EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2017

Market Place Based Energy Management for PEV Grid Integration

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Summary

In order to integrate Plugin Electric Vehicles (PEVs) into existing electrical installations, energy management systems (EMS) will become essential due to the power and energy required. Today's EMSes, however, often directly plan and control the energy consumption or production of each client device within its ecosystem based on preconceived device specific information. Due to the heterogeneous nature of these client devices (e.g. PEVs, heat pumps, ACs, battery energy storage, etc.), this method of centralized planning and direct control by an EMS is limited in its ability to scale and effectively support the complexity of each device it manages. A new concept is needed whereby energy management is possible without the EMS needing to know any device specific information such as a PEV's SoC[1] and departure time, or an AC's target and actual temperatures.

This paper is a working hypothesis which proposes that by distributing the system logic to the EMS clients and allowing them to independently react to the cost of energy and the availability of power, a more effective and scalable energy management system can be achieved based almost exclusively on price and power information.

Keywords: Smart Charging, Load Management, EV, EVSE, IoT

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[1] State of Charge (SoC)

1 Introduction

As PEVs continue to penetrate the market at in increasing rate, reaching an estimated global stock of over 2 million vehicles with 750 thousand thereof sold in 2016 alone [1], new demands are being placed on electrical infrastructures in order to charge these vehicles.

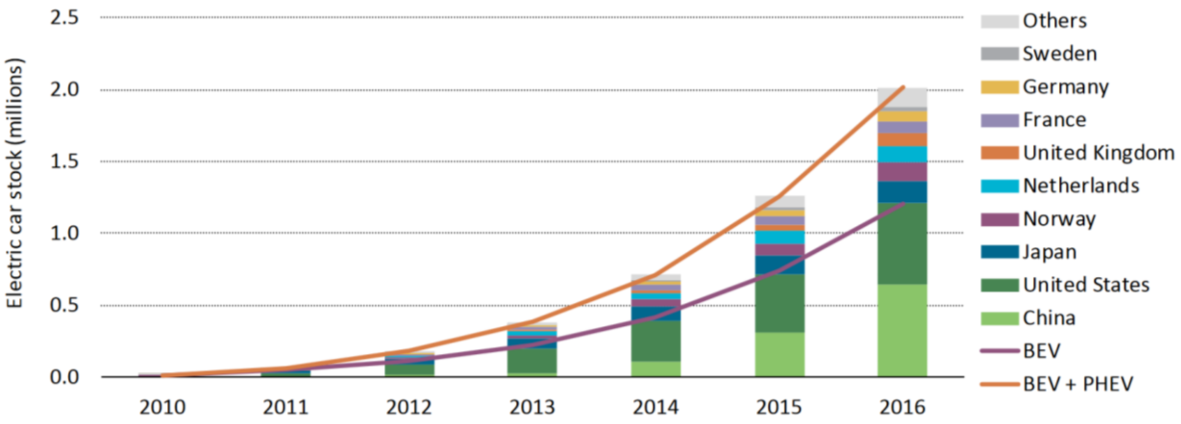

Figure 1: Estimated Global PEV Stock[2], 2010-2016 [1]

Not only are more PEVs making their way onto the streets in a shorter time, but the charging capabilities of these vehicles are improving as well. The next generation of PEVs will feature improved capabilities such as:

- greater driving ranges through increased battery capacities (>80kWh)
- shorter charging times through higher charging power (>20kW_{AC} and >300kW_{DC})
- smart charging through high level communication between the PEV and the EVSE[3]

The rapidly increasing PEV volume, increased battery capacities, and higher charging power present new challenges for integrating vehicles into existing electrical power distribution networks, a term frequently referred to as “Vehicle-Grid Integration” (VGI). Fortunately, the smart charging capabilities of these next generation PEVs allows them to be integrated into energy management systems. But how? Today’s EMSes typically directly control their clients (e.g. HVAC[4], energy storage, etc.) by dictating when and how they may draw power and consume energy. In order to effectively and dynamically manage its clients, an EMS must:

- have an intricate knowledge of each device within its ecosystem (characteristic load profiles).
- know which mode of operation each device is in and its current state (e.g., the washing machine is in eco-mode and in the middle of the spin cycle).
- know the user’s priorities when the demand exceeds the supply (e.g. which is currently more important, heating the home or charging the PEV?).
- Any client device fault conditions which arise and how to react to them.

Not only would the EMS need to know all this information for each client in its ecosystem, but it would have to know this for all makes and models of all devices to ensure scalability and interoperability. Something which is severely lacking today’s energy management systems. In order to overcome these issues, a new type of energy management is needed whereby only the essential device and domain agnostic

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[2] Estimated on the basis of accumulative sales from 2005

[3] Electric Vehicle Supply Equipment (EVSE)

[4] Heating, Ventilation, Air Conditioning (HVAC)

information is exchanged between the EMS and its clients. This will ensure scalability and interoperability between manufacturers.

2 Why Smart Charging is Necessary

2.1 PEV Charging Habits

Studies have shown that the majority of charging takes place in (semi) private environments. These being predominantly at a driver's private residence or place of work [2] [3].

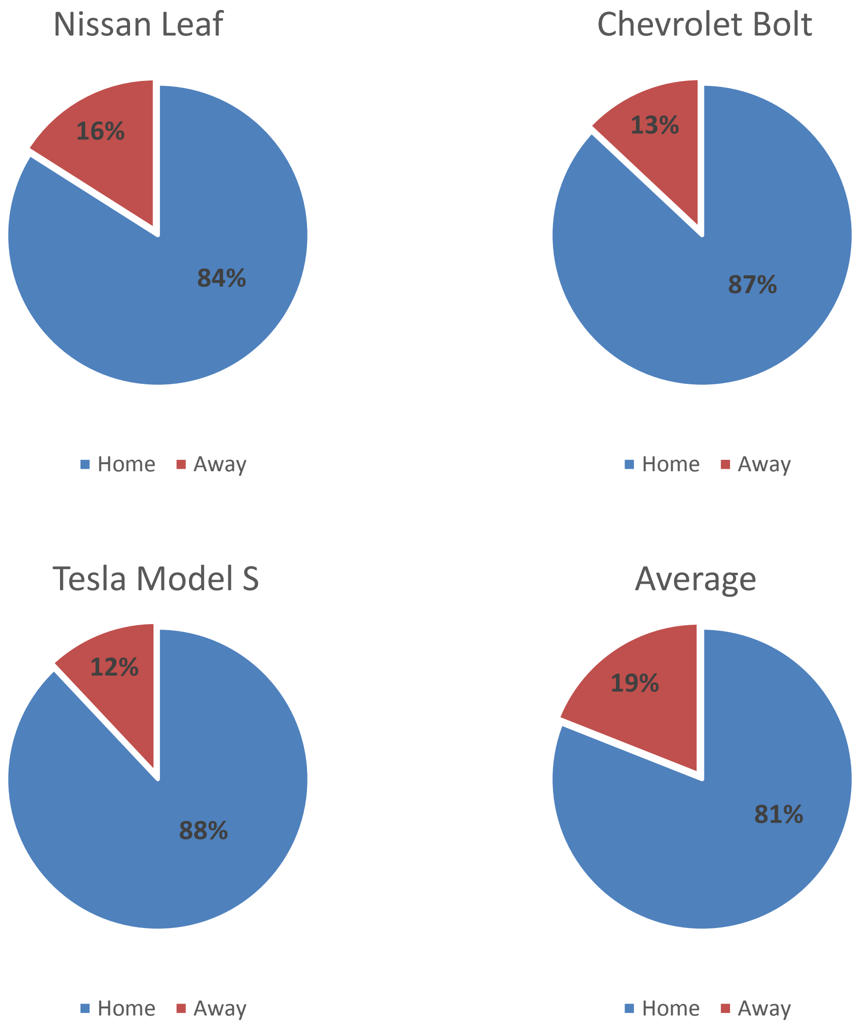

Figure 2: Home[5] vs. Away Charing [2] [3]

Although the distribution of home vs. away charging may change as more comprehensive public charging networks rollout and more people without access to private charging begin driving PEVs, we still expect to see a significant portion of charging taking place in private environments. Certainly, those PEV drivers who can charge at home will do so. Thus, when considering VGI it's important that solutions for home charging are not only user friendly, but are also well integrated into the driver's existing smart home, energy

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[5] Home in this context is a private, single family dwelling

management, PV[6] and energy storage systems. In other words, VGI at home cannot only consider the PEV but must also consider the household's other large energy consumers and producers, such as HVAC, PV and battery storage systems.

2.2 PEV Impact on Home Charging

Charging PEVs at home has a significant impact on both the amount of energy the household consumes, as well as the required power to charge the PEVs at their maximum rate.

A typical 4-person German household consumes roughly 4.200 kWh of electricity per year [4]. Assuming that the household includes 2 BEVs[7] driven an average of 14.015 km/year [5] at a consumption of 0,2 kWh/km, and charged 81% of the time at home [2], the total electrical energy consumption of the household would roughly double.

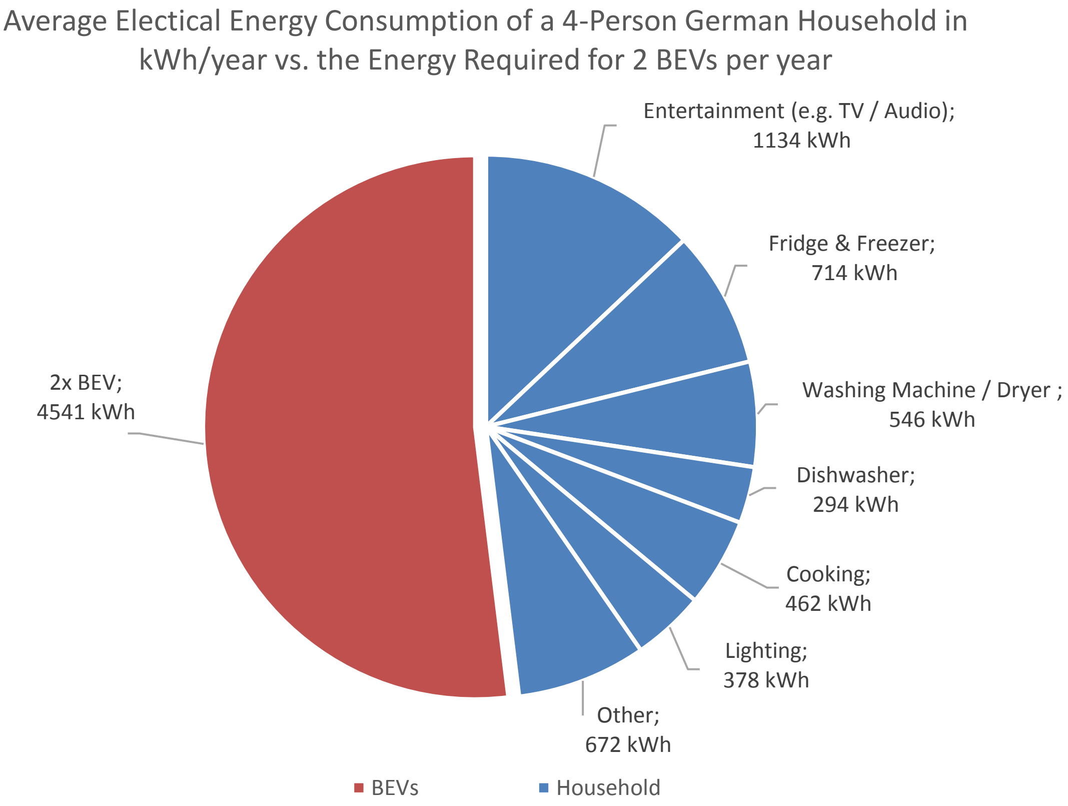

Figure 3: Annual Household Energy Consumption[8] (4.200 kWh) [4] vs. BEV Energy Consumption[9] (4.541 kWh)

On the other hand, PEVs will also place a significant burden on the electrical power grid in terms of peak-power. The Standard Load Profile (SLP) for a German household on an arbitrary day in winter, summer and spring/autumn shows the peak-power typically occurring at 19:30 [6]. Considering that most PEV drivers charge at home [2] [3], and presumably in the evening upon returning from work, then, as PEV volumes continue to rise [1] we can expect to see a significant increase in the SLP's evening peak. This increase could be several orders of magnitude higher than it is today due to that fact that the next generation PEVs will be capable of charging at much higher power.

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[6] Photovoltaic (PV)
[7] Battery Electric Vehicle (BEV)
[8] Average energy consumption for a typical 4-person German household excluding hot water heating
[9] 2 BEVs driven 14.015 km/year at a consumption of 0,2kWh/km and charged 81% of the time at home

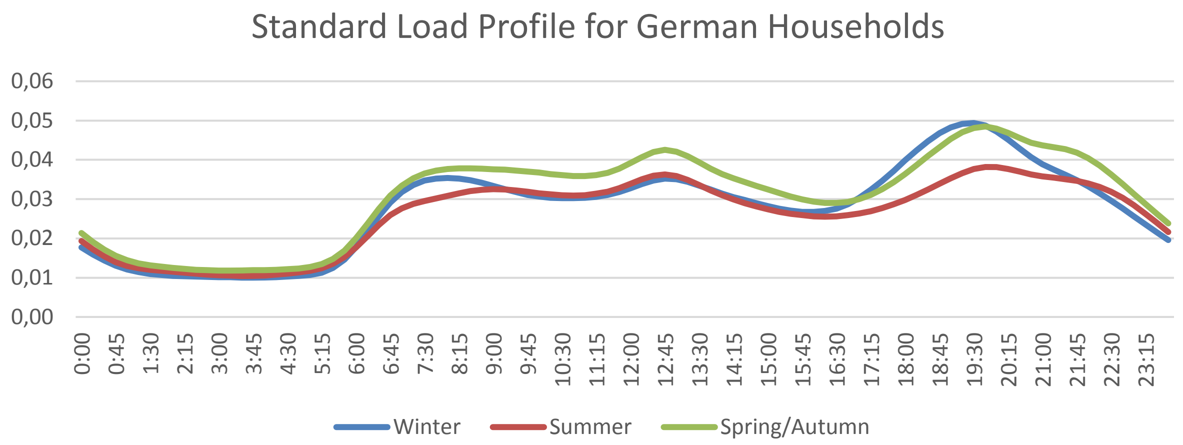

Figure 4: Standard Load Profile for a German Household [5]

In order to reduce the cost per charge and avoid large peak loads on both the distribution grid as well as within a building's local electrical infrastructure, smart charging is needed to ensure that PEVs charge according to the current grid conditions. This means that PEVs must dynamically receive grid relevant information, including the availability-of-power and the cost-of-energy, so that they may plan their charging schedules accordingly. This information forms the basis for smart charging and is fundamentally supported by ISO/IEC15118.

2.3 Smart Charging Stakeholders

The basic concept of smart charging is essentially to:

- reduce the cost of charging by utilizing off-peak tariffs and locally produced or stored energy (PV and battery storage systems), while simultaneously ensuring the driver's mobility needs (departure time and range) are met.
- avoid overloading the micro (e.g. a building's service connection point or mains) and macro (e.g. TSO[10]/DSO[11] network) gird by simultaneously charging too many vehicles with high power.
- ensure that the PEV's battery is not damaged by exceeding any of it technical limitations (power, temperature, etc.).

Ultimately, this results in three primary, high-level smart charging stakeholders.

2.3.1 The Drivers

Market studies suggest that at least 82% of PEV drivers in the USA have or are considering residential PV systems, while 88% of PEV drivers want "fast charging" at home [7]. This goes to show that the vast majority of PEV drivers want to reduce the total cost of ownership by charging as cheaply as possible with their PV systems. At the same time, drivers still want the peace-of-mind which comes with higher power charging at home. Although there is typically enough time to charge a PEV at home overnight, the ability to charge the vehicle over a short period of time using higher power increases the comfort and flexibility for the PEV driver in terms of charging.

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[10] Transmission Service Operator
[11] Distribution Service Operator

2.3.2 The Utilities

As PEVs introduce unprecedented residential loads which most distribution networks were not designed for, the utilities (TSO/DSO) are ultimately left with two choices. Either invest significantly in physically upgrading and reinforcing the grid to handle these new peak-loads, or enable smart charging to avoid the peak-loads (peak-shaving).

While smart charging seems to be the preferred solution, the utilities still want to maintain some form of control over charging PEV fleets to ensure that vehicles react to grid conditions as they charge or discharge.

2.3.3 The OEMs

PEV OEMs want to ensure the integrity of the vehicle's battery without publishing any proprietary information to an unknown third party (e.g. the EVSE or EMS). Thus, for the OEM, it is essential that the BMS[12] remains the master of the PEV's battery. Only the BMS shall decide how and when the battery shall charge.

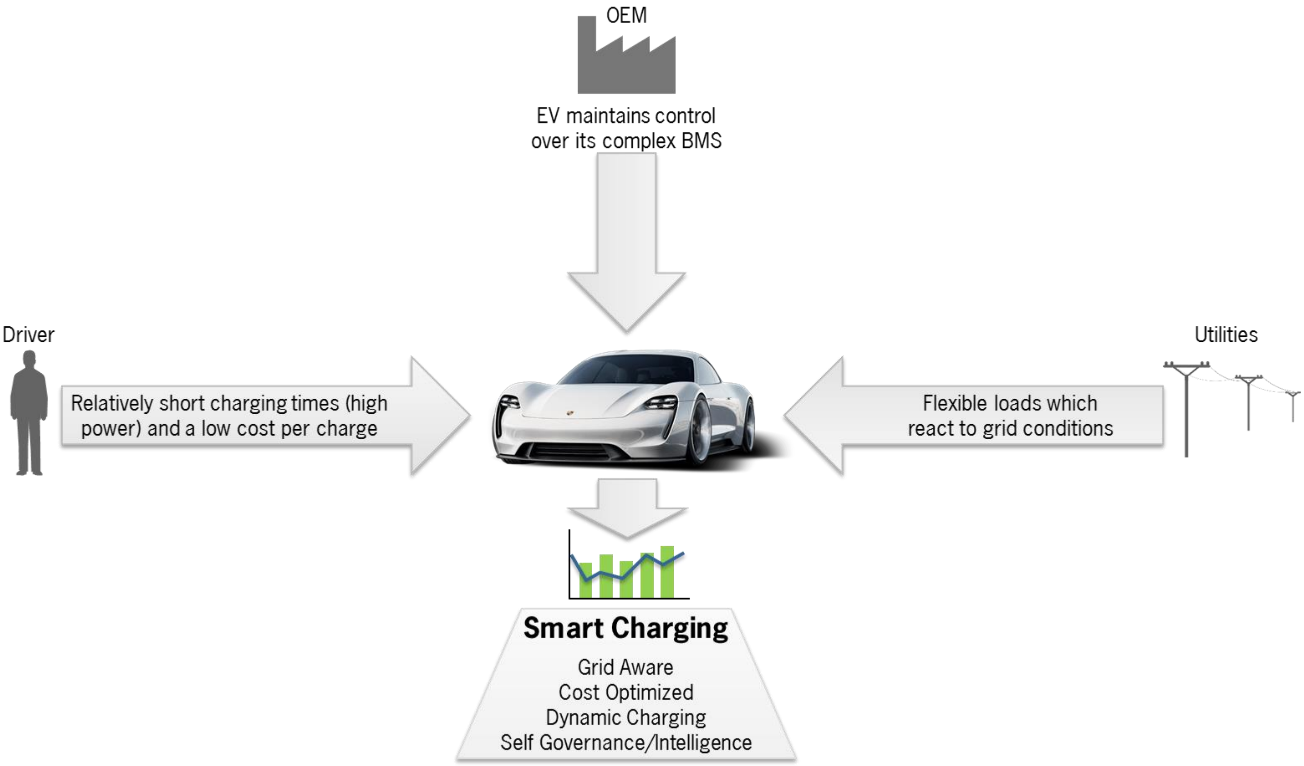

Figure 5: Smart Charging Stakeholders and Requirements Overview

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[12] Battery Management System (BMS)

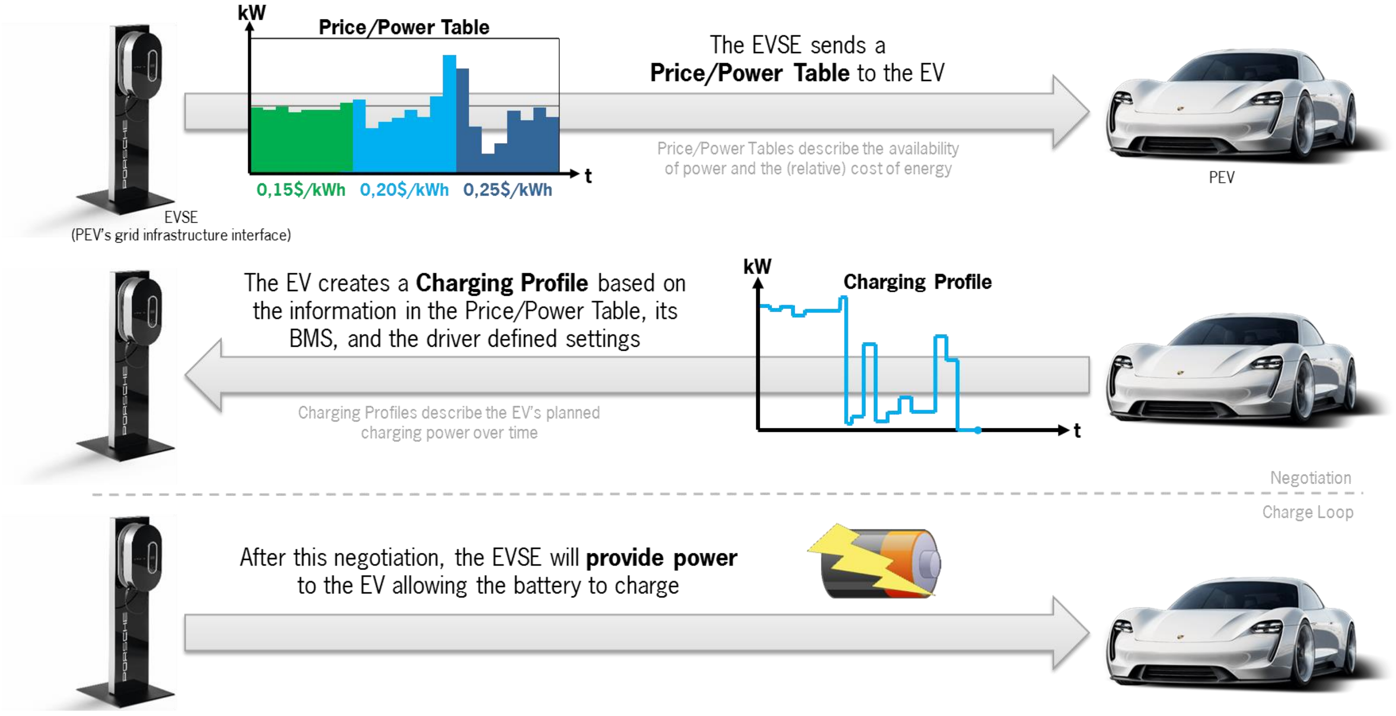
2.4 ISO/IEC 15118 Smart Charging

ISO/IEC 15118's basic principal of operation supports smart charging by allowing the EVSE to send the PEV so called Price/Power Tables. These tables encapsulate the forecasted grid conditions for the next several hours. Essentially, the price/power tables describe power availability over time, and the corresponding cost of energy in kWh. Simply put, the price/power tables represent the utilities requirements as a smart charging stakeholder.

Additionally, the PEV may receive the driver's requirements or mobility needs via some form of HMI. Although these are OEM specific, typically they include a departure time and a desired driving range which may be inputted as a target km, SoC, or kWh. The OEM may also allow the driver to input additional charging strategies or profiles. For example, charge as quickly or as cheaply as possible.

Finally, the PEV's BMS will create a so called charging profile based on the price/power tables, the driver's mobility needs, as well as the condition of the PEV's battery (temperature, SoC, etc.). The charging profile describes to the EVSE (the PEV's grid infrastructure interface) how the PEV plans to draw power over time (kW vs time). Of course the EVSE could determine the PEV's required energy amount (kWh) by calculating the integral of the charging profile (although this can also be communicated via ISO/IEC 15118).

Once the PEV and EVSE have agreed the proposed charging profile, the actual flow of electrons from the EVSE to the PEV will commence and the battery charges. At any time during the charging session, the PEV or the EVSE may initiate a renegotiate. This would happen if, for example, the driver's mobility needs change or the forecasted grid conditions change.



The EVSE sends a **Price/Power Table** to the EV

Price/Power Tables describe the availability of power and the (relative) cost of energy

The EV creates a **Charging Profile** based on the information in the Price/Power Table, its BMS, and the driver defined settings

Charging Profiles describe the EV's planned charging power over time

After this negotiation, the EVSE will **provide power** to the EV allowing the battery to charge

Figure 5: Simplification of the ISO/IEC 15118 Negotiation and Charge Loop

It's worth noting that this process of negotiation via price/power tables and subsequent charging is a form of energy management whereby the EMS client (the PEV) has independently decided how and when to draw power and consume energy without it being instructed how to charge by the EMS (the EVSE). Instead of the EVSE dictating to the PEV how to charge, rather, the EVSE gives the PEV incentives to charge at times when it's more favourable for the grid.

3 Energy Management Systems for VGI

PEV integration into power distribution networks is a challenging task but also provides opportunities in terms of energy management. PEVs will not only become the largest household energy consumer, roughly doubling the electrical energy consumption of a typical 4-person German household, but they will also place significant power demands on the gird with their >20kW charging capabilities (*see section 2.2 – PEV Impact on Home Charging*). This essentially leads to an Energy Management System (EMS) being required in order to reduce costs (e.g., maximizing the use of energy produced by domestic photovoltaic systems, or utilizing off-peak tariffs), and avoid system overloads (e.g., peak-power management).

Considering that a large portion of charging takes place in private residencies (*see section 2.1 – PEV Charging Habits*), overloading a building's service connection or mains will be one of the first issues encountered when several PEVs and/or high power appliances attempt to charge simultaneously. Eventually, as more PEVs are plugged in at car parks, apartment buildings and neighborhoods, the problem of overloading will propagate to the power distribution network if charging profiles are not adapted to the current grid conditions. In addition, as an increasing proportion of renewable energy enters the grid, this leads to a fluctuating and less deterministic energy supply which may not always correlate with consumer demands. In contrast to most other consumers, PEVs can offer the grid a certain amount of flexibility in terms of charging power and scheduling *(see section 2.4 – ISO/IEC 15118 Smart Charging)*.

In order to exploit the flexibility which PEVs offer the smart grid of the future, an energy management system will be essential to enable the exchange of information between the PEV and the grid infrastructure. The role of the EMS is to monitor grid conditions and relay the relative information to its clients.

3.1 EMS Strategies: Central vs. Distributed Logic

In the fifties the question of a planned economy vs. market economy was heavily disputed. Today, however, we know that an economy is too complex to be controlled or planned efficiently by a central entity, such as the state, and thus the market economy has prevailed.

Similarly, the way in which energy management is controlled and planned is being disputed. Until now energy production from fossil fuels is planned around a centrally forecasted demand while grids magnitudes are designed to accommodate a relatively short peak. As an increasing share of fluctuating renewable energy and power demand introduced by PEVs penetrate the grid, the effectiveness of today's centrally controlled energy management principles is questionable. As the Internet-of-Things ushers in a new generation of connected and intelligent energy consumers, the complexity and scale of energy management systems is likely to grow. While it is common sense that we have to influence the demand side to reduce cost, there remains controversy regarding if demand should be controlled by central planning or a market based approach.

3.1.1 Central Logic EMS: The Planned Economy Principle

In existing commercial applications, the EMS is often solely responsible for actively planning and controlling the energy consumption or production of its connected devices. This means that the EMS decides which device may consume or produce energy and when. Typically, this decision making process is achieved by utilizing preconfigured priority lists or algorithms which describe the optimal energy distribution in a given system. This requires that the EMS is configured and implemented by an expert with a deep understanding of the system. System modifications, such as introducing a new device, similarly require reconfiguration by an expert. In private households, where vehicles and other devices share the same service connection to the grid, the situation becomes more complex as new devices my join or leave the energy management ecosystem at any time. Furthermore, effective scheduling of household devices requires not only an understanding of their technical constraints, but also their customer specific usage which may change daily. In such complex systems, priority lists or simple static algorithms lead to suboptimal decisions and energy management. This ultimately leads to inefficient energy use or an unnecessary inconvenience for the user.

To improve the decision making quality of an EMS with central planning, the EMS would need to receive and process a significant amount of dynamic, device, and user specific information as displayed in Figure 6

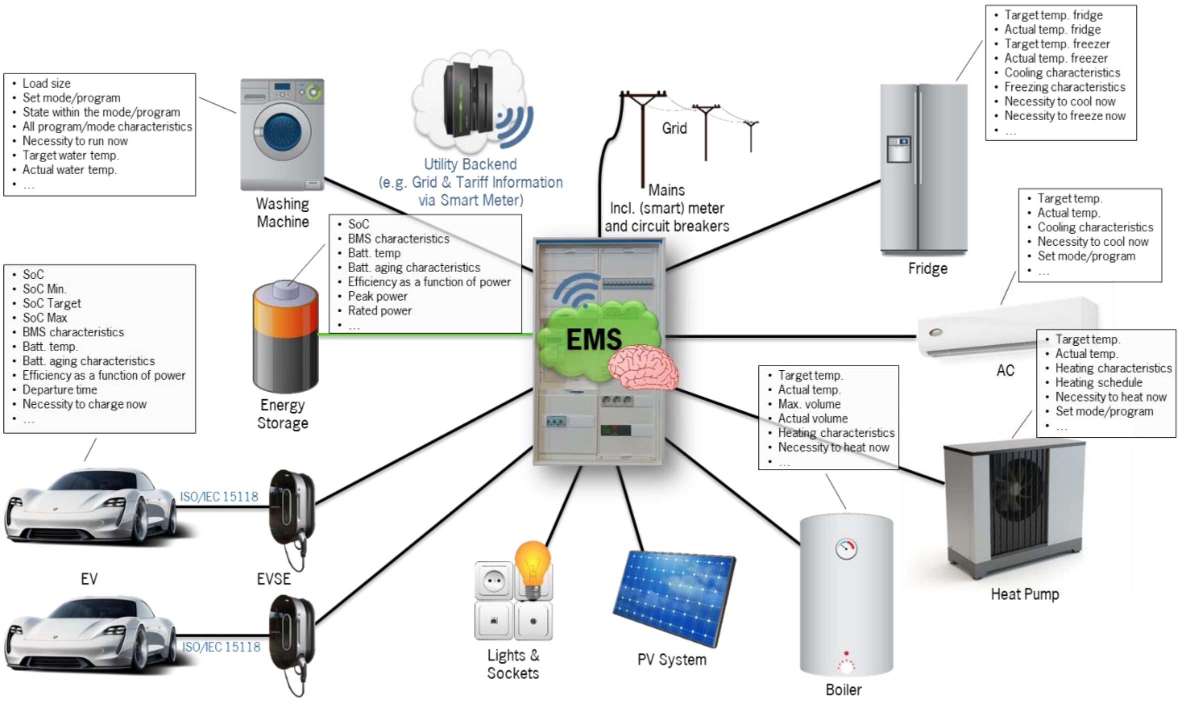


Figure 6: A centralized EMS intelligence requires significant device specific information

In addition to the wide variety of device types, there is a wide variety of manufacturers which each implement different device specific parameters for optimizing the energy efficiency of the device. This would mean that the EMS would potentially need to support "device specific drivers" in order to effectively manage all devices from all manufacturers. With every device update, or introduction of a new device type into the market, energy relevant parameters could change or be added, resulting in the EMS' device drivers needing to be updated as well.

Alternatively, to avoid having to update the EMS with every device update, bloated protocols are required which allows each device to disclose its manufacturer specific technical characteristics. Furthermore, the user would have to inform the EMS of how the device is intended to be used. This becomes problematic in (semi) public environments due to data privacy reasons. So even if energy management based on a centralized planning entity is possible, these systems fail to reach mass market adoption as they are too complex for a normal user, and suffer from scalability issues.

3.1.2 Distributed Logic EMS: The Market Economy Principle

In a market based EMS approach, the decision making process is no longer centralized within the EMS, but rather left up to each consuming device to decide for itself whether or not to consume energy, how and when. For example, a PEV knows how much energy it requires and when it needs to be finished charging. It knows this because the driver is able to input parameters such as departure time and target SoC. The PEV also knows the intricate details of its battery management system, and thus, when it receives price and power information from an EMS (via the EVSE), the PEV has enough information to decide for itself how best to schedule its charging profile. This same principal can be applied to other energy consuming devices allowing them to become smart, grid aware, energy devices. For example, a heat pump may allow the user to input a temperature range. The heat pump also knows its technical characteristics, thus, should it receive a price/power table, the heat pump is theoretically able to create its own, optimized heating profile. This process of negotiating via price/power tables creates a domain and device agnostic approach to energy management not only for VGI, but for all types of energy consuming devices.

To ensure that the power distribution network remains balanced in terms of supply and demand, the effects of price elasticity are employed in order to give devices an incentive to adapt their charging schedule. In other words, should the demand exceed the supply, the cost-of-energy would be increased. This would cause the PEV, for example, to reschedule its charging profile in an attempt to reduce its costs by planning to charge later (or earlier) when the price is lower. Should the supply exceed the demand, the opposite could be done so that the cost-of-energy is reduced which encourages the PEV to charge during this time. By doing this, the EMS is no longer dictating which device shall consume energy when, but rather giving incentives for any device to modify its behavior. The EMS is in effect acting as an energy “market place” whereby the price of energy reflects the relationship between the supply and demand.

Thus, the EMS’s “market place” allows all devices to buy and sell energy from one another by exchanging price/power tables via the EMS. The EMS essentially becomes an energy aggregator and informs each consuming device within its ecosystem of the availability-of-power and the cost-of-energy in the form of a price/power tables. A PEV capable of reverse power flow would “buy” energy from the EMS when it wants to charge, and “sell” energy back to the system (via the EMS) when it wants to discharge. A battery energy storage system could work in the same way.

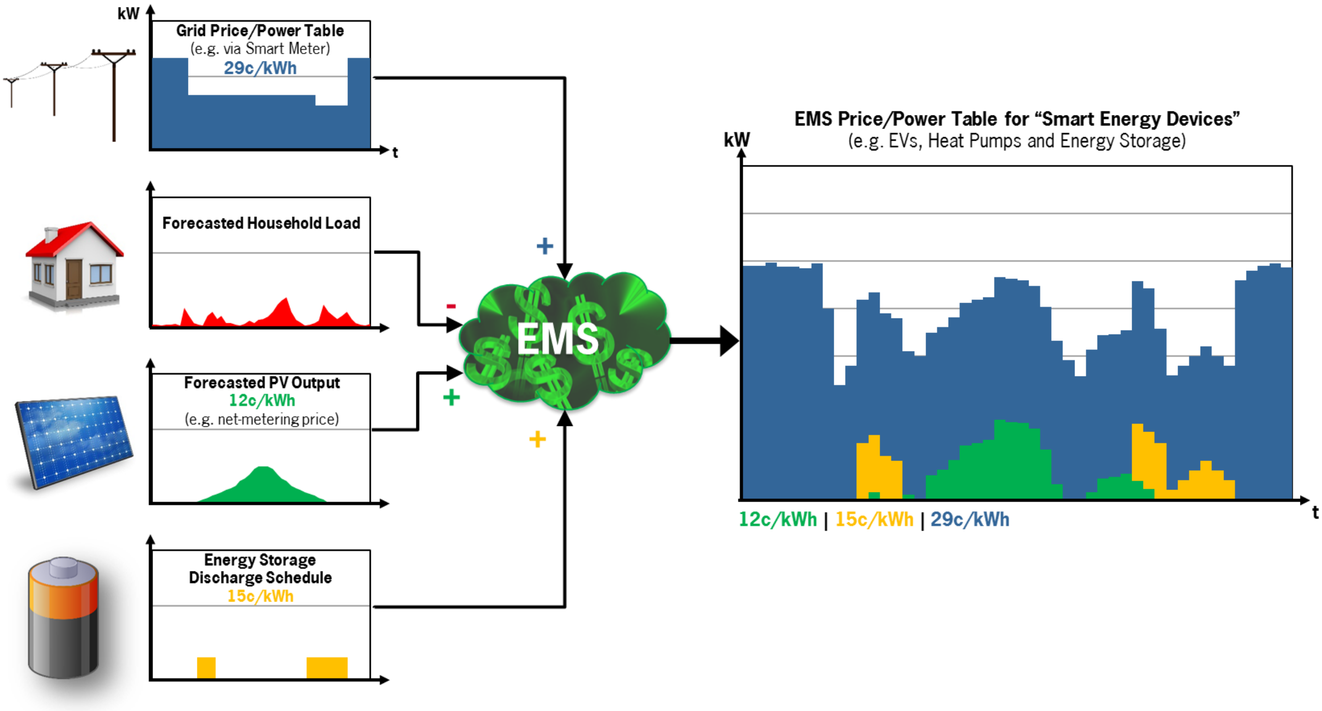


Figure 7: A market driven or decentralized EMS system acts as an energy aggregator and is primarily responsible for generating and distributing price/power tables which describe the availability-of-power and the cost-of-energy.

By allowing an EMS ecosystem to follow the principle of a market economy, the internal algorithms of all actors within the system are decoupled from one another. This means that each manufacturer is able to program their devices in a way which allows them reach their full potential in terms of electrical efficiency and capability. The EMS itself does not need to know why a certain device requires energy, or even what type of device it is. The EMS is simply interested in “trading” energy with whichever device requires it. There is no longer a need for the EMS to know any of the vast technical intricacies of the devices in the ecosystem either, as each device need only know its own technical parameters as well as its user defined settings.

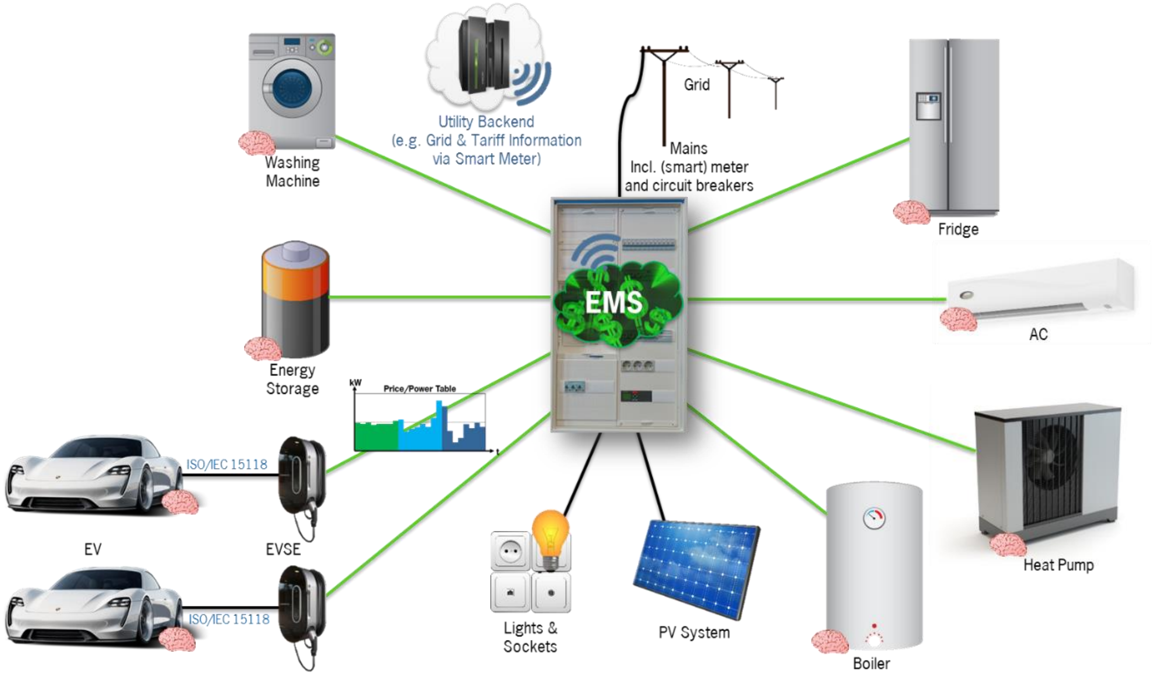


Figure 8: A market driven or decentralized EMS system requires no device specific information as the decision making logic has been distributed from the EMS to the individual energy consuming and producing devices.

However, as with any system of actors, some rules and control mechanisms have to be implemented to facilitate a trading scheme which leads to optimal results. The main problem to be solved is the potentially negative influence of the sequence in which devices reserve their energy demand. Without additional measures a device which urgently requires energy at a particular time may not be able to cover its demand as another device may have reserved the same timeslot due to an attractive price. Different strategies to solve this problem have been evaluated in a research project. Dependability, the level of intelligence needed in the EMS and the communication load differ significantly between the concepts. A scheme which is close to trading on today's commodity markets was found to be most dependable and efficient.

3.2 Conclusion

As the number of smart, connected devices grows, so too does the complexity needed to achieve intelligent energy management. The current way of doing this, though a central decision making process contained within an EMS, is not adequate to achieve optimal results in the future. A market based approach, which allows each device to make its own decisions, delivers better results, is less complex and allows for domain agnostic communication and integration.

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