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Regulatory framework and business models for charging plug-in electric vehicles: Infrastructure, agents, and commercial relationships

Tomás Gómez San Román, Ilan Momber*, Michel Rivier Abbad, Álvaro Sánchez Miralles

Instituto de Investigación Tecnológica, Universidad Pontificia Comillas, Madrid, Spain

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A B S T R A C T

Electric vehicles (EVs) present efficiency and environmental advantages over conventional transportation. It is expected that in the next decade this technology will progressively penetrate the market. The integration of plug-in electric vehicles in electric power systems poses new challenges in terms of regulation and business models. This paper proposes a conceptual regulatory framework for charging EVs. Two new electricity market agents, the EV charging manager and the EV aggregator, in charge of developing charging infrastructure and providing charging services are introduced. According to that, several charging modes such as EV home charging, public charging on streets, and dedicated charging stations are formulated. Involved market agents and their commercial relationships are analysed in detail. The paper elaborates the opportunities to formulate more sophisticated business models for vehicle-to-grid applications under which the storage capability of EV batteries is used for providing peak power or frequency regulation to support the power system operation. Finally penetration phase dependent policy and regulatory recommendations are given concerning time-of-use pricing, smart meter deployment, stable and simple regulation for reselling energy on private property, roll-out of public charging infrastructure as well as reviewing of grid codes and operational system procedures for interactions between network operators and vehicle aggregators.

1. Introduction

The integration of plug-in electric vehicles (EV) in electric power systems poses new technical, economic, policy and regulatory challenges (Galus et al., 2010; Pieltain Fernandez et al., 2011; Momber et al., 2011). Due to energy efficiency and environmental advantages over conventional transportation, the future of EVs seems promising (EPRI & NRDC, 2007). However there are still important technological and economic barriers mainly related with efficient and affordable storage technologies that will hopefully be resolved in the near future (Peterson et al., 2010).[1]

Regarding the environmental advantages of EVs over conventionally propelled transportation, i.e. fossil fuel dependent internal combustion engines; it has to be kept in mind that they depend on the generation mix of electricity production at the time of charging. In fact timing is one of the reasons for coordinated charging. However, certain studies conclude that, even in rather unlikely but most CO_2 intensive scenarios, both annual and cumulative GHG emissions could be reduced significantly, due to a certain electrification level of the car fleet under analysis (Electric Power Research Institute, 2007). It is assumed that agents are profit oriented and would act in response to economic signals such as retail tariffs or market prices for electricity and could then exert different levels of control on the charging of the contracted final EV users. The pricing of externalities caused by electricity production however is assumed to be represented in wholesale energy markets.

Abbreviations: A, ampere; AC/DC, alternating current/direct current; AGC, automatic generation control; BMS, battery management system; CC, controlled charge; CP, charging point or charging post; CPM, charging point manager; DER, distributed energy resources; DG, distributed generation; DSO, distribution system operator; EMC, energy management controller; EREV, extended range electric vehicle; EU, European Union; EV, (plug-in) electric vehicles; EVC, on-board electric vehicle controller; EVM, electric vehicle meter (on- or off-board); EVSA, electric vehicle supplier aggregator; EVSE, electric vehicle service equipment; FCM, final customer meter; HO, home/domestic; HV, high voltage; ISO, Independent System Operator; kW, kilowatts; kWh, kilowatt-hour; LV, low voltage; MV, medium voltage; PR, private area with public access; PU, public area with public access; SA, supplier/aggregator or retailer; SoC, state of charge; RES, renewable energy source; ToU, time of use; TSO, transmission system operator; UCO, uncontrolled charge; V, volt; V2B, vehicle to building; V2G, vehicle to grid; V2H, vehicle to home

* Correspondence to: C/Santa Cruz de Marcenado 26, 28015 Madrid, Spain. Tel.: +34 91 542 2800x2735.

E-mail address: ilan.momber@iit.upcomillas.es (I. Momber).

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[1] Numerous research and academic institutions together with governments recently have elaborated a significant number of studies on EV technology, see for instance EPRI&NRDC (2007), Valentine-Urbschat and Bernhart (2009), Electrification Coalition (2009), IEA (2009), National Academic of Sciences USA (2009), and The Royal Academy of Engineering UK (2010).

The European Parliament recently adopted a resolution for the promotion and support of electric vehicles for personal transportation (EU, 2010). In this resolution different actions are proposed in order to achieve a single European EV market. Among those actions the call for international or at least European standardization of charging infrastructures and technologies, including smart grids, with open communication standards, should be highlighted.

The currently perceived purchase premiums compared to internal combustion engines are widely being discussed and a multitude of different policy schemes to foster EV adoption is evaluated. A comparative study shows that from a user perspective one time support at the initial investment is highly appreciated. However, recurring instruments like an annual tax benefit are more effective yet usually smaller in volume (Kley et al., 2010a).

In addition to technological developments and policy measures, regulatory issues related to investment and deployment of the required infrastructure need to be formulated and adequately solved. Coherently, there is a need for discussing how and which agents should be authorized to provide EV charging and pricing of those services, as well as how EV storage capability could be appropriately marketed to provide vehicle-to-grid (V2G) services (Kempton and Tomic, 2005). However, an accurate calculation of the benefits is a complex task in order not to misunderstand or overstate the potential (Dallinger et al., 2011; Andersson et al., 2010).

Therefore, still many questions remain to be answered within a consistent regulatory framework considering rules and players in existing electricity markets. Setting the structure for a cost-effective development and deployment of the necessary charging infrastructures is a difficult task given the early stage of the industry. Predicting all possible occurrence of economically viable and socially desirable infrastructure development in accordance with smart grid requirements poses a great challenge for decision makers. It would involve determining the financing structure to be collective or private. Investment costs could be socialised among electricity consumers or more generally among all tax payers. Alternatively they could be recovered through EV user payments only. Furthermore it is yet unclear which agents should be responsible for developing them as well as whether the business would be bound to strong monopolistic regulation or characterized by competitive components. None of these questions is answered in Kley et al. (2011). Depending on the intended outcome, the charging infrastructure could be considered a fully regulated monopoly, as transmission and distribution grids are, or a corporate entity allowed owning and deploying charging infrastructure.

All of the above raised issues can be extended to specific infrastructure capable of using EV storage for grid service provision V2G as peak power or ancillary services, frequency regulation and power reserves. However, V2G contains yet another challenge. The conditions to incentivize vehicle owners to adopt direct charging management mechanisms and yield control over the battery system are yet to be found Pecas Lopes et al. (2010). According to that, a regulatory framework needs to maintain the utility's obligation to provide reliable electric service balanced with a vehicle owner's desire to sustain control in case of personal need.

As electricity for charging EVs is used for transportation, there are various controversial arguments for a price differentiation from other electricity consumption, for instance including taxes for development of transportation infrastructure or by the contrary giving it subsidies because of carbon emissions reduction relative to traditional internal combustion propulsion systems for transportation.

As an example of these issues, in California, the Public Utilities Commission has opened a rulemaking process, in which a number of issues are proposed for consultation with stakeholders. It is yet to be determined (i) how to implement obligatory variable tariffs, (ii) legal status of electricity resellers, (iii) incentive creation for users to adopt remote charge control of valuable[2] batteries, and (iv) allocation and recovery of investment in infrastructure in a fair non-discriminatory framework (CPUC, 2010a). Furthermore, there exists an intense discussion about critical metering policies in terms of metering arrangements (single, sub- and separate metering) and their implications on cost, installation time, and billing flexibility (CPUCb, 2010b).

In this paper, a conceptual framework is developed in order to provide the basis for giving an answer to the previous main issues of regulating future large scale EV integration. The regulatory framework for the organization of the European internal electricity market (EC, 2009) is taken as reference framework in which concepts must function. However, many of the proposed concepts remain partially valid for other markets or regulatory structures. Further on, different charging modes for providing energy and V2G services are identified and presented in detail.

The paper is organized as follows. Section 2 recapitulates each role of the existing involved agents in the electricity sector. Consecutively, the new agents related to the business of charging EVs are introduced to the reader. Section 3 introduces definitions of grid and charging infrastructures. Section 4 identifies metering, communication and control equipment for charging EVs. In Section 5, charging modes associated with charging at private parking sites as well as for public use are defined. Different basic charging modes, from electricity supply at home to public and private[3] charging stations are proposed in Section 6, while Section 7 provides alternative solutions of the basic variants. The same type of business models are revisited for providing V2G services in Section 8. Finally, conclusions and some policy recommendations are given in Section 9.

2. Agents

In this section, first, existing agents of the electricity sector are defined according to the functions assigned by EU legislation (The European Parliament, 2003). Then, new types of agents who would play relevant roles in developing EV charging infrastructure and providing charging services are defined: the EV charging point manager (CPM) and the EV supplier-aggregator (EVSA).

2.1. Existing agents

Distribution system operator (DSO): is the owner and operator of the distribution grid. It is assumed that distribution is legally unbundled from generation, transmission and particularly from supply and retail. Therefore, DSOs cannot trade energy. They only provide network services and are fully regulated monopolies.

Supplier or retailer(SA): is the agent who sells energy to final customers, the electricity end consumers. In countries where distribution and supply have been unbundled, final customers remunerate the supplier for the service, who in return procures the energy and pays the DSOs regulated charges for grid services and other system costs. In other countries without retail markets,

[2] If you compare electric vehicles (EREVs, PHEVs and BEVs) to cars equipped with conventional internal combustion engine based propulsion systems amongst others, one of the major disadvantage is the increased vehicles mass due to lower energy densities in the electrochemical (e.g. lithium ion) battery packs. To attain the needed levels of power and energy, that are expected by vehicle consumers concerning range and driving characteristics, the batteries have to be sized such that at current and projected production costs the EVs are going to be more expensive than conventional vehicles and the batteries will most likely present one of the most valuable components of the car (Kalhammer et al., 2007).

[3] Private refers to either domestic or commercial (corporate), i.e. non-state owned and not public.

distribution and supply activities are carried out by the same agent, the traditional vertically integrated utility.

Final customer: is the agent that requires electricity for end users and purchases it from a supplier. In general, by legislation, a final customer is not allowed to resell electricity to another final customer or to another agent. Final customers are residential, commercial or industrial customers. In some countries, small residential customers used to purchase electricity at regulated rates, while large customers negotiated a supply contract with any supplier. Nowadays, to promote efficiency, suppliers are required to provide every final customer with at least one time variable or load variable tariff option as permitted by EU directive 2006/32/EG (Beyer et al., 2009). Later on, it will be clarified that EV owners will not always be considered as final customers.

Independent System Operator (ISO) or transmission system operator (TSO): is responsible for keeping a secure system operation at the regional or national transmission level. For meeting this obligation he procures system services, such as operational reserves and frequency regulation, from market participants.

2.2. New agents

Plug-in electric vehicle (EV) owner: is the agent that owns an EV and requires electricity to charge its EV battery. In the future, he would be able to provide V2G services too. When charging, EVs would be physically connected to a charging point and in some scenarios the electricity could be provided by a specific **EV supplier** (see definition below).

In the following, we consider two main alternatives regarding the development of charging infrastructure: (i) privately owned charging areas with private or public access for EV owners, and (ii) public charging areas with public access for EV owners.

EV supplier-aggregator (EVSA): EV supplier is the agent selling electricity to the EV owner. For example EV owners could have a supply contract with an EV supplier valid in different charging points. The novelty about this agent is that its contracts are not location based or bound to a single final outlet. The customers, the EV users, will demand mobility and freedom to choose multiple charging points while remaining with the same EVSA. EV suppliers are retailers and therefore their business should be declared competitive activity unbundled from other vertical functions in the electric power system. EV suppliers in general are expected to aggregate multiple EVs to conduct an integrated management. In this case the EV supplier acting as aggregator could also play a key role in the future, providing V2G services to the ISO.[4] In the following the EV supplier-aggregator is considered a competitive business as other trading activities in the market. It should be noted that, in the near term home charging scenarios, the function of the supplier/retailer can be assumed by the retailer, which already contracts the final customer for domestic residential electricity sale.

EV charging point manager (CPM): It is assumed that the installation of charging infrastructure on private property will be made by the property owner. Acting as a **final customer** CPMs will buy the required electricity to charge its own EV or to resell it to other EV owners connected to the charging station under a commercial agreement. Different situations could be possible:

- A residential customer who installs an EV charging point at his/her home garage for private use.
- An office building owner who installs several EV charging points in the office parking area for private use of its employees.
- A commercial building owner who installs several EV charging points in its parking area for use of its clients.[5]
- An EV charging station owner who installs several charging points with different charging options, specifically fast charging modes, for delivering this service to the public.

By legislation, CPMs who resell electricity to a third party (EV owner) in a competitive activity would be defined as suppliers or retailers. In this case, the access to the charging services would be made available on the terms and conditions set by the CPM. For obtaining a license to exercise this type of activity, they should demonstrate technical capability and financial liability according to legislation. For instance, this type of agent has recently been defined by the Spanish legislation (Spanish Royal Decree-Law 6, 2010).[6]

In public parking areas, streets and areas with public access, the installation of EV charging points will be more expensive. To have a large roll out will involve substantial expenditure and risk. When involving the use of a public good such as the public location, the business should be regulated and charging stations developed by the corresponding **DSO** in the area. In this case, the infrastructure would be considered as other grid expenditures and the access to the charging points should be made universal to EV owners contracted with different EV suppliers. This way, it is avoided that private companies monopolize this limited resource. In the case of CPM acting on privately owned property, however, infrastructure could be installed and investment risk assumed by private agents while the activity would be open to competition depending on the development rights of the location.

2.3. Interactions of new and old agents

To sum up this section, Fig. 1 puts all the small pieces together and shows the potential interactions of new and old agents of the electric power system with the EVSA as the facilitating agent of the charge. The physical flow of electric power goes via the high voltage transmission system over medium to low voltage transmission systems to the final customer. The network operators recover their costs via the network access tariffs which is collected by the EVSA, together with the energy generation costs and passed on to the respective agents.

3. Grid connection and charging installations

In this section the definitions for network and charging infrastructures are introduced.

Distribution grid: consists of high voltage (HV), medium voltage (MV), and low voltage (LV) network installations, power lines and transformers, at which final customers are connected. Small residential customers are connected to the low voltage network while large customers, hundreds of kW, are connected to the medium voltage network. As it has been stated, DSOs are responsible for investment and operation of distribution grids.

Final customer connection point: is the interface between the distribution grid and the customer electrical premises. A meter is located at each final customer connection point, see Section 4.

[4] In Guille and Gross (2009) aggregators are proposed as the key agent for V2G implementation.

[5] In case of parking areas at office or commercial buildings, the building owner already has a metered electricity supply. Then he can independently meter the EVs connection points if he wants to bill each charging point, or by the contrary there is no need for metering if the service is not directly related to consumption.

[6] The Spanish legislation defines this agent as the charging manager (“gestor de cargas”, in Spanish).

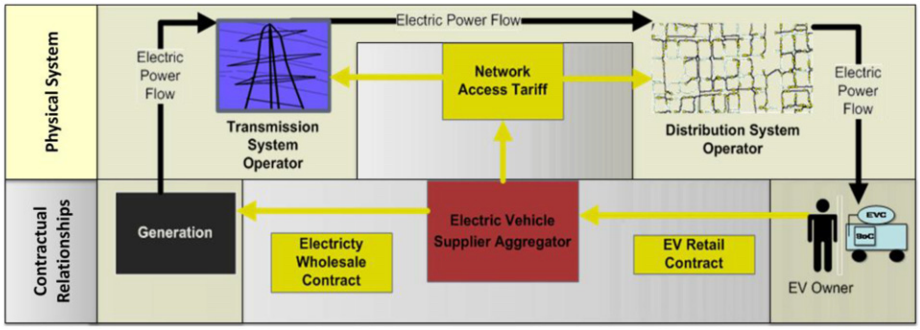

Fig. 1. Interactions between agents in the electric power system with EV.

EV charging infrastructure: is composed of one or several EV charging points and their connections to the distribution grid, i.e. Electric Vehicle Supply Equipment (EVSE). In some cases, additional equipment such as transformers, generators or storage devices can be part of the EV infrastructure in order to provide an efficient and reliable service. In this proposal, investment, operation and maintenance of EV charging infrastructure is responsibility of CPMs in privately owned parking areas, and of DSOs in public parking areas. In case of residential customers with a charging point for particular use, located at a private property, the owner of the property would be in charge of installing and maintaining the charging point with notification to the DSO. In cases of commercial or office buildings and charging stations, the parking owner or its supplier should also notify the corresponding DSO of the number and installed capacity of the charging points while asking for the required connection capacity.[7]

EV charging point or charging post (CP): is the connection point between the EV and the charging infrastructure, where the EV is plugged-in to be charged.[8] A single or multiple charging posts would make up a **charging station**.

4. Metering, communications and control

In this section, definitions about the proposed metering, control, and communication equipment are detailed.

Final customer meter (FCM): it is located at the final customer connection point. It is known as the "utility meter". It meters the energy consumption (kWh) and peak consumption (kW) in a period of time. Measurements can be collected by time-of-use, in peak and off-peak hours for instance. Smart meters can collect hourly measurements and include bi-directional communication with the DSO and with the supplier to include different features regarding pricing and control. In many systems, DSOs are in charge of the installation of final customer meters. Depending on national legislation, the meter could be owned by the network operator of the distribution system but in general does not have to, as long as the proper measurement is assured by independent third party companies. In any case, the regulation of ownership should follow national regulation as it is existent for regular (non-EV) meters. There should not be any specific conflict in the metering of EVs regarding the ownership. Suppliers should also have access to the information provided by the meter. It is assumed that a reliable bi-directional communication system would be established between the meter and the DSO, and the supplier. The final customer has direct access to the information provided by the meter. Smart meters with the possibility of time-of-use (ToU) prices could be required as compulsory for those final customers with EV charging points, i.e. for CPMs.

EV meter (EVM): would meter the energy consumption, the peak consumption and the period of time during which an EV has been connected to a charging point for billing purposes. EV meters can also be embedded in the car. In some cases, EV meters would communicate with the EV supplier for billing and potential remote charging control.

Charging station: Fig. 2 shows a simplified scheme of a charging station with associated infrastructure. It can be observed that a FCM is located at the interface with distribution, and EVMs are located at each charging point.

4.1. Visualization

The use of green colour represents the assets that are owned and operated by the DSO, while the elements belonging to intermediary agents in facilitating the charge of electric vehicles are pictured in different shades of red and the physical equipment that can be associated to final customers is represented in blue or yellow.

All agents are situated at the upper part of each figure, all physical equipment on the lower part, communication ties are within the physical section.

Energy manager controller (EMC): is a controller, similar to an energy management system or energy box, operated by the corresponding CPM or EVSA (Livengood and Larson, 2009). It schedules a charging programme for each of the connected EVs. The coordination between the energy manager controller and the on-board EV charge controllers should always be ensured for a correct operation of the charging process. A reliable bi-directional communication system should be implemented between both controllers.

Electric vehicle meter (EVM): it provides information about energy consumption, peak consumption, and times of connection on request.

Standardization: Characteristics and functions of EV charging points including EV meters, and EV connectors should be standardized. On-board charge controller and meter functions should be also standardized. Open communication architectures for exchanging information between controllers and meters should be also defined. The aim is to ensure open access to markets for charging infrastructures and EV manufacturers.

For instance, in the EU the standardization organizations are CEN, CENELECT and ETSI. Standards need to be addressed to a variety of topics to achieve interoperability, allow for competition in manufacturing, and agree on communication protocols as well

[7] Final users with EV charging points, i.e. CPMs, may have to modify its utility meter to include time of use (ToU) electricity rates differentiation at least between peak and off-peak hours.

[8] In the USA, the EV connection standard SAE-J1772 was approved in January 2010. This standard provides two different levels of charging interface: Level 1 operates up to 120V/16A and Level 2 operates up to 240 V/80 A. In the future a DC high power connector (150–250 A) will be also defined by this standard.

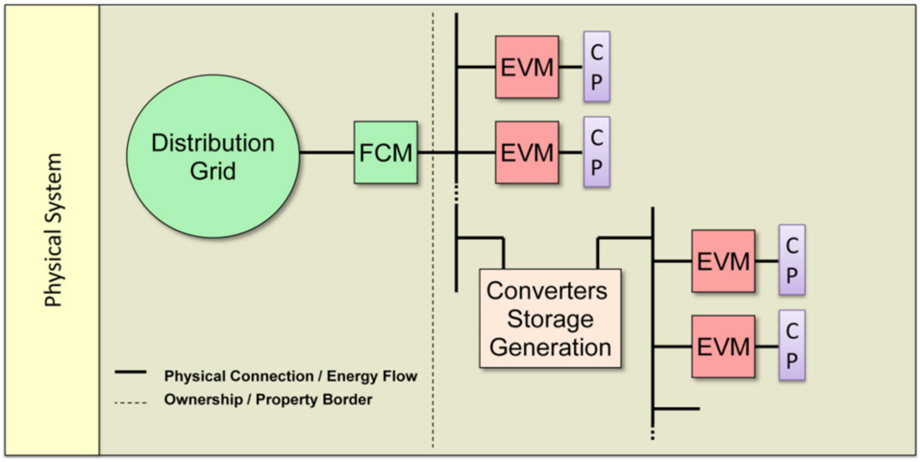

Fig. 2. Charging station infrastructure. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

as the information to be exchanged. Furthermore they can improve safety of certain products. For more details please refer to Bending et al. (2010).

In addition, inside each EV the following measurement and control devices should be included.

On-board EV state of charge indicator (SoC): measures the state of charge of the EV battery as a percentage of the full charge or in kWh.

On-board EV controller (EVC): is a programmable controller that provides a menu of alternatives to the EV owner for charging the EV battery during its connection period.[9]

5. EV charging modes and coordination between EVCs and EMC

5.1. Clarification of terms

To enhance the current discussion this paper offers a set of definitions of terms, such that there is a clear and common understanding of the arguments. It might make sense to agree on a single and unique terminology to facilitate the debate about alternative regulatory approaches. This section contributes to this discussion very briefly:

5.1.1. Regulatory option

For the purposes of this paper a regulatory option is a set of rules that describes the responsibilities of agents of the electric power industry in rolling out public electric vehicle charging infrastructure. In particular, it is determined by certain agents' charging station ownership and or operation according to predefined regulatory principles. It also defines the rules of investment recovery and remuneration of the provided service.

5.1.2. Charging mode

A charging mode defines a situation in which an EV can be charged. It is determined by factors such as charging point location, interacting agents and their relations for delivering the final product or providing the final service, as well as the level of control over the charge and degree of sophistication for the charge.

5.1.3. Business model

A business model describes how a product or service is provided, including perceived value creation of a certain product for a final customer. It is internal to one single agent and usually easy to assess by spending strategic thoughts on opportunities and threats.

5.1.4. Market model

A market is an arrangement or a place where supply and demand meet for exchanging or trading a certain product or service. For instance, there are markets for ancillary services, energy (day ahead, intra-day) and so forth. A market model therefore describes the rules by which this trading platform functions. In the electric power system markets should not be confused by regulatory options—as done by EURELECTRIC (2010).

The requirements for charging infrastructure and communication modes between on-board EV charge controllers (EVC) and the energy management controller (EMC) would basically depend on the type of access, private or public, of the charging point (CP). Therefore two different situations are considered: (i) CP located in a private property for particular use of its owner, and (ii) CP with public access for different EV owners.

5.2. Uses of charging points

5.2.1. Charging point for residential use

The charging point located in a residential home or private property (garage or parking) belongs to the car owner for private use.[10] It is composed of a standard EV connector, locked by a key, and connected directly to the low voltage (LV) board of the house, as the rest of the home LV circuits. In this case, the charging point is intended only for normal charging rates, being rated at the LV nominal voltage and the standard rate currents, for instance 230 V at 16 A, which allows charging powers of 3 kW.[11]

In this case there is no need for an EMC. The EV owner would use the on-board EVC menu to specify its charging needs during the expected time of connection. The EVC menu would have the

[9] This controller is going to be coordinated with the EV battery management system (BMS).

[10] In this section it is assumed that the private parking is located in a residential house for use of its owner. Similar charging schemes can be implemented in parking places with private or limited access and use by always the same EV owners under the terms and conditions set by the parking owner.

[11] A charging power of 3 kW during five hours means 15 kWh and, assuming 0.2 kWh/km as the required energy for an EV, provides a charge for driving a distance of 75 km that is larger than the average daily commuter distances.

following alternatives:

- *"Local" autonomous mode*: where for instance the user specifies the start and end times as well as the energy required (i.e. the final state of charge(SoC)), or
- *Optimization mode through prices*: where for instance the user specifies the disconnection time and the energy required (i.e. the final SoC) and provides hourly charging energy prices for the whole connection period, then the EVC optimizes hourly charging rates to minimize the payments. This option would be only interesting in case of smart meters with the possibility of hourly measurements and a supply contract with ToU or hourly energy prices.

Under this model the charging point owner, who is the same as the home and car owner would pay the charging infrastructure (EV connector and connection cable). The investment plus installation cost for this charging point is estimated at 1200€.[12] This estimate does not include the option of communication between the EVC and the supplier pricing information system.[13] The charging infrastructure cost could be partially financed by public funds together with the purchase of the first EV.

5.2.2. Charging point for public use

The charging point or post is located in a public or privately owned parking area with public access, i.e. by various EV owners. The charging point belongs to a CPM or to the DSO in case of a public area. The charging point would have a user interface with the following functions[14]: (i) user identification, (ii) grant physical access to establish the connection of the vehicle, (iii) measuring energy flows, (iv) billing, and (v) physical locking after payment. It would consist of an EV standard connector for normal charging rates, i.e. 230 V at 16 A, or fast charging rates, i.e. 230 V at 80A, and the corresponding LV cables connected to the LV board. If the charging point is located in a park or street with public access, it should be protected against vandalism. There are different alternatives to charge the EV.

- *Connection and metering mode*: the EV owner connects the vehicle and through the EVC menu and knowing real-time energy prices uses the "local" autonomous mode of the vehicle.
- *Optimization mode in "remote" control at a fix rate*: the EV owner connects the vehicle and through the EVC menu provides the time of connection, the required energy, and the mode "remote" charging, associated with attractive charging rates offered by the EVSA. For this option, a communication between the EMC and the EVC is established where the EMC sends changing charging set points during the period of connection and the EVC follows those charging set points.

The investment and maintenance cost of each charging point, including communications and software, is estimated between 4000 and 10,000€ (Kley et al., 2010b).[15] When several charging points are considered aggregating a significant power of several hundreds of kW, for instance 40 normal charging points and 10 fast charging points add 340 kW, the cost of a MV/LV transformer and other distribution grid reinforcements should be added (Pieltain Fernández et al., 2011).

An estimation of charging infrastructure costs depends on types of charging points, private, semi-public and public, the inclusion of the billing feature or not, and the power rate in kW (3.7–11–22–63 kW). Incremental charging rates to allocate those infrastructure costs are estimated between 1 and 13 c€/kWh depending on the aforementioned assumptions in Kley et al. (2010b).

6. Main EV charging modes

In this section, the three main charging modes for charging EVs are presented. It is expected that in the short-term charging EVs at home during nights will be the most practical and therefore common alternative, as it is sufficient to most people's driving behaviour. However, public charging on public property as well as privately owned charging stations could provide complementary charging modes to cover the needs of EV owners. Under these three types of charging modes, the role for developing the required charging infrastructure is assigned to different agents.

There is an ongoing debate about the best way of allocating communication intelligence and metering devices among the electric vehicles and charging infrastructure. There is a considerable argument for and against both possibilities, having implications for example on the details of the billing systems' processes, its components and operability consistent with current legislation (Link et al., 2010). However, this analysis does not enter in this type of discussion; it rather focuses on the main charging modes and according relationship of existing and upcoming agents.

In the following all charging modes are classified and hierarchically separated by the degree of sophistication, that is, whether they include V2G capabilities or not. Each charging mode is named according to its classification, including the characteristics: charging point location (CP_LOC), intermediate agent for organizing energy procurement or system services (INT_AG), and the degree of sophistication and control over the charging process (CONT_OPT). The charging point location can assume the occurrence of HO for home charging, PR for private area with public access and PU for public area with public access.

The intermediate agent can be the regular energy supplier aggregator for demand side management, denominated SA, the charging point manager, CPM, or the electric vehicle supplier-aggregator (EVSA). The distinctions concerning the control and level of complexity[16] of the charging process are called UCO for uncontrolled charging and CC for controlled charging. Vehicle to home V2H as well as vehicle to building V2B is the name for local optimization of energy bills, and vehicle to grid V2G for ancillary network and system services procured by the grid operators (Fig. 3).

[12] This value is based on historical records of California installer companies presented at the CPUC workshop in March 2010 (ClipperCreek, 2010). However in Kley et al. (2010a, 2010b) calculated values are between 200 and 300 Euros for private charging installations in Germany. In another study in USA (Morrow et al., 2008) values between US$800 and 2150 per charging point are calculated for residential, apartment complex, and commercial facility charging infrastructure for Levels 1 and 2 of charge.

[13] In the future pricing signals would be provided by suppliers mainly through internet.

[14] In some cases all these functions would not be needed. For example in private areas with public use as office or commercial buildings or privately owned parking areas the charging electricity service can be considered as part of a labour or commercial relationship, and then not billed.

[15] Total costs of charging infrastructure, taking into account investments for hardware, power electronics, charging cable, etc. as well as operation and maintenance, may vary depending on the type of access of the charging point and the provided power of the connection. Public charging infrastructure with power ratings above 11 kW may be as expensive as 4000–17,000 € (Kley et al., 2010b).

[16] In uncontrolled charging (UCO) modes there is no management system directly signaling the load set points depending on the electric power system needs while in controlled charging (CC) there is an energy management controller (EMC) involved that optimally dispatches the loads. Note that in both cases the possibility to react to economic signals such as ToU tariffs exists.

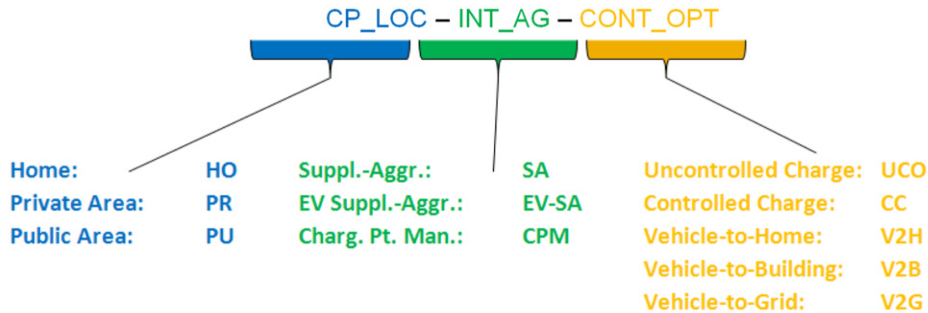

Fig. 3. Classification logic for charging modes.

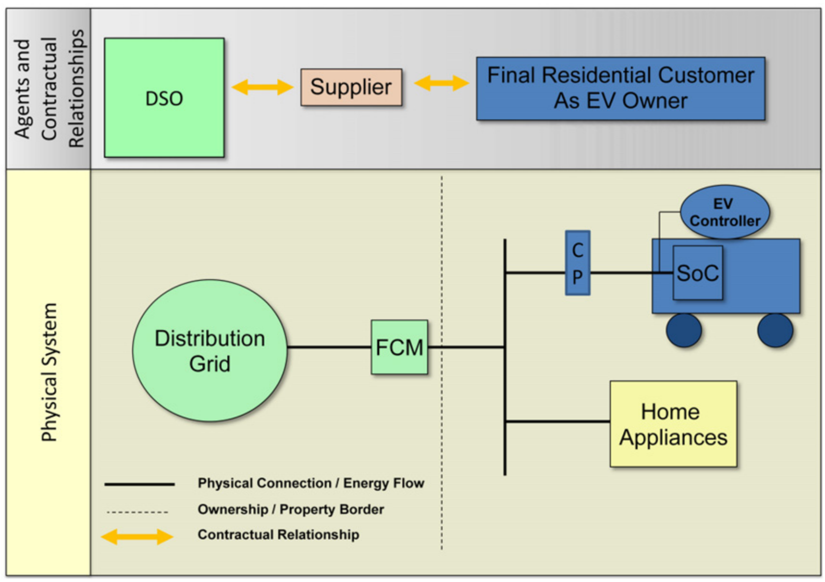

Fig. 4. EV charged at home as domestic electrical appliance (HO-SA-UCO).

6.1. *EV home charging (HO-SA-UCO)*

Under this model the electricity used for charging the car is priced under a unique supply contract for the house (final customer). The home owner will install the EVSE with the EV charging connector.

Agents involved: the home owner, the supplier, and the DSO.

The home owner will notify the supplier about the maximum required charging power whereas the supplier will notify the DSO if additional power demand is required under the supply contract (Fig. 4).

Contracts: The supply contract between the supplier and the residential final customer would be a contract with at least ToU prices, i.e. peak and off-peak prices to promote charging at off-peak hours, or it could be a more sophisticated contract with hourly time prices that promotes an integrated management of the EV with the rest of the loads. In this case the FCM should be upgraded to a smart meter in order to measure hourly consumptions. The supplier will pay the DSO for the corresponding regulated network charges.

Communication and charge control: The EV owner would programme his EVC in accordance to his/her driver requirements and simultaneously minimizing electricity payments to the supplier. The supplier can offer the home owner an integrated management of his loads as well. In optimization mode there needs to be a communication of price signals between the supplier and the EVC.

Settlement: The settlement of the contract would be based on the total home electricity consumption according to the prices set in the contract. These prices in general would be: (i) a demand charge (€/kW-month), and (ii) an energy charge (€/kWh) with different ToU rates or hourly prices.

Under the scheme of mode HO-SA-UCO, as presented above, it is not possible to bill the electricity used for transportation differently from domestic energy consumption. If this was the intention, as for instance necessary when including special rates or taxes on transportation, the connection of the EV charging point should be metered too. In Fig. 5 two independent meters are installed for this purpose. A series connection with subtractive calculation for billing would also be possible (PG&E, 2010). In these cases, the home owner could have two different supply contracts or rates, the former for billing the home electricity consumption and the new one for EV charging with an EVSA for instance.

6.2. *Public street charging (PU-EVSA-CC)*

Charging infrastructure in public areas with public access imply a different regulatory approach, as there are potentially multiple agents with complex inter-relations involved. The charging modes for public use on public property pose certain specific contests for policy makers. The deployment of the infrastructure as a public good requires the allocation of the charging posts to follow transparent, objective and easily understandable criteria.

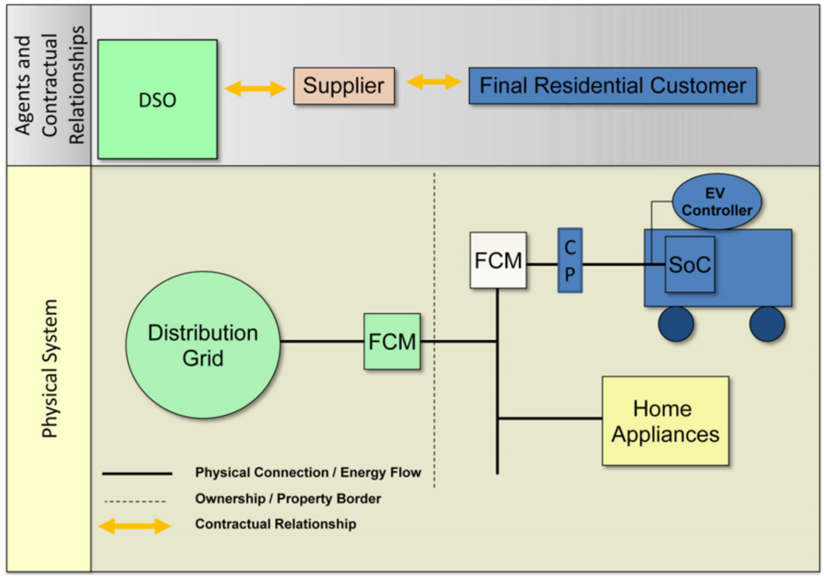

Fig. 5. EV charged at home with sub-meter for separate EV electricity billing (HO-SA-UCO).

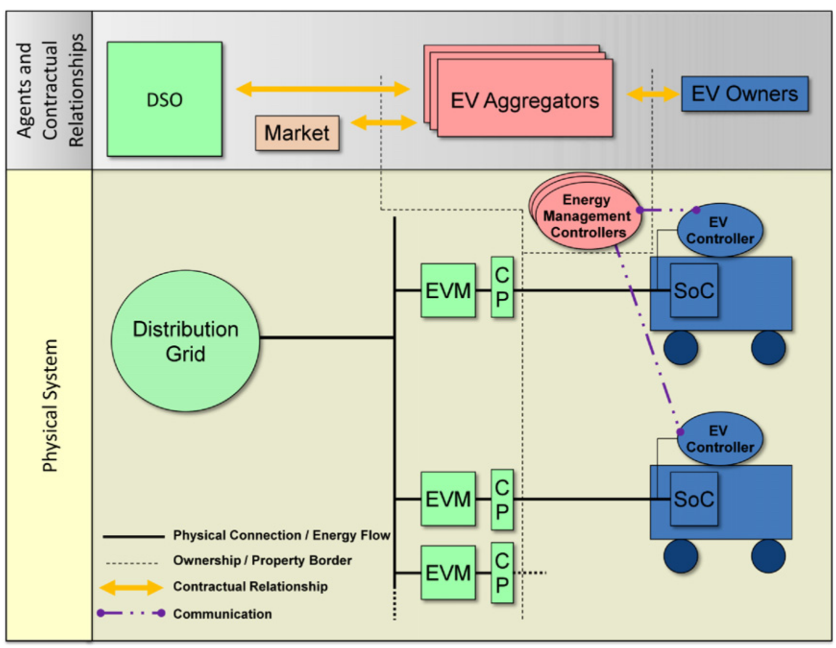

Fig. 6. Public street parking area with multiple EV suppliers (PU-EVSA-CC).

Public authorities such as regulatory commissions, local governments and municipalities, therefore need to derive suitable roll out plans for society as a whole. Infrastructure costs are not negligible and therefore significant public funds are at stake.

In this scenario, the local DSO would install the charging infrastructure in a public parking site for public use of EV owners. EV owners would park cars and remunerate their corresponding EVSAs for charging services. Analogue to existing regulation for monopoly grid services, EVSAs would pay a regulated fee to the DSO for using wiring and connection points.[17] In Fig. 6, this charging mode is represented.

Agents involved: EVSAs, EV owners, and DSO.

Contracts: EV charging posts are installed by the local DSO as part of the distribution network, in order to have low cost and fast installation of standard chargers. Billing will follow the same system that DSOs have in place for other transactions. Charging points should be made accessible to any EVSA with no discrimination or monopoly practices. EVSAs will sign contracts with EV owners for EV charging. EV owners will pay the electricity bills to the contracted EV suppliers (EVSA), the same or different from the one that supplies his home, giving the right to charge at any of EV public charging points. The EVSA would pay regulated

[17] Implicitly it is assumed that most probably CPs are going to be part of the DSO owned and operated grid. Charging stations and charging points being a crucial part of the infrastructure, the same justification for regulating these as monopolies applies as for other parts of the distribution and transmission networks. Once being installed, charging infrastructure in connection with low voltage or medium voltage distribution networks, the investment for parallel infrastructures is economically unattractive for any potential competitors. For an in-depth discussion of different regulatory options for charging infrastructure with public access on public property please revert to EURELECTRIC (2010).

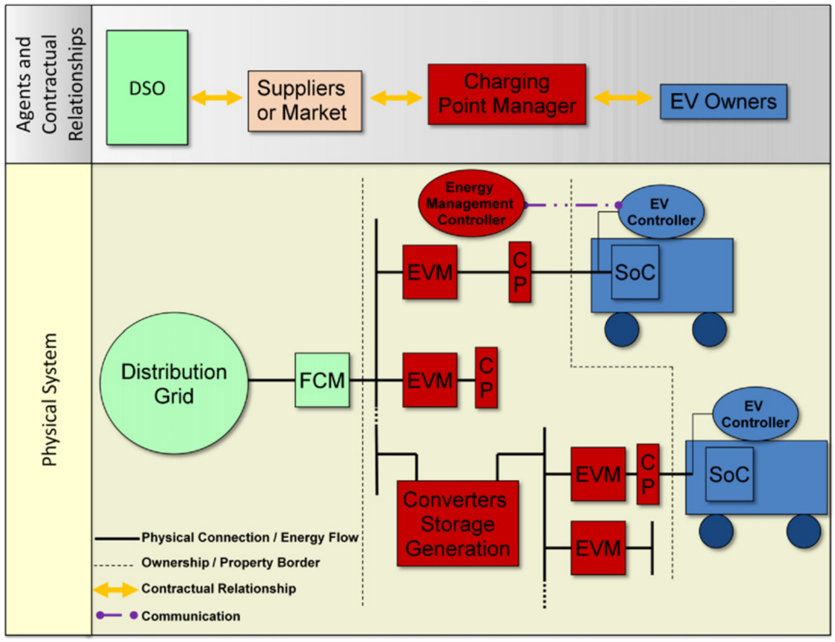

Fig. 7. Privately owned charging station offering special services (PR-CPM-CC).

network charges to the DSO for paying back grid and charging infrastructure costs.

Settlement: Each EVSA aggregates multiple contracts with different EV owners with the preference to charge in public parking areas and homes, in order to benefit from load aggregation and other economies of scale. EVSAs, taking the role of the traditional supplier, would be obliged to pay regulated network fees to the DSO for the use of the charging point as a function of the energy consumption measured by the EVM, the time of connection, and the required power.[18] In a competitive environment, the EVSAs contract the EV owners and pass on the regulated charges by designing end user tariffs according to the market conditions.

Communication and charge control: Under this scheme, when an EV is connected at the parking site, the on-board EVC communicates the time of connection and the energy demand to the EMC. Then, the EMC would provide the EVC with a charging schedule that satisfies those requirements. The EVSA could optimize energy volumes and periods for charging EVs in order to maximize profits. The design of the contracts between EV owners and EVSAs is a key issue in order to achieve the desired profitability.

6.3. *Charging stations on private property with public access (PR-CPM-CC)*

On privately owned property, where vehicle parking access is nevertheless open to customers, such as shopping facilities, dedicated roadside charging stations and commercial office buildings of various use, the regulatory framework needs to bear unique characteristics. If the deployment of the charging station is undertaken by private entities that simultaneously procure and resell energy, the incumbent view of unbundling retail from distribution does not strictly apply any more. In this logic, the characteristics of mode PR-CPM-CC are shortly proposed in the following.

A charging station owner acting as CPM installs the required infrastructure. He would buy electricity from a supplier and will provide EV charging services to EV owners.[19] Charging infrastructure may include additional equipment to convert, store, or even produce electricity in order to optimize and diversify the types of charging modes offered to their customers. In case of dedicated charging stations for sure AC/DC converters and associated connection equipment would be required to provide fast and ultra-fast DC charging modes. Furthermore, local stationary storage capacity could, theoretically, be useful for energy price arbitrage. For instance, the station could store significant amounts of energy during periods of low demand and inexpensive electricity in order to offer competitive charging prices during peak hours. Finally the combination of this storage capability with local generation sources based, for instance, on renewable energy, can provide this business with additional profits. Fig. 7 represents this charging mode schematically.

Agents involved: Charging station owner (CPM), EV owners, supplier and DSO.

Communication and charge control: Each EV will communicate its charging requirements through the on-board EVC to the EMC, and the EMC will optimize its charge subject to the imposed charging constraints.

Contracts and settlement: There would be a supply contract between a supplier and the charging station owner (CPM) as a final customer, or the charging station could participate directly in the energy market. In the first case, the station owner would negotiate ToU energy rates or hourly prices and demand response services. The supply contract would be settled according to the energy and peak demand measured by the FCM, which should be a smart meter.

[18] The implementation of these settlement arrangements would require new ways of relationship between EV suppliers and DSOs and methods for allocating the infrastructure cost that need further investigation.

[19] In the description of this model it is assumed that a dedicated charging station is selling charging services to EV owners. However in case of other private parking areas, as commercial or office buildings, the relationship with EV owners can be much simpler and energy metering and billing services could not be needed.

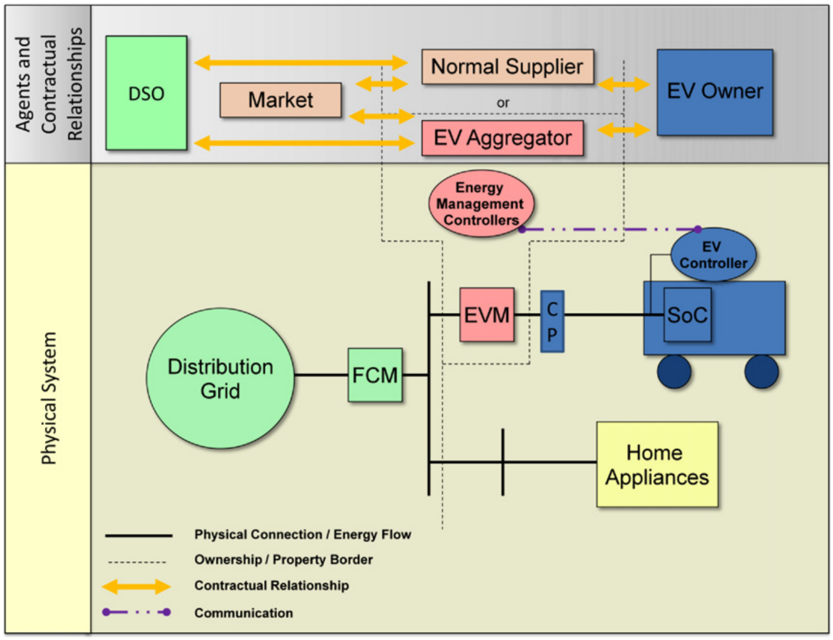

Fig. 8. EV home charge under EVSA management (HO-EVSA-CC).

The charging station owner would notify the supplier of the required connection capacity and the supplier would forward this information to the DSO. The supplier would pay to the DSO the regulated network charges based on the volumes measured by the FCM.

Each EV owner will be charged according to the energy amount transferred to the battery and measured by the EVM, the type of charge (regular, fast or ultra-fast) and the time when the charge was made. Charging at peak hours would be more expensive than at off-peak hours.

The profitability of this business will be determined by the capability of offering differentiated charging services that could not be obtained at home or in public parking areas and would be needed and appreciated by EV owners.

7. Alternative EV charging modes

In this section more EV charging modes are presented. These models are based on the three main models described in Section 6, albeit including some changes or additional possibilities.

7.1. *EV charge at home under EVSA management (HO-EVSA-CC)*

In this model the EVSA acts as an intermediate agent buying energy from a supplier or participating in the market while reselling this energy to EV owners, who are managed under a charging contract. The EVSA could conduct an integrated energy optimization by aggregating several charging points at the residential level (Section 6.1 mode HO-SA-UCO) in addition to the EV contracts associated with public charging points (Section 6.2 mode PU-EVSA-CC). As aforementioned, this scheme allows separate pricing of energy consumed at home for transportation purposes, and therefore it allows including specific taxes or special rates (Fig. 8).

Agents involved: the EV owner, the EV aggregator, and the DSO.

Communication and charge control: The home owner installs the EVSE and notifies the EV aggregator the maximum required charging power. The EV aggregator will install the EVM and communicate his EMC with the on-board EVC. Under this scheme, the EVC will communicate the time of connection and the energy demand to the EMC when the EV is connected at home. Then, the EMC will provide the EVC with a charging schedule that satisfies those requirements. The EV aggregator will optimize energy volumes and periods for charging EVs in order to maximize its profits.

Contracts: A charging contract between the EV aggregator and the EV owner. On the other hand, the aggregator would sign contracts with other suppliers or would buy energy in the market, while paying network charges for each connection point to DSOs.

Settlement: The charging contract between EV aggregator and EV owner will be settled according to the energy volumes and peak power measured by EVM, considering the prices and other conditions agreed upon. The supply contract between other suppliers and the EV aggregator will be settled according to the energy volumes measured by FCM and the agreed prices and condition. The EV aggregator would negotiate one single supply contract for providing energy to many charging points. The EV aggregator would pay network charges to distribution system operators for each connection point according to regulated rates and volumes measured by FCM.

Observe that under this scheme it would also be possible to introduce vehicle-to-grid services through the EV aggregator, for instance providing power for the grid at peak hours or offering frequency regulation to the ISO (see modes ⁎-EVSA-V2G in Section 8).

7.2. *Commercial or office building with EV parking and integrated management of energy (PR-CPM-V2B)*

In this model, it is assumed that the building acts as a CPM. It purchases energy to resell it to EV owners.[20] EV owners can be employees in an office building or customers in a commercial building. The CPM strategy is to maximize its profit as the difference between energy payments to the supplier and revenues

[20] In this case it is assumed that the office or commercial building has a specific type of relationship with parked car owners, therefore it could provide the charging electricity service as part of this labour or commercial relationship, there would not be necessarily a payment from the EV owner to the building owner.

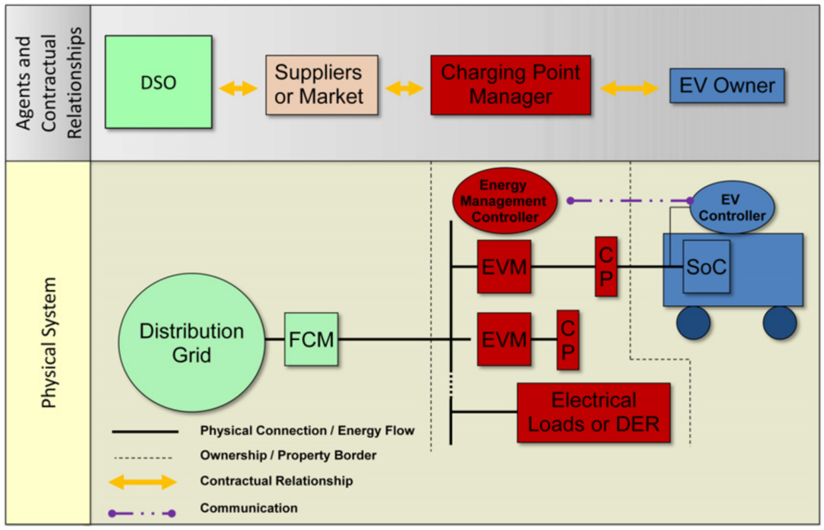

Fig. 9. Office building with integrated energy management (PR-CPM-V2B).

from EV charges or simply minimize energy payments to the supplier (Momber et al., 2010).

The building owner acting as CPM would install the required charging infrastructure. As it has been explained in Section 4, the cost of this infrastructure would depend on the type of parking access, the requirement for billing or not, the available charging power, etc. For instance, in Fig. 9 the case in which the CPM will measure individual consumptions in each charging point (EVM) for billing purposes and will manage the charging periods through the EMC is represented. The infrastructure cost associated with this scenario is clearly much higher than the case where there would not be billing of energy, neither need for EVMs, nor management of the charging periods, and no need for EMC and communications.

Agents involved: the office building owner acting as CPM, the EV owners, the supplier, and the DSO.

Contracts and settlement: The supply contract between supplier and building owner as a final customer is settled according to the energy measured by the FCM. This can be a traditional regulated contract with a demand charge and differentiated ToU energy rates, or a more advanced contract including a smart meter with hourly prices or critical peak pricing.

The building CPM can agree on the conditions for EV charging with the vehicle owners. The charge for services from building to EV owner will be paid according to the energy measured by EVM and the agreed price.[21] The building owner would disclose the supplier the additional required connection capacity while the supplier would forward this information to the DSO. The supplier would pay the DSO the regulated network charges based on the volumes measured by the FCM.

In the most sophisticated management mode, the CPM will conduct an integrated energy dispatch taking into account its energy needs as well as the volumes and periods of charging required by connected EV owners. This would result in an optimization problem where the decision variables would be the power to be injected into the EV batteries in each period of time, for instance every 15 min. Therefore each EVC will communicate to the EMC its requirements and the EMC will optimize the charging schedule for each EV connected sending back this information.

In this charging mode another possibility for the building owner is to delegate all the control and management of EV charging to an EV aggregator, as it was proposed previously for residential EV charging.

8. EV charging modes for provision of V2G services by EV aggregators

In the previous models we have assumed that the main goal was to supply electricity to charge EV batteries according to EV owners' driving requirements. The vehicle to grid (V2G) concept presents more sophisticated EV charging modes that require further technology deployment and contractual arrangements. EVs connected to the grid can be a valuable resource by injecting power into the grid and/or providing frequency regulation reserves that would help to optimize power operation and minimize system costs. EVs would obtain some revenues in exchange. According to Sortomme and El-Sharkawi (2011) V2G can be implemented with merely unidirectional power flow.

To make this mode possible, EVs would be equipped with an inverter and a control system that would inject power from the battery to the grid or vice versa, and the EV meter would count energy flows in both directions.

The EV aggregator will optimize the EV resources as storage that can be charged in some periods and discharged in others, always subject to driving constraints imposed by EV owners. In addition, he/she could subscribe specific contracts with an Independent System Operator (ISO) to provide regulation reserves or to sell or buy energy in real-time or day-ahead markets. In those cases specific metering and communication equipment should be deployed to meet the requirements to participate in those markets.

It is clear that despite the fact that one single CPM could provide V2G services, this type of business would make only sense if an EV aggregator pools at least hundreds of EV units to acquire an equivalent size of MWs while benefiting from economies of scale in order to participate in the ISO markets.

Therefore, all the presented previous models can be revisited assuming that EVs have V2G capability.

[21] Energy costs associated with charging parked vehicles on a daily basis are estimated to be very low. For instance, daily charges of 15 kWh, 5 h connection at 3 kW, will allow driving a distance of 75 km at a cost of 2.25 €, assuming an electricity rate of 0.15 €/kWh. This cost can be integrated in the parking ticket or given for free to employees.

8.1. EV managed at home as storage resource to minimize electricity payments (HO-SA-V2H)

This is a variant of the first mode HO-SA-UCO presented for EV charging at home. In the proposed variant there is no need for EV aggregators because the EV does not provide services to the ISO.

If the supply contract subscribed by the residential customer has different electricity prices for peak and off-peak hours then the EV can be managed to store energy at off-peak prices and to produce that energy at peak prices minimizing the home electricity payments in terms of capacity and energy. The dispatch of the EV as a generator needs to me managed by an energy management system, most probably requiring additional investment. The profitability of this strategy will be determined by EV parking times at home, EV battery efficiency and degradation, as well as hourly electricity price spreads (Momber et al., 2010) (Fig. 10).

This type of business can be of interest for suppliers that offer those services to residential customers making an integrated management of their energy consumptions including EVs.

8.2. EV connected at home providing V2G managed by an EV aggregator (HO-EVSA-V2G)

This EV charging mode is a variant of previously presented HO-SA-V2H. In this case the EV aggregator would manage EVs with V2G capability to buy and sell energy at the day-ahead and real-time markets to provide regulation reserves under supervision and control of the ISO.

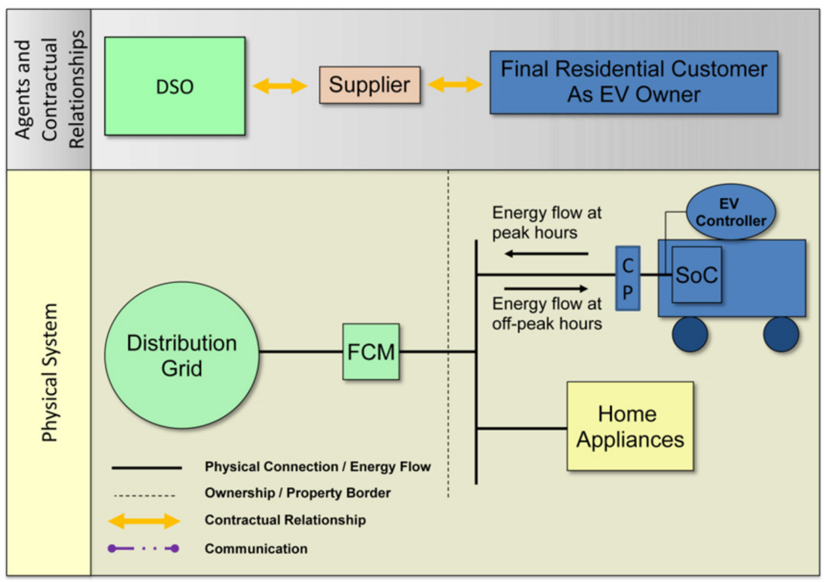

Fig. 10. EV providing V2G to minimize home electricity payments (HO-SA-V2H).

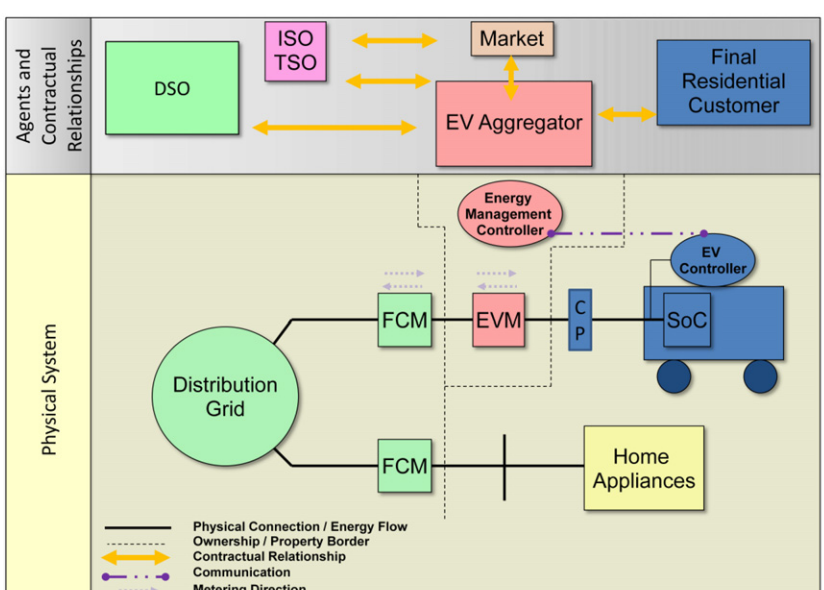

Fig. 11. Aggregator providing V2G services at home (HO-EVSA-V2G).

The measurement equipment should be bi-directional. The EV management controller (EMC) should have a communication system with the ISO in order to put energy bids and to follow automatic generation control (AGC) instructions to provide regulation reserves. AGC is used by system operators for maintaining the frequency at its target value, which requires that the active power produced and/or consumed be controlled to keep the load and generation in balance (Fig. 11).

The EV aggregator will be compensated by the ISO or TSO for the services provided and he will compensate the EV owners too. The optimization of management strategies and the sharing of profits among the EV manager and EV owners is a complex mathematical programming problem (Beer et al., accepted for publication).

8.3. EVs connected at public parking sites, office or commercial buildings providing V2G managed by an EV aggregator (PR-CPM-EVSA-V2G)

The EV charging mode with V2G for areas with public access would be similar to home charging presented in the previous section. It would be possible to pool V2G capabilities of connected cars with a contract with an EV aggregator for providing V2G services. The control and management of EV connected batteries would be assumed by the EMC of the aggregator. In these cases, similar metering, communication and contract arrangements with the ISO or TSO, as described for mode HO-EVSA-V2G, would be required too.

8.4. Tree overview of the provided models

To summarize the different models that have been discussed in the previous section and highlighting their relationship between each other the following overview graphic is provided. Fig. 12 sorts the different charging modes by their characteristics concerning the access of the charging point into three main branches, i.e. "Private Area with Private Access", "Private Area with Public Access" and "Public Area with Public Access"). Furthermore it distinguishes them vertically between the more realistic short term arrangements and rather long term solutions concerning the sophistication of the control over the charge (UCO, CC, V2G, V2H, V2B). The size of the scenarios hints the probability of occurrence in the near term.

9. Conclusions and recommendations

In this paper regulatory issues for integration of plug-in electric vehicles in the electricity sector have been identified and several proposals regarding the definition of new agents, charging infrastructure ownership and development, as well as future EV charging modes with commercial relationships between involved agents have been made.

In this proposal a new agent called the EV charging manager or the EV charging point manager (CPM) has been introduced. CPMs are in charge of developing charging infrastructure in privately owned parking areas and charging EVs acting as a final customer in the market. In public areas, it has been proposed that the local

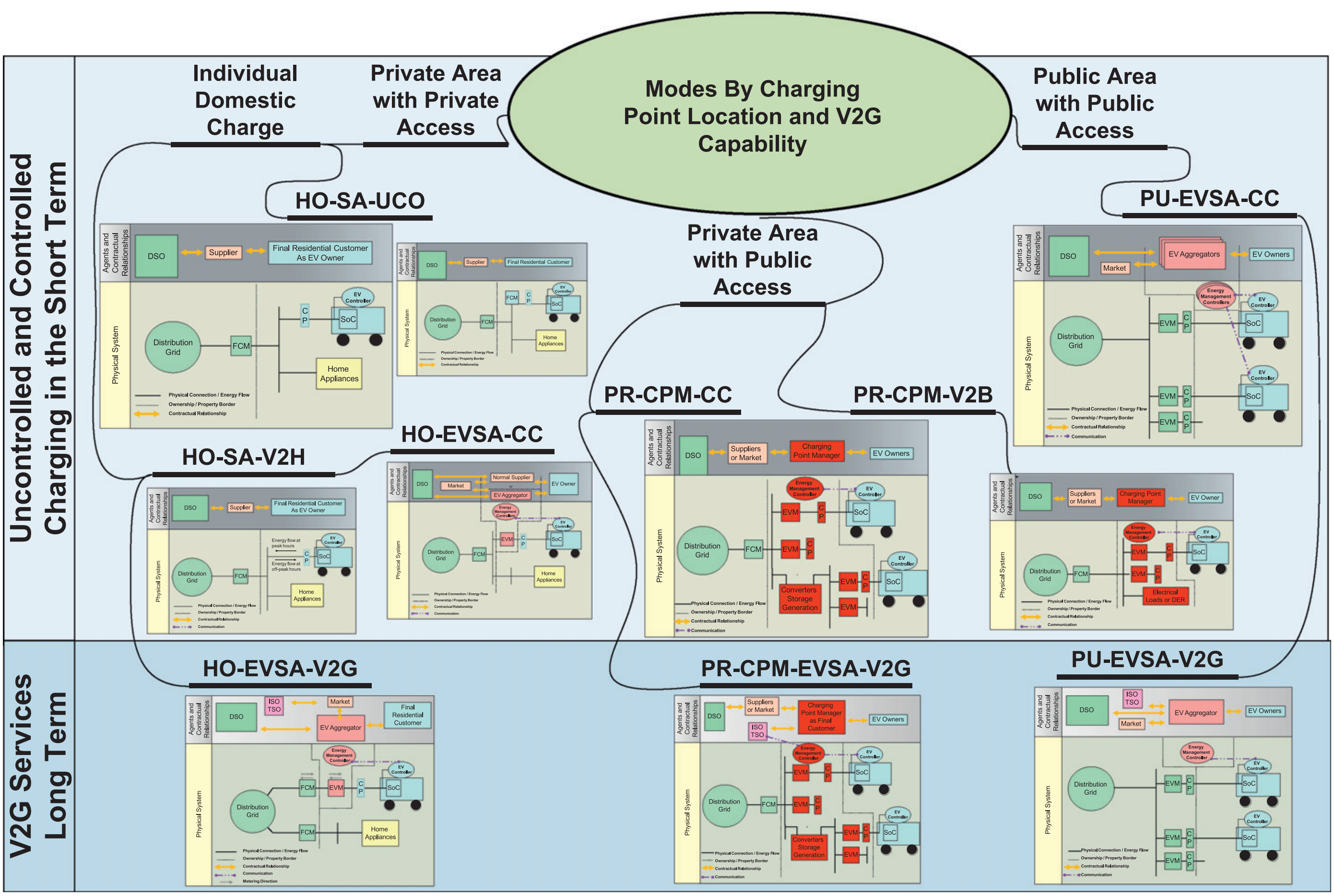

Fig. 12. Charging mode overview.

Table 1
Summary of the three main EV charging mode.

EV charging mode	Short description	CP developing entity	Agents involved	Contracts	Charge control optimization
HO-SA-UCO	Charged at home as other domestic appliance	EV owner	EV owner	EV owner with supplier	Local autonomous
	Separate, sub- or on-board metering arrangements		Supplier	Supplier with DSO	Local optimization
	One unique supply contract for electricity		DSO		Remote optimization
PU-EVSA-CC	Public property with public access for parking with multiple EV charging points	DSO	EV owner EVSAs	Each EV owner with custom EVSA	Fast charging does not allow for load management optimization
	Low cost and fast installation of chargers		DSO	EVSAs with DSO	Long term street parking may allow remote optimization managed by EVSAs
	Multiple suppliers have access to manage different customers at the same CP		Supplier or Market	EVSA with market or intermediate Supplier	
PR-CPM-CC	Public access to charging station on private property with option to have local generation, storage devices and fast charge services	CPM	EV owner	Each EV owner with custom CPM	Fast charging does not allow for load management optimization
			CPM	CPM with DSO	
			DSO		Stationary storage and generation allow for local optimization by CPM
			Supplier or Market	CPM with market or intermediate Supplier	

DSO will develop the costly charging infrastructure providing public access to EV owners. EV suppliers will have contracts with EV owners for selling charging services in public parking areas. Furthermore, the role of EV aggregators for pooling multiple EV owners for providing V2G services to the ISO or TSO is a relevant new agent within this proposal. CPMs and EV supplier-aggregators are considered qualified and authorized market agents who provide EV charging services and V2G services on a competitive basis. Table 1 summarizes the three main elaborated proposals with the criteria concerning agents involved, contracts, programming charge control, and CP developing entity.[22]

EV charging modes have been formulated for EV charging at home, at public parking areas and for dedicated charging stations. Infrastructure costs and charging points requirements in terms of communications and control varied significantly depending on the aforementioned options. For instance, charging at home during nights could be a generalized alternative with minimum infrastructure costs. On the other hand, fast charging at dedicated charging stations would involve higher costs.

Therefore, from a regulatory point of view, the integration of EV in electric power systems can be foreseen in a three phased process.

9.1. Key actors and business models

In the near term, EV home charging and charging in private areas, such as shopping and office parking areas will be the most probable scenario with a relatively low penetration of EV. In this initial phase, EV charging could be based on time-of-use prices, in which hours of low system demand and little network utilization are less expensive. For implementing multiple rate tariffs for residential and other low voltage customers with EVs, installation of smart meters as an interface with the electricity utility company is highly recommended. In this phase it is required to allocate the charging periods within those hours with low prices by implementing simplified approaches of given control concepts.

Moreover in this initial phase, legislation should develop the figure of charging point manager acting on private property with public access allowed to resell energy for EV charging as a final customer in the electricity market. Current legislation only allows retailers to buy and sell energy in the market. To foster the uptake of these new agents and increase the number of charging options to the final user, the regulation should keep the technical requirements and financial liabilities for CPMs as simple as possible in comparison to the ones required currently for retailers.

In the second phase, with high EV sales uptake a massive deployment of smart charging as well as the development of more public-street charging infrastructures is recommended.

Charging infrastructures in public sites would be more expensive, DSOs, today in charge of developing the electricity distribution grid, are in the most favourable position to own and operate those charging public points. Legislation should ensure a stable regulatory framework to recover the associated investment expenditures.

On the other hand, in this second phase, the emergence of a new business model called EV supplier-aggregator is foreseen, contracting high numbers of EV and exert a higher level of control over the charge. The aggregator shall be responsible for a system favourable load management and hedging risks in electricity markets. To assure the smooth functioning of the system operation, the aggregator should also respond to needs coming from network operators, in order to cooperate as well as solve operational and/or security problems in the grid. There is still a need for more quantitative research in order to assess costs and benefits and added value of those new agents. As it has been said, the implementation of control concepts is crucial for the success of this type of new business.

Merely in the third phase, the rather long term development stage of EV integration, vehicle fleets participating in the provision of ancillary and balancing services procured by transmission system operators or DSOs for local requirements would be a reality. It is in this phase where EV supplier/aggregators specialized in those services will develop. If this is the case, the

[22] The alternative models from Section 7 as well as the V2G models presented in Section 8 are derivatives of the three main models and therefore not summarized in detail.

implementation of the most sophisticated control and measurement version of control concepts will be required.

9.2. Market design and network regulation

From the developed framework, conclusions and recommendations can also be drawn about market design and network regulation.

Methodologies to approve and accept DSOs' capital as well as operational expenditures when calculating allowed revenues should be rephrased to include new installations for public charging infrastructure.

The installation of smart meters for final customers as potential EV users connected to a low voltage grid should be made compulsory. In this way those customers will have access to time-of-use tariffs offered by retailers, instead of staying under a flat regulated tariff (which still exist at least in some EU countries). In addition, load profiles for residential customers with EVs in the retail market would be adequately considered.

Future controlled charging or vehicle-to-grid should be explicitly considered by system operators in order to postpone or reduce network investments and make use of EV capability. That would require a review of grid codes and system operational procedures.

9.3. Outlook

Further models for including the provision of V2G services are by far the most sophisticated in terms of technology requirements and commercial relationships between involved agents. Benefits and costs should be carefully evaluated in future research.

It is strongly recommended that supply contracts for CPMs and EV owners would be based on cost-reflective network charges and energy market prices, i.e. with demand charges and ToU or hourly price differentiation. The installation of smart meters is necessary to facilitate the implementation of time differentiate rates even in case of home charging applications.

In the proposed framework, EV suppliers would be free to design tariffs and set EV charging rates being considered competitive businesses. It is expected that charging infrastructure costs could be recovered, and electricity procurement costs passed on to the final customer, while obtaining a business margin. Despite considering CPMs and EVSAs competitive businesses, authorization and registration for such activity should be controlled by regulatory authorities as it is practiced for other suppliers, forming a part of the electricity market.

If due to energy or transportation policies it is decided to charge or to subsidize EV electricity consumption, these agents, CPM and EVSAs could be the ones in charge of collecting taxes or applying discounts when billing EV charging services. In the same manner, environmental policies on carbon emission trading and pricing could be implemented by controlling the amount of electricity used for charging EVs through those agents. Alternatively, taxes or subsidies could be directly applied to each EV owner according to its energy consumption measured by its on-board meter.

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References

Andersson, S., Elofsson, A.K., Galus, M.D., Göransson, L., Karlsson, S., Johnsson, F., Andersson, G., 2010. Plug-in hybrid electric vehicles as regulating power providers: case studies of Sweden and Germany. Energy Policy 38 (2010), 2751–2762.

Beer, S., Gómez, T., Dallinger, D., Momber, I., Marnay, C., Stadler, M., Lai, J. An economic analysis of used electric vehicle batteries integrated into commercial building microgrids. IEEE Transactions on Smart Grid, accepted for publication. doi:10.1109/TSG.2011.2163091.

Bending, S., Ferdowsi, M., Channon, S., Strunz, K., 2010. MERGE D1.1—Mobile Energy Resources in Grids of Electricity Deliverable 1.1. EU. 〈http://www.ev-merge.eu/images/stories/uploads/MERGE_WP1_D1.1.pdf〉.

Beyer, Catharina, Heinemann Christoph, Tusch Tobias, 2009. Einführung von lastvariablen und zeitvariablen Tarifen. 〈http://www.bundesnetzagentur.de/cae/servlet/contentblob/153298/publicationFile/6483/EcofysLastvariableZeitvariableTarife19042010pdf.pdf〉.

California Public Utilities Commission (CPUCa), 2010. Order Instituting Rulemaking on the Commission's Own Motion to Consider Alternative-fueled Vehicle Tariffs, Infrastructure and Policies to Support California's Greenhouse Gas Emissions Reduction Goals. Rulemaking 09-08-009. January.

California Public Utility Commission (CPUCb), 2010. Utility Role in Plug-in Electric Vehicle Charging—A Staff Issues Paper of the Energy Division August 30.

ClipperCreek, 2010. Innovative infrastructure for electric and hybrid vehicles. Presented at the Workshop Organized by the California Public Utilities Commission on "Accelerating the installation of Home Charging Equipment". March 16, 2010. Available on 〈http://www.cpuc.ca.gov/PUC/energy/Climate+Change/〉.

Dallinger, D., Krampe, D., Wietschel, M., 2011. Vehicle-to-grid regulation reserves based on a dynamic simulation of mobility behavior. IEEE Transactions on Smart Grid. 2 (2), 302–313. Available at: 〈http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5756687〉 (accessed 4.06.11). doi:10.1109/TSG.2011.2131692.

Electrification Coalition, 2009. Electrification Roadmap: Revolutionizing transportation and Achieving Energy Security. November.

EPRI & NRDC, 2007. Environmental Assessment of Plug-In Hybrid Electric Vehicles. Volume 1: Nationwide Greenhouse Gas Emissions. 1015325. Final Report, July. pp 1–56.

EURELECTRIC, 2010. Market Models for the Roll-Out of Electric Vehicle Public Charging Infrastructure. EURELECTRIC Concept Paper.

European Communities (EC), 2009. Directive 2009/72/EC Concerning Common Rules for the Internal Market in Electricity and Repealing Directive 2003/54/EC, Electricity Directive.

EU, 2010. European Parliament resolution of 6 May 2010 on electric cars. P7_TA-PROV(2010)0150.

Galus, Matthias D., Zima, Marek, Andersson, Göran, 2010. On integration of plug-in hybrid electric vehicles into existing power system structures. Energy Policy 38 (11(November)), 6736–6745. doi:10.1016/j.enpol.2010.06.043 〈http://linkinghub.elsevier.com/retrieve/pii/S0301421510005070〉.

Guille, C., Gross, G., 2009. A conceptual framework for the vehicle-to-grid (V2G) implementation. Energy Policy (2009). doi:10.1016/j.enpol.2009.05.053.

International Energy Agency (IEA), 2009. Technology Roadmap: Electric and Plug-in Hybrid Vehicle Vehicles (EV/PHEV). Available at 〈www.iea.org〉.

Kalhammer, Fritz R., Kopf Bruce M., Swan David H., Roan Vernon P., Michael Walsh P., 2007. Status and Prospects for Zero Emissions Vehicle Technology—Report of the ARB Independent Expert Panel 2007. Cell. Sacramento, California.

Kempton, W., Tomic, J., 2005. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. Journal of Power Sources 144, 280–294.

Kley, F., Wietschel, M., Dallinger, D., 2010a. Evaluation of European Electric Vehicle Support Schemes. Fraunhofer ISI Working Paper, vol. S7, pp. 1–28. Retrieved from 〈http://www.isi.fraunhofer.de/isi-de/e/publikationen/workingpapers_sustainability_innovation.php〉.

Kley, F., Dallinger, D., Wietschel, M., 2010b. Assessment of future EV charging infrastructure. International Advanced Mobility Forum, 9–10 March, Geneva.

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Kley, F., Lerch, Christian, Dallinger D., 2011. New business models for electric cars—a holistic approach. Sustainability and Innovation. Karlsruhe. Karlsruhe. 39 (6), 3392–3403. 〈http://www.isi.fraunhofer.de/isi-de/e/publikationen/workingpapers_sustainability_innovation.php〉.

Link, Jochen, Eberhardt Tim, Benoit Pascal, Noeren Dominik, Wittwer Christof, 2010. Infrastructure comparison of stationary and mobile metering concepts for electric vehicles. In: Smart Grids & E-Mobility.

Livengood, Daniel, Larson, Richard, 2009. The energy box: locally automated optimal control of residential electricity usage. Service Science 1 (1), 1–16 〈http://sersci.com/magazine/V1N1.pdf#page=6〉.

Momber, I., Gómez, T., Venkataramanan, G., Stadler, M., Beer, S., Lai, J., Marnay, C., Battaglia, V., 2010. Plug-in electric vehicle interactions with a small office building: an economic analysis using DER-CAM. IEEE 2010 Power and Energy General Meeting, Minneapolis, MN, 25–29 July.

Morrow K., Karner, D., Francfort, J., 2008. Plug-in hybrid electric vehicle charging infrastructure review. U.S. Department of Energy Vehicle Technologies Program—Advanced Vehicle Testing Activity. Final Report. INL/EXT-08-15058. November. pp 1–34.

Momber, I., Gómez San Román, T., Rivier, M., Cossent, R., 2011. Merge D5.1 — New Actors and Business. Models for the Integration of Electric Vehicles, 1–67. Available at: 〈http://www.ev-merge.eu/images/stories/uploads/MERGE_WP5_D5.1.pdf〉.

National Academic of Sciences USA, 2009. Transitions to Alternative Transportation Technologies—Plug-in Hybrid Electric Vehicles. Executive Summary. Available at 〈www.nap.edu/catalog/12826.html〉.

Pecas Lopes, J.A., Silvan Polenz, A., Moreiraa, C.L., Cherkaoui, R., 2010. Identification of control and management strategies for LV unbalanced microgrids with plugged-in electric vehicles. Electric Power Systems Research (2010). doi:10.1016/j.epsr.2009.12.013.

Peterson, Scott B., Whitacre, J.F., Apt, Jay, 2010. The economics of using plug-in hybrid electric vehicle battery packs for grid storage. Journal of Power Sources 195 (8(April)), 2377–2384. doi:10.1016/j.jpowsour.2009.09.070 〈http://linkinghub.elsevier.com/retrieve/pii/S0378775309017303〉.

Pieltain Fernández, L., Román, T.Gómez San, Cossent, R., Mateo Domingo, C., Frías, P., 2011. Assessment of the impact of plug-in electric vehicles on distribution networks. IEEE Transactions on Power Systems 26 (1), 206–213. doi:10.1109/TPWRS.2010.2049133.

PG&E, 2010. Presentation by Saul Zambrano at the Workshop organized by the California Public Utilities Commission on "Accelerating the installation of home charging equipment". 〈http://www.cpuc.ca.gov/PUC/energy/Climate+Change/〉.

Sortomme, Eric, El-Sharkawi, Mohamed A., 2011. Optimal charging strategies for unidirectional vehicle-to-grid. IEEE Transactions on Smart Grids 2 (1 (March)), 131–138. doi:10.1109/TSG.2010.2090910 〈http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5661888〉.

Spanish Royal Decree-Law 6, 2010. On measures for the economic and employment recovery. Boletin Oficial del Estado. April (in Spanish).

The European Parliament, 2003. Directive 2003/54/EC of 26 June 2003 Concerning Common Rules for the Internal Market in Electricity, vol. 2002. 〈http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:176:0037:0037:EN:PDF〉.

The Royal Academy of Engineering UK, 2010. Electric vehicles: charged with potential. May. Available online at 〈www.raeng.org.uk/ev〉.

Valentine-Urbschat, M., Bernhart, W., 2009. Powertrain 2020—The Future Drives Electric. Roland Berger Strategic Consultants Report, September. pp 1–95.