,s} + EV_{sch,s}\right) \qquad (3)$$

In (3): R_s and ρ_s respectively are utility rate charged to customers and spot market energy price; $L_{ac,s}$ and $L_{sch,s}$ are per-scenario realized and scheduled hourly utility demand, respectively; $EV_{ac,s}$ and $EV_{sch,s}$ are per-scenario realized and scheduled hourly EV power draws, respectively.

In this optimization model, the systemic methodology addresses the identification of scheduled hourly EV power draws, $EV_{sch,s}$, as dependent on systemic factors that can be considered by indexed parameters K_X, K_Y, K_Z, which relate $EV_{sch,s}$ and PFD_s attributes to the following vectors of variables:

- $\bar{X}$: extension of distributed areas managed by the aggregator within the SUG perimeter and car fleet characteristics.
- $\bar{Y}$: aggregator's strategy of service offer, determined by the criteria of managing the EV service potential of the cars fleet.
- $\bar{Z}$: customers' behavior modes.

The indices K_X, K_Y, and K_Z are defined as system parameters because they are functions of its state. These parameters can help identify the main quantitative features of the EV service within the Sub-SUG model, in particular the hourly EV charging service profile associated with the EV aggregator's bid and the related economic estimates, as shown in Fig. 2.

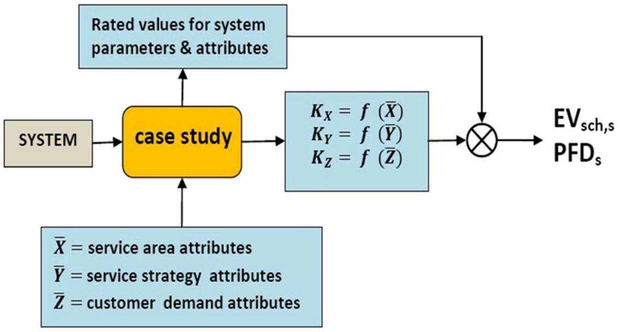

Fig. 2. Systemic approach for EV service identification

Therefore, every scenario *s* has to be dealt with by referring these parameters to the rated conditions of the system. This can be achieved by assigning each scenario the proper values of K_X, K_Y, and K_Z, within the range [0, 1], through careful system analyses or design criteria based on systemic methodologies.

Note that any power generation, load, or responsive demand (beside unidirectional V2G) can be included in (2) to particularize the individual terms of the equation.

The constraints to be considered in the trading problem formulation regard the imbalance modeling, the operation of the generating units and the EV charging. These constraints have to be formulated as equations or inequalities. In particular:

- *Imbalances:* the discontinuities in either the imbalance-up (over-generated power in excess of combined schedule) or the imbalance-down (under-generated power in deficit of combined schedule) should be modeled.
- *Operating constrains:* thermal power output limits, scheduled renewable power limits, ramp up/down limits and minimum start up times should be included as inequalities.
- *EV charging constraints:* proper inequalities should be introduced to express that the battery cannot exceed its maximum charge capacity and cannot charge at a rate greater than its charging rate. Additional equations or inequalities should be introduced to model the EV states of charge at certain times of the period of study (e.g. before the first morning commute and at the end of the day). Finally, inequalities to ensure the EV power draw being always between the bid capacity limits should be considered as well.

Many of the data required for formulating aggregator and optimization models should be obtained from statistical databases. Unfortunately, EV market and related technologies are truly emerging; therefore very few statistic data are currently available. In this respect, aggregator and optimization models should be considered as typically affected by generalized uncertainty and therefore built up using proper and robust methodologies, capable to deal with probabilistic formulation and stochastic variables.

V. SIMULATION

An application of the methodology is here given considering a simple but concrete case study, with the specific target of demonstrating implementation criteria and flexibility of the proposed approach. This case study addresses the maximization of profits for a small EUA owned by an independent operator that serves as a distributed aggregator. This operator - e.g. public operator, managing the parking services for the municipality – aims to adapt its own organization and service strategy to participate in the electricity market as an interface for end-users. As shown in Fig. 3, the EUA can represent either an aggregator's energy manager (EV-MG interface) or the SUG's manager serving as a market operator (e.g. ESCO).

The EUA includes two parking lots – *PKA*, an inner city parking lot suitable for short-term parking, and *PKB*, an extra-urban parking lot for commuters. These parking lots have inverse functional dependency between parking time and price, due to their different locations.

The case study is implemented as an optimization problem, with equation (2) rewritten as follows:

$$PROFIT_{EUA} = \pi \cdot (PFD_{PKA} + PFI_{PKA} + PFD_{PKB} + PFD_{PKB} + PFL) \tag{4}$$

assuming s=1. PFD_{PKA} and PFD_{PKB} are the profits from EV charging in parking lots *PKA* and *PKB*, respectively. PFI_{PKA} and PFI_{PKB} are additional profits due to parking service provision, hence representing the imbalance term of eq. (2). PFL represents the revenues from load available to support unidirectional V2G in ancillary service provision. A probabilistic approach can be considered to model π in an off-line subroutine that assigns this factor values varying in the range [0, 1]. In this case, it is assumed π=1, as the reference framework considered for the simulation is that of real-time (RT) trading, where costing techniques based on the RT pricing paradigm are adopted.

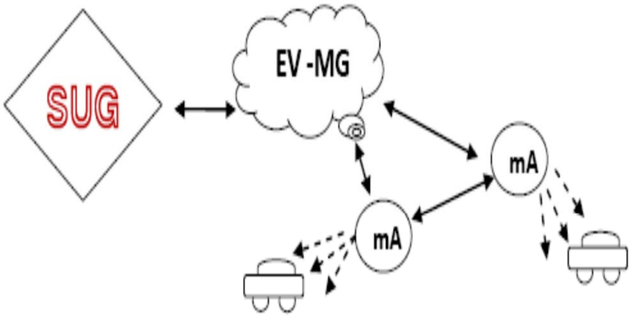

Fig. 3. Architecture of EUA considered in the case study

Two different situations are simulated.

- <u>Case 1:</u> the aggregator applies variable tariffs for parking, and RT energy price for EV charging service.
- <u>Case 2:</u> the aggregator applies variable tariffs for both parking and EV charging services.

The problem is characterized via indices K_X, K_Y, K_Z as follows:

- K_X: Service area attributes are supposed not included in the aggregator's service strategy (e.g., the aggregator is choosing how to invest based on approximate evaluation of revenues, in an early planning stage). In this case, K_X is not a variable within eq. (4) but instead it is a parameter of the problem.
- K_Y: This index is a variable of the problem and within the objective function, which takes into account the different characterization of the aggregator's service strategy offer in the two cases.
- K_Z: As costumers' behavior is not considered, this index is neglected.

For this study, energy prices are taken from the 2012 U.S. EIA report; load and EV data are taken from [12]. Each parking lot is assigned certain capacities to host internal combustion engine (ICE) cars or EVs, and prices that vary linearly with number of cars hosted. Three different scenarios are considered for the two cases, where EV parking spaces ($N_{EV,lim}$) respectively are 50%, 40% and 30% of ICE car parking spaces ($N_{IC,lim}$). For reference, some of the characteristics are summarized in Table I.

Simulation results are depicted in Fig. 4, which shows the maximum profits obtained in each case as well as the contribution from the different resources of revenue. Note in particular that main contribution to the total profit comes from PKB, due to its higher hosting capacity, whereas loads give the lowest profit. The average contribution (in %) from each revenue resource in both cases is shown in Fig. 5.

TABLE I. DATA

	PKA		PKB		
	$N_{EV,lim}$	$N_{IC,lim}$	$N_{EV,lim}$	$N_{IC,lim}$	*L (kW)*
50%	200	400	500	1000	80
40%	160	440	400	1100	50
30%	120	480	300	1200	50

	PKA		PKB	
	Parking ($/h)	*EV charge (c/kWh)*	*Parking ($/h)*	*EV charge (c/kWh)*
Case 1	y=a+bx	18	y=a+bx	15
Case 2	y=a+bx	y=a+bx	y=a+bx	y=a+bx

Two observations should be done regarding the assumptions made. First, K_X has been supposed as a parameter; however, in the hypothesis of limited investment capability for the aggregator, this index would be modeled as a variable function. Secondly, in order to introduce a scheduling strategy, the assumption of RT pricing should be removed.

IV. CONCLUSIONS AND FUTURE WORK

This paper presents a new methodology for the systemic study of V2G integration in EUAs. MG and SG concepts are recalled to develop a new modeling paradigm, the SUG, which is suited to flexibly represent the different complexities possibly arising from the V2G integration. Proposed methodology and model are then applied to the electricity market context to analyze the new mechanisms introduced by the participation of an EV service entity in the short-term energy trading of an EUA. Unidirectional V2G is considered for the EV entity. Since the energy trading problem should be addressed as an optimization problem, the SUG model is translated into mathematical formulations that properly take into account the EV service via attributes characterized by indices.

An illustrative but realistic case study is used to demonstrate the implementation criteria and the effectiveness of the approach. The methodology is flexible, and therefore the made assumptions do not restrain the possible extension of the case study to more complex physical structures. This extension can be easily achieved through the systemic implementation of general SUG model architecture and associated computation tools.

The mainly conceptual work presented here is the first result of a research study devoted to developing robust methodologies and tools for the assessment of V2G integration in the electricity scenario. Future work will focus on implementing the proposed methodology on real cases. This also envisions accurate parametrical and sensitivity analyses of the EV attributes as well as accurate modeling of the uncertainties via robust statistical/probabilistic techniques.

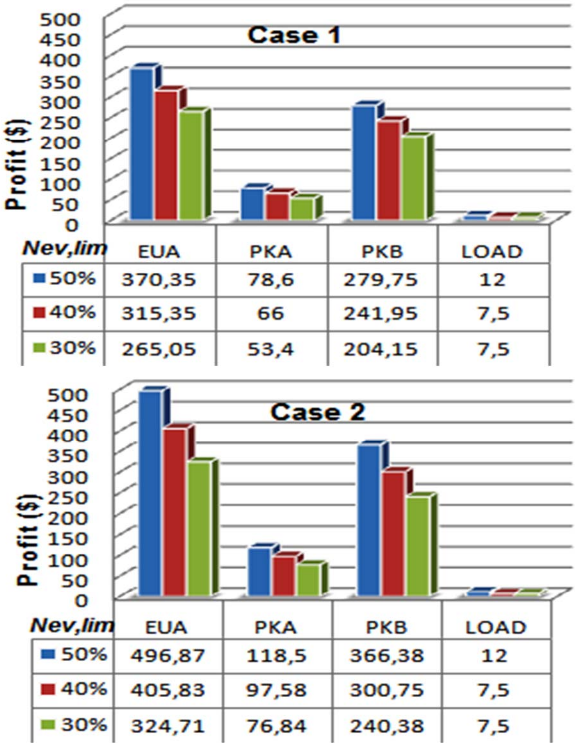

Fig. 4. Maximum profits for EUA and other service resources

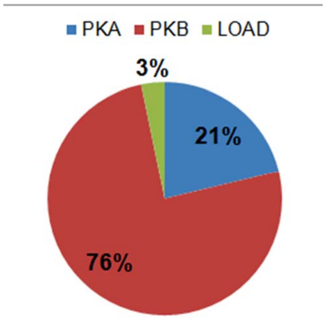

Fig. 5. Average contribution of each source of revenue to EUA profit

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