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Electric vehicle integration in a real-time market

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Electric vehicle integration in a real-time market

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Abstract

This project is rooted in the EDISON project, which dealt with Electrical Vehicle (EV) integration into the existing power grid, as well as with the infrastructure needed to facilitate the ever increasing penetration of fluctuating renewable energy resources like e.g. wind turbines. In the EDISON project, the EV is introduced as an energy buffer used to store excess energy produced at off-peak hours, while at the same time potentially benefiting the consumer by offering cheaper charging. This role as a buffer, predominantly used for delayed charging, also known as "smart charging", can also be used for ancillary services to help stabilize the grid at critical periods, e.g. by providing near instant up- or down regulation.

The initial goal of this project is to develop the components for a simulation platform for large scale EV integration studies. By interfacing the EV simulation with an externally simulated model of the power grid, it is be possible, in real-time, to simulate the impact of EV charging and help to identify bottlenecks in the system.

In EDISON the vehicles are aggregated using an entity called a Virtual Power Plant (VPP); a central server monitoring and controlling the distributed energy resources registered with it, in order to make them appear as a single producer in the eyes of the market. Although the concept of a VPP is used within the EcoGrid EU project, the idea of more individual control is introduced through a new proposed real-time electricity market, where the consumers will have direct access to the current price. As opposed to the hourly spot-price market of today, the real-time market see price updates as often as every couple of minutes. To allow the individual resources to react to these changes, independent of each other, so called "smart controllers" are needed at the device level. In order for this market to work, however, the proper ICTnetwork- and server-infrastructure has to be developed.

The primary goal of this PhD project, has been to investigate the scope of this ICT infrastructure, required to realise price-signal based charging of electric vehicles, in accordance with the EcoGrid EU market.

Resumé

Dette projekt er udsprunget af det danske EDISON projekt, der omhandlede integrationen af elbiler i det eksisterende elnet, samt den nødvendige infrastruktur til at lette den stadigt stigende udbredelse af vedvarende energikilder som f.eks. vindmøller. I EDISON, blev elbilen introduceret som en energikilde til lagring af overskydende energi, produceret på tidspunkter hvor det øvrige forbrug ikke er tilstrækkeligt til at absorbere det, hvilket på samme tid kommer forbrugerne til gode, ved at tilbyde billigere opladning. Denne evne til at lagre energi, der primært bruges til at flytte ladningen til mere gunstige tidspunkter, også kendt som "intelligent ladning", kan ligeledes anvendes til balancering af elnettet i kritiske perioder, da bilen er i stand til næsten øjeblikkeligt at reagere og yde op- eller nedregulering.

Det indledende mål med dette projekt er at udvikle komponenterne til en simuleringsplatform, til test af elbils integrering i større skala. Ved at sammenkoble elbils simulering med en eksternt simulering af elnettet, er det muligt, i realtid, at simulere effekten af elbils opladning for derved at identificere og afhjælpe flaskehalse i systemet.

I EDISON blev bilerne styret ved hjælp at et såkaldt virtuelt kraftværk (VPP), bestående af en central server der både overvåger og styrer de tilkoblede energiressourcer, og derigennem får dem til at fremstå som én producerende enhed. Selvom begrebet "virtuelt kraftværk" anvendes inden for EcoGrid EU-projektet, er idéen om mere individuel kontrol indført via realiseringen af et foreslået realtids marked, hvor forbrugerne har direkte adgang til den aktuelle pris. I modsætning til det eksisterende spot marked, hvor energien handles for de enkelte timer i døgnet, vil prisen i det foreslåede realtids marked blive opdateret hvert femte minut. For at kunne tillade individuelle ressourcer at reagere på disse ændringer, uafhængigt af hinanden, er det nødvendigt med såkaldt "intelligent styring" på enheds niveau. For at denne markedsmodel kan fungere, er det derfor nødvendigt at udvikle den fornødne IT infrastruktur.

Det primære mål for dette PhD projekt, har været at undersøge og klarlægge omfanget af denne ICT infrastruktur, for derigennem at kunne demonstrere prisstyret ladning af elbiler, i relation til EcoGrid EU.

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External collaborators (IBM, Eurisco) During the course of the project, several partners were involved in anything from discussing standardization, developing demonstrations or project related documentation. Among these partners I am especially thankful for the corporation with IBM Research Switzerland and Eurisco.

The office (Peter, Andreas, Francesco) To my colleagues in the office in Lyngby. Word has it, that it is the final resting place for any houseplant, but I will have no part of that **?**; if they could survive on coffee or soft drinks on the other hand...

Colleagues (Thomas, Sergejus, Shi, Junhjie, Philip . . .) Thanks to the rest of my colleagues at CEE, especially those from the Electric Vehicle (EV) group. Thank you Thomas, Sergejus, Shi, Junjie and Philip for your collaboration, the interesting discussions and (where relevant) for being excellent travel companions to various conferences/events.

The guys in the Danish Smart Grid Research Network (DSGRN) I would like to thank my co-founders of the Danish Smart Grid Research Network, with whom I have had several interesting talks over the years, while arranging our academically- and technically interesting - not to mention popular - events all over the country. With any luck, the network will outlive us all.

Family + friends Lastly, I would like to thank my friends and my loving family for their support throughout the years, and for believing in me no matter the situation; I am especially grateful for having been left in peace to write this thesis :)

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Acronyms

AC Alternating Current

BMS Battery Management System

CAN Controller Area Network

DC Direct Current

DER Distributed Energy Resource

DTU Technical University of Denmark

EV Electric Vehicle

EVSE Electric Vehicle Supplu Equipment

GLPK GNU Linear Programming Kit

GPS Global Positioning System

GSE Generic Substation Event

GSM Groupe Spécial Mobile

HTTP HyperText Transport Protocol

ICE Internal Combustion Engine

ICT Information and Communication Technology

IT Information Technology

LMP Locational Marginal Price

MMS Manufacturing Message Specification

NSS Negative Side Signalling

OCPP Open Charge Point Protocol

OEM Original Equipment Manufacturer

OPC OLE for Process Control

PF PowerFactory

PLC Power Line Communication

PWM Pulse Width Modulation

RBAC Role Based Access Control

REST REpresentational State Transfer

RTP Real-Time Price

SOAP Simple Object Access Protocol

SOC State Of Charge

TLS Transport Layer Security

TSO Transmission System Operator

UDP User Datagram Protocol

V2G Vehicle-to-grid

VPP Virtual Power Plant

WP Work Package

Chapter 1

Introduction

Almost since the dawn of motoring, electric propulsion has been at the technical frontier. Sadly the so-called Internal Combustion Engine (ICE) vehicles quickly took the lead, and has dominated the scene ever since, but things are slowly starting to change. The history of EVs, which is an interesting subject in itself, shows that there has been several movements aimed at making the EVs as accessible to the masses as its ICE cousins. First, in the early days of Thomas Edison and Henry Ford, later during World War II and lately in the 80s and early 90s, which ended, as depicted in the fill *Who killed the electric car*, with General Motors systematic eradication of their EV1.

Figure 1.1: Danish *Ellert* ca. 1985

Even Denmark, who has never really been known for its car making traditions, was participating. Probably most memorable, was the three wheeled *Ellert* depicted in figure 1.1.

The primary means for any vehicle is transportation, but for all the prior attempts at bringing EVs to the masses, this was the only goal. In the middle of the 2000s, the world started to experience the next movement towards electric transportation, but things have changed and some very large players in the energy sector are now cheering on the development.

All over the world, government are posing ever stricter pollution requirements, aimed at limiting the environmental impact. One of the ways this is done, is to strongly push for the introduction of more- and more renewable energy production. Of the most talked about renewable resources, are typically wind turbines and photovoltaic installations. Because of its location in northern Europe, it should come as no surprise that Denmark has bet the heaviest on wind generation. Unlike the more traditional means of power generation, such as nuclear, hydro and the burning of fossil fuels, the renewables are prone to deliver a less production.

Throughout the energy sector, the EVs are greatly expected to become available as a balancing resource, in the form of their large, often unused batteries. Because of the great expenses in keeping balancing resources maintained and operational, there are great value in utilizing existing underutilized resources for this purpose. The EVs represents exactly such a resource, because they spend most of the time parked, and unlike the traditional means for balancing, they do not suffer from any mentionable ramping constraints.

Besides smart charging, many of the most valuable services potentially provided by EVs require fast response times, sometimes in the order of seconds. Since it is unrealistic to have the EV owners stand by the phone, a natural progression has been to remote control enable all the vehicles. Because Original Equipment Manufacturers (OEMs) have not been focused on enabling these features in the vehicles, this has brought about a series of challenges ranging from the EV connectivity in terms of plug standardization to the Information and Communication Technology (ICT) systems required to compute the necessary control strategies.

1.1 Research goals

The focus of this project was twofold, though not unrelated. The initial focus was on the design, development as well as testing- and demonstration of a centrally aggregated platform for EV charging and ancillary services; this was largely carried out in relation to the overall EV integration strategy outlined by the EDISON project. Following the end of EDISON, the focus was shifted towards the real-time market proposed by the EcoGrid EU project. Whether the distributed charging, with continuously updated prices, would significantly change things and if so, how, was one of the main questions to be answered. This comprised a study into the realtime markets as well as the resulting ICT requirements needed for moving part of the control away from the central aggregator and into the EVs.

From the overall project goals and vision (above), the resulting questions and research goals led to the project being partitioned into a series of Work Packages (WPs):

WP1	Overview of current research
WP2	Development of EV simulation framework
WP3	Simulation testing and initial grid-impact studies
WP4	Market research (with emphasis on real-time markets)
WP5	Specification of real-time market ICT requirements
WP6	Implementation of real-time market demonstration
WP7	Testing and demonstration
WP8	Evaluation and recommendation

1.2 Outline ot the thesis

This report covers the work carried out in relation to the WPs defined in the study plan (listed above). Some of these are further documented in the attached publications (see publication list further down). The chapters that make up the report, are as follows:

Chapter 2 : Describes and discusses related research project in relation to the PhD project and its questions/goals. This work primarily relates to the research carried out in WP1. This initial research into the general state of EV integration and related ICT resulted in the author co-authoring the two book chapters A5 and A1].

Chapter 3 : Covers the findings of the market research from WP4. The chapter continues with a description and discussion of the proposed EcoGrid EU 5-minute market. Parallel to the market research carried out in WP4, the author was responsible for the EcoGrid EU market specifications, documented in A4.

Chapter 4 : Deals with the EV users, their requirements and will (need) to change, if any, during the shift from centralized to decentralized charging. The work discussed in the chapter relates to WP5 and publications A2, A5 and A1. In addition, the driving analyses conducted as part of WP2 gave both valuable insight into real EV user behavior, as served as a stepping-stone for the further development of EV simulation components.

Chapter 5 : Offers an overview of the current state of EV connectivity, including not only the ongoing battle of the EV connectors but also the services offer-able through the use thereof. During the project, components for a grid-aware EV simulation was done in WP3, which is also covered in A1, A5 and A6 as well as the resulting patent described in A3.

Chapter 6 : Gives an overview of the EDISON ICT infrastructure and the transition to EcoGrid EU. It discusses the IT systems needed for price-signal control, the most relevant existing EV related standards and offers recommendations for utilizing them. WPs 6 and 7 both feed into this chapter, which lead to the experiments outlines in chapter 7. This research into the field of EV ICT as well as outcomes of subsequent demonstrations, has largely been documented in A1 and A5. Further studies in relation to supervised projects, resulted in the secondary publications B2 and B3

Chapter 7 : Presents and discusses the experiments that were made in relation to distributed charging optimization. The chapter also includes recommendations refinements and other future works. This is a continuation of the WP 6 and 7 efforts from chapter 6. As of this writing, no core publications has been submitted, but the work strongly relates to secondary publications B4 and B5.

Chapter 8 : Contains a summation of the essentials of the chapter summaries along with the future work and general recommendations defined by WP8.

1.3 Publications

This section outlines the publications made in relation to the PhD project. To make it easier to form an overview of the contributions, the publications have been split into three categories: *Core publications*, *Secondary publications* and *Patents*.

1.3.1 Core publications

The core publication are primarily the ones spearheaded by the author, or where the author played a substantial part in the creation thereof. They include a couple of papers, a couple of book chapters, a technical report and a patent application. These publications are included as appendices.

A1 Anders Bro Pedersen, Peter Bach Andersen, Joachim Skov Johansen, David Rua, José Ruela, João A. Peças Lopes
ICT Solutions To Support EV Deployment

"Electric Vehicle Integration into Modern Power Networks", ISBN 978-1-4614-0133-9, pages 107-154, 2013 (published)

A2 Anders Bro Pedersen, Andreas Aabrandt, Bjarne Poulsen, Jacob Østergaard
Generating Geospatially Realistic Driving Patterns Derived From Clustering Analysis Of Real EV Driving Data
Proceedings of IEEE Innovative Smart Grid Technologies (ISGT), 2014, (accepted for publication)

A3 Anders Bro Pedersen, Sergejus Martinenas, Thomas Meier Sørensen, Peter Bach Andersen
Enabling smart charging of electric vehicles by remote control of PWM signal via modem
Patent application (submitted)

A4 Anders Bro Pedersen, Dieter Gantenbein, et. al.
Identification - Requirements on central ICT platform and software
EcoGrid EU Workpackage 3 Task 1 deliverable, 2011.
NB: Due to the report being restricted, only the public executive summary has been attached in the appendix.

A5 Peter Bach Andersen, Anders Bro Pedersen, Einar Bragi Hauksson, Dieter Gantenbein, Bernhard Jansen, Claus Amtrup Andersen, Jacob Dall
Smartly Charging The Electric Vehicle Fleet
"Smart Grid Applications", ISBN 978-1- 1180-0439-5, pages 381-408, 2012 (published)

A6 Francesco Marra, Dario Sacchetti, Anders Bro Pedersen, Chresten Træholt, Esben Larsen
Implementation of an Electric Vehicle Test Bed Controlled by a Virtual Power Plant for Contributing to Regulating Power Reserves
Proceedings of the IEEE Power and Energy Society - General Meeting, pages 1-7, 2012 (published)

1.3.2 Secondary publications

Besides the core publications, the authors has also contributed a series of other publications, referred to here as the secondary publication list. These include works where the author has played a smaller role, such as the case for supervised work of projects closely related to the PhD project.

B1 Anders Bro Pedersen, Einar Bragi Hauksson, Peter Bach Andersen, Bjarne Poulsen, Chresten Træholt, Dieter Gantenbein
Facilitating a Generic Communication Interface to Distributed Energy Resources - Mapping IEC 61850 to RESTful Services
Proceedings of IEEE International Conference on Smart Grid Communications (SmartGridComm), 2010, pages 61-66 (published)

B2 Bo Søborg Petersen, Daniel Winther, Anders Bro Pedersen, Bjarne Poulsen, Chresten Træholt
Integrating Intelligent Electric Devices into Distributed Energy Resources in a Cloud-Based Environment
Proceedings of IEEE Innovative Smart Grid Technologies (ISGT) Europe, 2013 (published)

B3 Lasse Orda, Jesper Bach, Anders Bro Pedersen, Bjarne Poulsen, Lars Henrik
Utilizing a Flexibility Interface for Distributed Energy Resources Through a Cloud-Based Service
Proceedings of IEEE International Conference on Smart Grid Communications (SmartGridComm), 2013 (published)

B4 Shi You, Junjie Hu, Anders Bro Pedersen, Peter Bach Andersen, C. N. Rasmussen, Seung-Tae Cha
Numerical Comparison of Optimal Charging Schemes for Electric Vehicles
Proceedings of IEEE Power and Energy Society - General Meeting, 2012 (published)

B5 Andreas Aabrandt, Peter Bach Andersen, Anders Bro Pedersen, Shi You, Bjarne Poulsen, Niam O'Connell, Jacob Østergaard
Prediction And Optimization Methods For Electric Vehicle Charging Schedules In The EDISON Project
Proceedings of IEEE Innovative Smart Grid Technologies (ISGT) US, pages 1-7, 2012 (published)

For ease of reading, table 1.2 gives an overview of publications- chapter relations as described in the thesis outline.

Chapter 2 :	A1, A5
Chapter 3 :	A4
Chapter 4 :	A1, A2 A5
Chapter 5 :	A1, A3, A5, A6
Chapter 6 :	A1, A5 (B2, B3)
Chapter 7 :	(B4, B5)

Table 1.2: Publication overview - *primary* and (*secondary*)

1.4 Supervision

Besides the authors own concrete work, the PhD project also helped to inspire a series of other project, which was consequently supervised by the author. The most noteworthy of these projects, which greatly contributed to this PhD project, are listed in the sections below.

1.4.1 Master projects

- Anders Ørskov Christensen & Jonas Falck Frederiksen
  Distributed Decentralized EV - Architecture and Requirements Specification
  2011 **?**

- Lasse Dreisig Orda & Jesper Bach
  A Generic Framework for Communication of Distributed Energy Resources through a Cloud-based Service
  2013 **?**

- Bo Søborg Petersen & Daniel Lingberg Winther
  Integrating Intelligent Electric Devices into Distributed Energy Resources in a Cloud-Based Environment
  2013 **?**

1.4.2 Bachelor projects

- Joachim Skov Johansen
  Design and Implementation of an Electric Vehicle Charging Station
  2011 **?**

Chapter 2

Related research

2.1 Introduction

This projects presents an overview of some of the activities, that are most relevant to this project, including several search- and demonstration projects as well as a brief discussion of the most current OEM activities. This primarily relates to the research carried out in WP1. The initial research into the general state of EV integration and related ICT resulted in the author co-authoring the two book chapters A1 and A5.

2.2 Research projects

With governments all over the world pushing for an ever increasing penetration of renewables, in a continued stride to rid themselves of their dependence on fossil fuels, the EVs have almost universally been hailed as one of the major stabilizing factors in the future power grids. As a result, numerous trial-, research- and demonstration projects have been created, focusing, in one way or another, on EV integration.

2.2.1 National

Being essentially an island nation, facing the North Sea, with little more than trees to shield it from the wind, it is no wonder that Denmark is betting heavily on wind power. In the spring of 2012, the Danish Parliament voted for an ambitious goal of 50% wind penetration by 2020 and complete independance from fossil fuels by 2050. Considering the fluctuating nature of most renewable resources, it is no wonder the Smart Grid have won great favour in Denmark, which is reflected in the number of EV related projects.

EDISON

The Danish funded EDISON project (short for "Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks"), was, as the name implies, focus on the EV integration in relation to, especially, wind power. Like *FlexPower*, but unlike EcoGrid, the focus of EDISON was not market development, but rather a first step into EV control for the purpose of facilitating load shifting and other ancillary services. The employed system architecture, discussed in further detail in 6, was based on a central aggregator or Virtual Power Plant (VPP). The concept of a VPP is not new, and has been covered by other projects such as the MERGE and FENIX projects. The broadest covering VPP concept, controlling a vast array of DERs, is the **GVPP!** (**GVPP!**) **?**. The EDISON **EVPP!** (**EVPP!**) is a refinement of this, in that it only deals with EVs **?**.

FlexPower

Both EcoGrid EU and *FlexPower* are based on controlled end-user consumption through the use of price-signals, but where EcoGrid EU proposes an entirely new market, sending price-signals directly to the consumers, the main goal of *FlexPower* is to achieve the same using the existing market mechanisms. Depending on the ICT, most importantly the communication and protocol mapping, there is no real difference from an EV perspective. This is discussed further in chapter 6.

While the *FlexPower* project is not part of this study, the author did spend some time consulting on the structure of the design of the *FlexPower* price signal, called *FlexPrice*. Since this format is not unlike the one developed for EcoGrid EU, it is not covered extensively in this report. For more information on the price signals, see chapter 6.

NIKOLA

The NIKOLA project, named after the Serbian American inventor of the same name, is an EV integration project started at Technical University of Denmark (DTU) in collaboration with select national and international partners. The focus of the project is grid- and user services as well as enabling standards.

2.2.2 International

Elsewhere around the world, the strive to incorporate EVs into the power grid is not less as strong as in Denmark.

EcoGrid EU

The EcoGrid EU project, under which a substantial part of this PhD project was carried out, is a large EU financed demonstration project, with the goal of enabling end-user participation in regulation, through the introduction of a new 5-minute real-time market. Because of the ties to this PhD project, the EcoGrid EU project is references and discussed further through most of this report.

COTEVOS

The COTEVOS project, of which DTU Risøis a partner, was launched in late 2013 and focuses on EV interoperability.

V2G - University of Delaware

The EV research group at the University of Delaware, had made some great strides towards proving the viability of EVs as a valuable resource to the grid **?**. Focusing heavily on a Vehicle-to-grid (V2G) based platform, the project made groundbreaking progress in 2011, when they signed a contract with local the local energy company *NRG Energy* to deliver EV based balancing services.

eMobility (RWE)

A large scale integration and demonstration project, *e-Mobility* was started by *RWE* and the *Daimler AG*. Based on a 100 vehicle trial in the city of Berlin, the project aim was the development of standards to better the EV infrastructure.

The EV Project

The largest EV deployment project in the world, *The EV project* was started in 2010 with a $100 million grant from the US Department Of Energy. Counting more than 60 partners and activities in 21 major US cities, the project is nearing a staggering quarter of a billion kilometers driven. The goal of the project is the preparation and development of infrastructure, to pave the way for the next generation of EVs.

Green Emotion

Not nearly as big as *The EV project*, the trans European *Green eMotion* project is the largest of its kind in Europe. With a budget of €42 million, partly funded by the European Commission, the *Green eMotion* project is part of the European Green Cars Initiative (EGCI), aimed at supporting the EU climate goals.

2.3 OEM interest

Besides the academic project mentioned above, there is also a growing interest for EVs and electric mobility, and a number of OEMs are now starting to realise the added possibilities of EVs. Following the tragic events following the earthquake in Japan in 2011 and the ensuing Fukushima nuclear disaster, where many Japanese people were without power, the benefits of being able to power a house using an EV became more interesting. Lately Nissan has started focusing on this technology, often referred to as *V2H*, which is discussed in chapter 5. While this cannot be consider a grid service, per se, the required technologies are very similar and the consequent step to grid-service participation is small.

2.4 Sub-conclusion

The use of EVs as energy storage, has nearly universally been dismissed as being financially unsound. The costs resulting from the extra (whole) cycles put on the battery, more than makes up for the modest gain achievable from the average buying and selling of electricity B4. This does not necessarily mean that there will not be times where doing so could pay off, but as such price extremes rarely happen, and if so only for shorter periods of time, this concept has not been addressed any further in the project.

Since most within the energy sector believe EVs can play an important role in grid stabilization, the author finds it tragically ironic that the very government that pushes so hard for green- and renewable research, puts such high taxes on all road vehicles. Sadly battery technology still has some way to come, but in the meantime plug-in hybrids could not only help fill the void and help people overcome their range-anxiety, but most are equally capable of participating in grid friendly services. While it is admirable that the so-called full EVs have remained exempt from taxation in Denmark, the taxation of hybrids should be changed. As an example, the Nissab Leaf, which is one of the most popular EVs in the world, has a 24kWh battery and costs little more than €27 000. In comparison, the Opel Ampera (Europe's version of the Chevrolet Volt, and ironically "car of the year" in Denmark in 2012), has a 16kWh battery, but with Danish taxes still costs a whopping €87 000. As a result, Opel has managed to sell just a few.

Chapter 3

The move towards real-time markets

3.1 Introduction

This chapter presents a brief introduction to the existing danish electricity markets, along with its mechanisms and drawbacks. Following this, is an introduction to the proposed EcoGrid EU real-time market, related to EV integration and consumer involvement. This is the result of the of WP4, which in part also played into A4.

3.2 Existing markets in Denmark

Trading electricity in Scandinavia today, is not unlike trading any other tangible volatile priced commodity, thanks largely to the existence of Nord Pool Spot **?**. Nord Pool Spot A/S was established as an independent company in 2002, but was originally founded as “Statnett Marked” by the Norwegian Transmission System Operator (TSO) “Statnett” in 1993. Today the market, which is owned partly by the TSOs of Norway, Sweden, Finland and Denmark, is among the largest of its kind and traded 493TWh in 2013 alone **?**.

The overall market platform consists of two main mechanisms, namely the forward markets and the ancillary services market. The former is where the trading of electricity happens, according to various time horizons described below in table 3.2. Where the forward markets are settled before the actual time of operation, the ancillary service markets exist to help correct any imbalances that may have risen **?**.

The regulating market mechanism falls under the responsibility of the national TSOs, which in the case of Denmark is the government owned Energinet.dk. It is the last line of defense, so to speak, against a grid collapse

Bilateral contracts	These are energy contracts that are settled long before the time of operation, sometimes months if not years in advance.
Day-ahead market	Named *Elspot*, this market operates on an hourly basis, ranging from midnight to midnight, and is settled at noon the day before the day of operation. This is where the bulk of the electricity trading is carried out.
Intra-day market	Some producers, especially those based on renewables such as wind and solar, can have difficulties forecasting their own production to far in advance. For this reason, the intra-day market, called *Elbas*, was created to allow them to limit their losses.

Table 3.1: The forward market mechanisms in Scandinavia

caused by a lacking equilibrium of production and consumption, and offers three layers of protection.

Primary reserve	This up- or down regulation must be activated within 15-30 seconds. Half can be made available within 15 seconds, but all most be provided before 30 seconds.
Secondary reserve	For the slower acting reserves, these should come online within 15 minutes. The primary reserves are supposed to be able to deliver until then.
Tertiary reserve	The very last line of defence, the tertiary reserves are manually activated.

Table 3.2: The forward market mechanisms in Scandinavia

Because the TSO has to go out and buy regulating power, the penalty imposed for not delivering as promised on the forward contracts, is noticeably higher than the original- or even current energy price. This high penalization, reflected in the price of regulating power, makes for a huge potential for the EVs. Much of the existing reserves being maintained, includes generators, stationary battery installations or flywheels. Since the EVs carry around a battery anyway, which, when plugged-in, can be made to react within seconds, the ancillary services offer a great financial benefit to both owners as well as TSO **?**.

3.3 EcoGrid EU

In order to even participate in the above mentioned markets, the requirements will rule out even the wealthiest of the private consumers. Not only is there a energy/power minimum, no doubt to limit the number of acting small time players in the market, but since any participant also needs to be able to cover the potential penalties imposed by the TSO, a substantial bank guarantee is required.

These requirements are what gave rise to the VPP concept pursued in EDISON and similar projects, and it is also what drives the vision of the EcoGrid EU project.

As illustrated by figure 3.1 the proposed EcoGrid EU market sits comfortably between the existing regulation markets and the frequency controlled reserves.

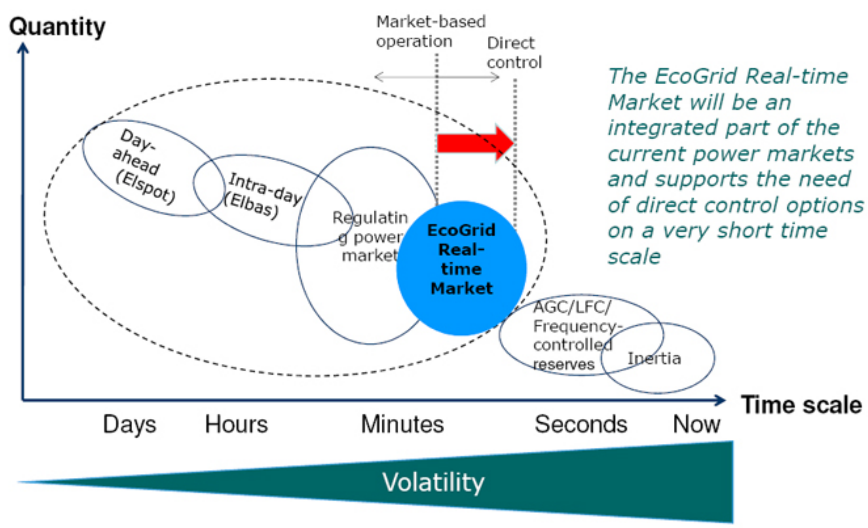

Figure 3.1: Illustration of where the EcoGrid EU market fits with the existing market solutions, *source: EcoGrid EU website* **?**

Looking at the figure, one could be forgiven for only regarding it as a unique market, but in fact it essentially comprises both the day-ahead-, intra-day- and regulating markets in the form of three price-streams. As illustrated later in chapter 7 and below in table 3.3, there are three streams included in the EcoGrid EU signal.

As a result of the existing market mechanisms described earlier, there is actually a real-time price in the system, but it is not broadcasted. Based on the *Elspot*, *Elbas* and the regulation prices, this is more or less how the EcoGrid EU price-stream is calculated. Now, broadcasting just the real-time price signal to the consumers, would not benefit them much, since that hardly gives them a chance to plan their response. Prices are relative, and without the means to tell whether one price is high or low, no one would know when to act.

Day-ahead	Essentially the spot price as known from the *Elspot* day-ahead market (24 x 1 hour)
Hour-ahead	Hourly forecast (12 x 5 minutes) designed to reflect regulation needs as a result of e.g. difference in wind, solar etc.
Real-time	The 5-minutely real-time price, meant to tweak the hourly forecasted price (last resort)

Table 3.3: The three EcoGrid EU price streams

This is covered again in chapter 7, but consider the case of a roaming EV that arrives in a new area for the first time. Even if existing units in the area could make due with a single price stream, storing the history of the real-time price, the EV would have no clue until it had been parked there for a while.

User interaction

In EcoGrid EU the user interaction is key, which is why the project has set out to provide a web portal allowing any participant to follow not only the price-streams, but also keep track of their own consumption. If users are to trust automated systems, there needs to be a certain degree of transparency.

3.4 Sub-conclusion

While the EVs have been predicted to play a great role in future electricity grids, its success in doing so is largely dictated by consumers willingness to allow their vehicles to participate in such endeavours. Short of passing laws forcing them to do so, the greatest incentive remains the financial benefits. It is a well known fact that electricity prices vary throughout the day, and at times fluctuate greatly, but as long as the actual price is such a small part of the prices billed to consumers, the incentive remains somewhat hidden.

In a sense the move towards a more liberalized electricity market, which is what the real-time markets represent, is a positive move for both the consumers and the energy sector as a whole. In theory, the installation of a smart-meter and an Internet connection, is all that is required to partake. Even in the EcoGrid EU project, there are currently participants who manually adjust their consumption according to the price. It should come as no surprise, that this is not as efficient as could be, unless they stay up monitoring the signals 24/7. An automated response is much more suited for this, and that is what the remaining chapters of this report are about.

Chapter 4

The EV users

4.1 Introduction

With all the recent pushes from the energy sector, to further the introduction of the EVs, the owners of the vehicles remain the primary customers. Despite the best intentions, from both the users and the energy sector as a whole, the vehicles have (presumably) been bought to be driven and no customer will remain happy for too long, if their vehicle is, in any way, made unavailable to them as a result of ancillary service participation. The work in WP5 and the consequent analysis of, among others, the "Test an elbil" have resulted in A2.

4.2 The EV as a resource

As discussed in chapter 2, a growing number of EV trial- and demonstration projects are being carried out all over the world. In Denmark alone, a sizable amount of EV data has been collected in recent years, in trials designed to give ordinary people a day-to-day introduction to what it is like driving an EV. One such project is the "Test en elbil" project (English: Test an EV), which is run by the danish company Clever A/S. The project, which is also described in A2, comprises some 180+ EVs which are lent out to select families on a three month basis.

Because EVs have not been available for large-scale real-world studies in the past, earlier studies have had to rely on data collection from ICE vehicles **?**. In these studies of driver behaviour a common question sought answered, which greatly relates to the EVs projected potential as a resource, is the availability; that is: how much time does the vehicle spend stationary?

Since the battery, which is the actual resource sought used, is only accessible when grid connected, it is a very valid question. Of course if varies from driver to driver, depending on things such as job type and commute distance, but the availability typically lies in the +90% **? ?**. Despite these number not being based on actual EVs, they have proven fairly accurate. During the PhD project, a preliminary study was carried out on the "Test en elbil" data, and though one might expect a borrowed EV, with a shorter range than an ICE vehicle, would be driven less the availability was actually slight lower. As can be seen from the plot in figure 4.1, the availability dropped just shy of 90% with an average of more than 96%. Like the ICE studies, this looks very promising for their involvement in future grid services.

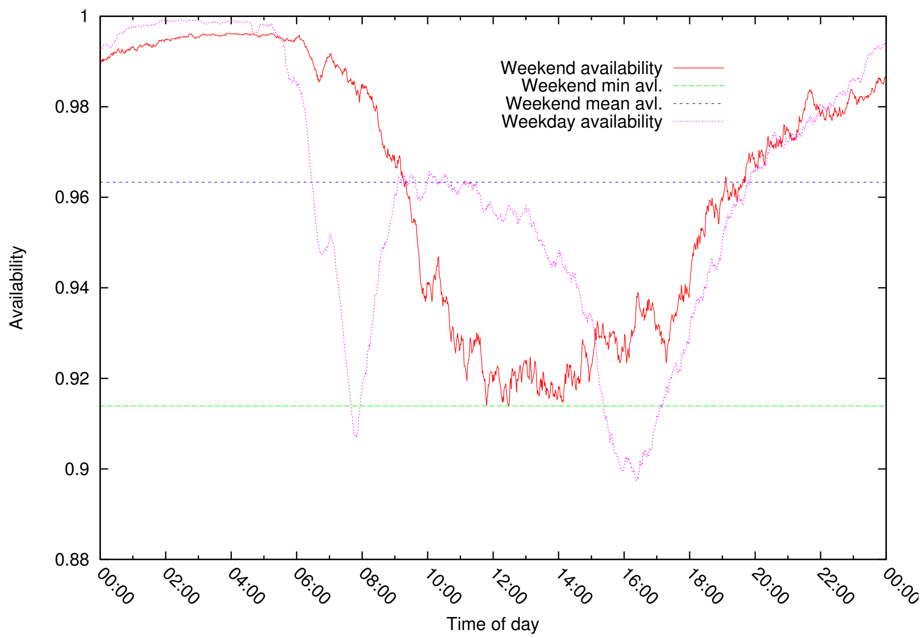

Figure 4.1: Plot of the average weekly availability for a chosen EV in the "Test en elbil" project. A2

Further studying the plot in figure 4.1, one will likely make a couple of interesting observations. As indicated in the legend, the weekday- and weekend days are plotted individually, which is also clearly visible in the typically observed daily commutes. Because the first errand of the day, for most people, is the drive to work, the morning peak appears very sharply around 7:45. In the afternoon, after work, people tend to do most of their alternate driving, leading to a significantly wider peak. Because of the length of the average working day, the beginning of the afternoon peak, however, will usually be steeper than the later side, since the length of the errands differs.

Unlike the weekdays, the weekend days do not display the same two peaks, since the driving is typically more diverse. Not only is the nightly stay prolonged by a later departure, but the use of the vehicle appears spread out during the whole day. Likewise, in this particular case, there is a small but noticeable difference in the amount of night driving, presumably originating from social errands.

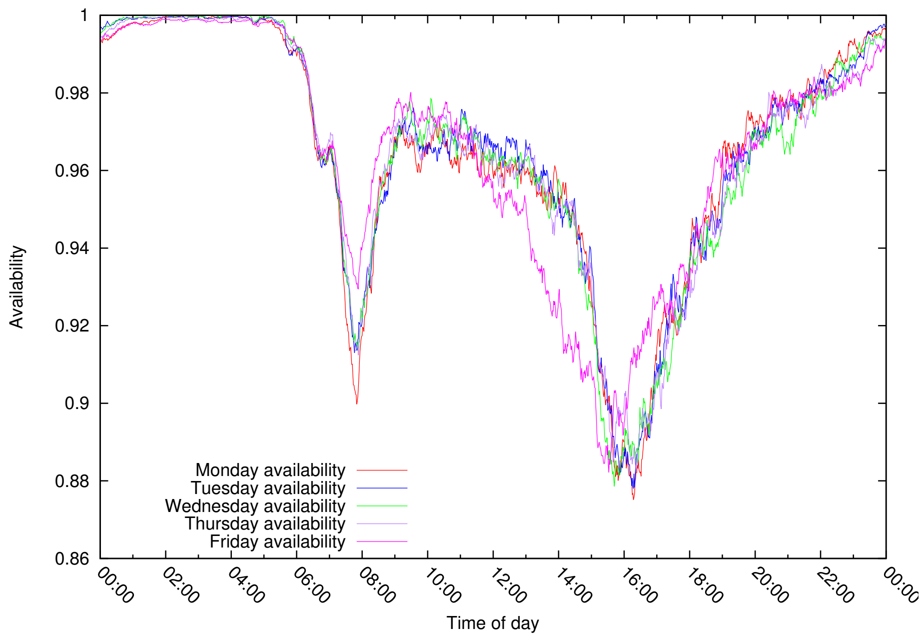

Figure 4.2: Plot of the availability for the individual weekdays for a chosen EV in the "Test en elbil" project. A2

Finally, the plot in figure 4.2 shows the individual weekdays and how they compare to each other. The first four days are remarkably similar, but again there are amusingly familiar trends to be found in Friday. Not only does the higher morning availability indicate more dispersed driving times, but the afternoon peek happens noticeably earlier than the rest of the week. When observing the end of the day, the Friday availability also seems to suggest more late night driving in keeping with the previously observed trends for the weekend.

4.3 Adhering to user wishes

In order to successfully carry out intelligent charging or partake in providing ancillary services, there are a number of basic parameters that needs to be known; the most important of which relates to the energy requirements and the arrival- and departure times for the vehicle. As hard as it would be filling a glass of water blindfolded, without spilling that is, properly scheduling the charging of an EV without knowing its SOC or when it will be leaving, is not possible without arriving at a far less than optimal result. The only prudent strategy in this case, is "charge as fast as possible, as soon as possible"; a strategy commonly referred to as "dumb charging".

Not only will the charge usually be more expensive, as some of the highest prices are found around the time people normally come home from work, but with the battery being filled early the potential for load shifting and regulation is lost.

4.3.1 Direct user involvement

In lack of a better option, the most obvious- and implementation-wise simplest solution for obtaining this information, is by asking the user. This is not a desirable solution for a couple of reasons. For starters, constantly nagging the users about their expected departure time and energy needs, will likely result in them growing tired of participating in the program and opting out. With the ones that stay, there is a high risk that they will eventually grow lacy and start caring less about the accuracy of what they are indicating. The likely result from this, is either that conservatism will result in more "dumb" charging, or that optimistic expectation to their own behavior will lead to an under-charged vehicle and consequently lots of frustration.

4.3.2 Predicting driver behavior

In B5 a prediction method, based on exponential smoothing, was successfully shown to accurately determine the plug-in periods of the drivers along with their projected energy needs, based on their past history. This was implemented in the EDISON VPP and used in some of the demonstration discussed in later chapters.

With the process automated, the users can essentially plug-in their vehicle and walk away, only to come back to a fully (smart) charged vehicle. Naturally, unlike the case of direct user involvement, failure to properly predict the parameters of the next trip, will leave the users disgruntled. Therefore, the accuracy of these prediction are very important, which means walking a fine line between cost and conservatism.

4.4 Classification of charging locations

Logging locational data from any satellite based system, is never 100% accurate. Building, trees and other obstacles along with the rotation of the earth, means the number of visible satellites vary. Because of this the accuracy of the signal fluctuates, sometimes as much as 15-20 meters. To clean up this sort of data, a clustering algorithm is typically used to group adjacent locations based on a given set of parameters. In A2 the DBSCAN algorithm is employed to do just that, and coupled with a couple of additional heuristics, shown to be useful for classifying locations into known charging locations such as *home* and *work*. The screenshot in figure 4.3 shows the original data set on the left, with a stricter and stricter classification moving right. The remaining three clusters shown in the plot, represent the locations classified as *home*, *work* and lastly the most predominant *other* location.

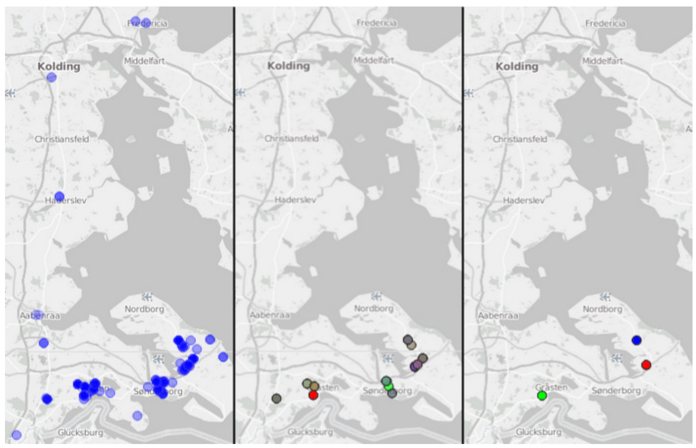

Figure 4.3: Selection of location for a given EV, shown along side an increasingly stricter clustering (left to right)

The main goal of this analysis, was to derive a method for stochastically modelling EV behavior in time as well as space. Though larger EV projects do exist, mocking about with charging algorithms using real vehicles will only lead to displeased users. For this reason, and that EVs still have not come even close to the penetrations previously predicted, large scale simulation are still a necessity. Because one of the main purposes of this exercise is bettering the grid, the coupling of EV simulations with grid simulations represents a natural progression.

Once classified, the locations can form the base of a stochastic analysis of the vehicle behavior in relation thereto. In figure 4.4, the plots on the left represent the probability of the vehicle being in either of the states *home*, *work* or *other* at any given time of the day. Described further in A2, this can then be used to model the EV in a Markovian way. The left side of the figure, shows a series of trial runs based on this model.

To properly determine the load caused by the charging EVs, they need to be mapped to the correct feeders in the grid models; this is where the spacial element to the simulation comes into play.

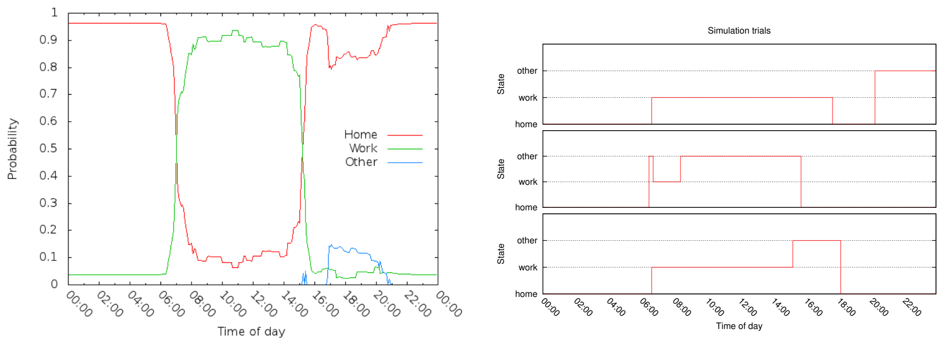

Figure 4.4: Plot showing locational probabilities (left) along side resulting trials (right)

Since merely replaying the data with the original locations is not a realistic representation of the EV penetration, the given behavior should be mapped to other locations. By using a database of existing *home* and *work* addresses, suitable pairs can be chosen that match approximately the distance as the original. Once these have been determined, a routing algorithm can determine the most natural routes between them. Coupled with an acurate model of an EV drive train, the consumption can be accurately derived. The illustration in figure 4.5 shows a route across the island of Bornholm, with the dots representing homes (red) and businesses (purple). Besides the distances, some road map databases also contain elevation and nearly all include things such as the speed limits of the individual roads. Since most people tend to drive close to the given limits, that coupled with e.g. elevation changes and turns can lead to a very accurate consumption model.

The prediction method utilized in B5, and discussed earlier, was developed for use in EDISON, but has yet to be tested in an every day scenario. The method discussed above, for locational classification based using clustering and the consequent stochastic method for simulating EV behavior, has yet to be implemented in a large-scale simulation. As indicated in the discussion, elements of the methods could feed into each other to derive a more accurate prediction, which is a goal that should be pursued.

4.5 Sub-conclusion

A preliminary analysis of the "Test en elbil", was performed in relation with the locational classification study for A2. Part of this analysis included a comparison with previous studies, which suggested an availability of at least 90% **?**. The author has verified that in case of the "Test en elbil", the availability

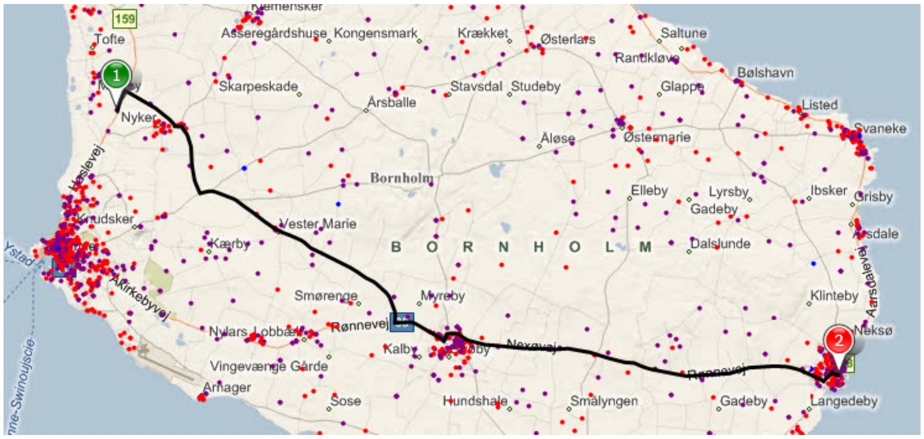

Figure 4.5: Illustration of a route plotted across the island of Bornholm

was a fairly good match for the previous studies, with an average availability of no less than 94%. Assuming the tested EVs were driven to the same extend as the users would normally use their ICE vehicle, this could be even better than projected, for the EVs participation in grid-related services.

Through the participation of various EV demonstration projects, the author has investigated the required user information needed for an EV to be centrally aggregated. Following the continued work with decentralized charging, these parameters were found to more or less transferable, though in cases derived- or derivable from different sources.

4.5.1 Future works

In B5 the historic log of trip starts-, ending- and distances are used to predict future trips and implicitly the charging periods that lie between them. Because the duration of any stay is closely tied to the location, the prediction should be refined to include this information as well.

Like the vehicles of "Test en elbil", the DTU fleet suffer from the same Global Positioning System (GPS) inaccuracy. There is currently a project underway at CEE, tasked with developing a next generation data logger for EVs. While the logger already contains satellite based tracking, combining this with an inertial tracking system could further improve the accuracy, especially in urban areas. Besides maintaining a fix where otherwise not possible (parking garages, tunnels etc.), the greater accuracy should also lead to less non-classifiable locations derived from the clustering analyses.

Chapter 5

Grid connecting EVs

5.1 Introduction

Following research carried out by the author, into the current state of EV connectivity, this chapter presents the typical challenges encountered in connecting EVs to the grid. It offers an overview of the current state of EV connectivity, the ongoing battle of the EV connectors as well as the services offer-able through the use thereof.

Through the continued work with EV integration, both in the project and in relation to various demonstrations at DTU, the author has gained a good insight into the topic. The publication A1, A5 and A6 are a direct result of this. Most importantly, the work relating to EV connectivity, has spawned the patent outlined in A3 and towards the end, describing a method for smart charging most of the existing EV fleet with little modification to the vehicles themselves.

Related to the grid integration, are the simulation components developed as part of WP3 for grid-integration studies, which are discussed towards the end.

5.2 Charging connectors

During previous attempts at revolutionizing transportation by electrification, a number of vehicles were developed such as the danish *Ellert* depicted in figure 1.1. Common for all, however, were that they were designed for low power home charging, resulting in them using traditional household outlets.

With the EVs becoming more widespread and with ever increasing battery capacities, the need to increase the charging currents followed suit. As people start traveling further and further from their home, coupled with the need for higher charge rates, more and more public chargers have also emerged. Since the traditional house hold plugs are not built for higher power, and offer limited protection against neither the elements nor tampering/foolishness, new connectors were developed.

In a manner very similar to the long raged war on cellphone charging connectors, the world of electric transportation has seen it share of disagreements on the subject. Too many connectors have existed over the course of just the last decade, to go through here, but luckily the selection has thinned out and only a few remain.

Until recently, only two real competitors existed on the European arena, both of which are shown in figure 5.1. The IEC62196 Type 1, favoured by companies such as Renault and Nissan, and the IEC62196 Type 2, which has been the preferred connector of, among others, the Daimler group and VW.

Figure 5.1: The two most popular AC charging connectors on the market - IEC 62196 Type 1 (left) and Type 2 (right), often referred to simply as Mennekes and J1772. A3

Common for most of the previous connectors, including the ones in figure 5.1, is that they have all been for AC charging. In this pursuit for ever increasing charge rates, the internal vehicle chargers have by some been deemed insufficient. This led to the development of off-board Direct Current (DC), along with even more connectors. Most predominant of these has been the Japanese CHaDEMO connector. Since the sole purpose of a DC charger is fast charging, little flexibility remains for any of the otherwise grid-centric services related to this study. For this reason, fast chargers have not been given much attention, but this could change in the future. The strive for greater battery capacity will likely never cease, and with more and more vehicles charging in the public domain it would only required the DC chargers to be made dynamically controllable, before they become interesting within the domain of smart grids. In the meantime, significant progress has been made in advancing AC charging, pushing the charge rate up to 44kW. Since a larger charger in the vehicle would add too much weight, a method for using the motor in the vehicle was developed at DTU **?**.

5.3 Communication

In recognition of the benefits for controlled EV charging, several pushes have (and are being) made for standardizing the communication with the EVs.

5.3.1 Wireless

For wireless communication, there are essentially two main competitors: Groupe Spécial Mobile (GSM), which would be a directly link from the back-end to either EV or EVSE or a short range radio wave based standard such as 802.11 or ZigBee, which would link EV and EVSE **? ?**.

While wireless communication is typically the easiest to implement, it does have one major drawback with utilized for EV communication, namely the inability to identify exactly which EVSE a vehicle is plugged into. If there was a method/standard in place, which would allow the EV and EVSE to identify one another, a wireless solution, if stable, would work just fine. Unfortunately no such standard is currently in place, which has led to the pursuit of wired communication instead.

5.3.2 Wired

For wired communication, using the existing connectors, the two most viable methods are:

- Power Line Communication (PLC), which communicates by adding a modulated signal to the frequencies already present in the cables. A technique already popular for connecting house hold smart meters.
- Negative Side Signalling (NSS), developed by the V2G team at the University of Delaware, which uses the negative side of the PWM signal specified by the IEC61851 standard (see further description in following sections) **?**.

One important issue with PLC, is that if improperly installed the signal will propagate backwards through the grid connection, and will get picked up by other equipment in the area. This problem is essentially the same as with wireless communication. In **?**, the author suggest that the PLC component in the EVSE be installed on the EV side of the EVSE breaker, so to isolate the EV as long as the breaker is open. Once paired, the breaker can be open without risk of miscommunication .

There are already a number of PLC based solution in existence, and *Home-Plug*, which is the most predominant is available in multiple home networking solutions exceeding 500Mbps.

For NSS, the *Control Pilot* pin (see figure 5.1) is used to carry the communication. If is a simple solution, which biggest flaw is it's lack of standardization. The second biggest drawback of the technology, is the limitations in speed. Because NSS relies on existing circuits, the theoretical speed that can be obtained is severely limited. Granted it is more than fast enough for EV control under current circumstances, but who knows what requirements will exist in the future.

5.4 Standards

Several standards are already present within the domain of EV connectivity and ICT, with varying degree of support and implementation. Three of the most crucial, which are also covered in this thesis, are depicted in figure 5.2.

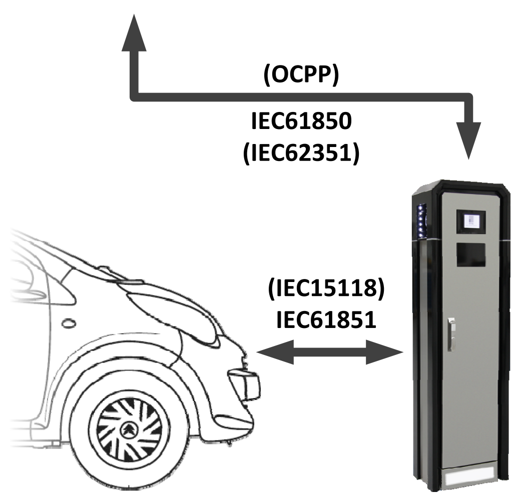

Figure 5.2: Standards overview in relation to EV, EVSE and back-end.

5.4.1 IEC61851

The IEC61851 is the de facto standard for EV to EVSE connectivity, and is consequently supported by all new vehicles and charging equipment. The primary reasoning for IEC61851 is conformance and safety, ensured by a series of mechanisms that are meant to stop the flow of power between EV and EVSE unless certain requirements are fulfilled.

Charging modes

Along with the safety mechanisms, IEC61851-1 categorizes EV using the four modes listed in table 5.1. Since the first two modes are meant for use without an EVSE, traditionally they are not associated with any form of intelligent charting. This can, however, be achieved using a direct communication with the vehicle, as described in the patent application A3 (see end of this chapter). In this case *Mode 2* can be made to allow smart charging, and in certain specific cases also *Mode 1*. Since modes 2 and 3 require the vehicle to support IEC61851, enabling smart charging in *Mode 1* will require slight changes to the vehicle connector.

Mode 1	$\leq 16A$	Charging using typical power outlet
Mode 2	$\leq 32A$	Charging using typical power outlet using in-cable IEC61851 compliant device
Mode 3	≤ 250	Charging from dedicated charging spots (EVSE) using EV connector with various safety/control measures in place (PP, CP etc.)
Mode 4	≤ 400	Off-board fast charging (DC charging)

Table 5.1: Listing of charging modes as defined by IEC61850 **?**

The last mode (*Mode 4*) is DC charging, which has yet to see any real use in smart-grid related setups. Most of these chargers do draw large amounts of power from the grid, when in use, but are generally not made scalable like those embedded in the vehicles (DC). Since fast chargers are large and expensive, they are by their very definition only used when needed and the vehicles therefore spend as little time fast charging as possible. Because of this, they are not interesting in a smart charging context and have largely been disregarded in this project.

Charging control/limitation

An integral part of IEC61851, which plays a crucial role in the patent described in A3, is the $1kHz$ PWM signal that is used to vary that permitted charge rate from the EVSE. As seen in figure 5.3, the controlled rate is almost linear from the minimum of $6A$ to the maximum supported power of $80A$.

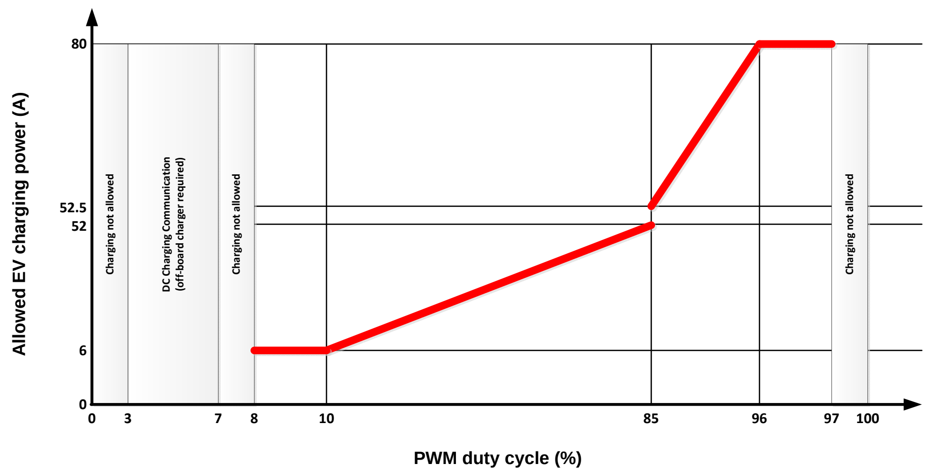

Figure 5.3: Illustration of PWM signal as defined by IEC61851. *Source: IEC61851* **?** *(redrawn)*

5.4.2 IEC15118

In keeping with the desire to facilitate over-the-cable communication, one of the more promising emerging standards is the IEC15118 **?**. To facilitate the development of the standard, an project named *OpenV2G* was started by Siemens, which currently offers an open source implementation of the IEC15118 **?**. The standard, which still has some way to go before being finalized, is designed to enable EV to EVSE communication over the cable, using PLC. Because it only focuses on the connection between vehicle and charging-spot, it fails to address the further communication between EVSE and back-end.

While the standard defined a series of data-types for communicating, is remains relatively open in terms of the actual communication, allowing any existing- or future protocol to be run on top of it. For the sake of this project, it means a price-signal could be sent directly to the EV as well as explicit commands from a price-controlled VPP. Unfortunately, between the standard being incomplete and the lack of hardware support in the DTU fleet, no IEC15118 based experiments could be completed.

It is important to note, that because the load bearing cables are used and not the *Control Pilot*, IEC15115 does not interfere with IEC61851, allowing for future upgrades with no change to existing hardware.

5.4.3 V2G or V4G

A very hot topic in the domain of EV research, is the concept of V2G, a term which was first coined by AC Propulsion, a California based EV drive-train manufacturer.

Some followers will have you believe that it is the actual act of back-feeding, in other words transferring energy from the vehicle battery to the grid through the charging cable. A more general understanding of the term, is anything that relates to grid-friendly services provided by a plugged in vehicle.

When planning for- and optimizing the charging of an EV, there are a number of variables to consider, such as:

- The expected plug-out time (ie. the duration of the plug-in period)
- The current- and target SOC
- The performance of the charger, which directly relates to the ability to achieve the target SOC)

When considering the first understanding of the term V2G, one comes to realize that the only affected variable is the charging performance. From the perspective of the grid operators, what is really needed to maintain stability, is relative changes. What that means is that the vehicle will be charging irregardless of the grid, but in order to help balance things, the vehicles will be (either directly or indirectly) asked to throttle their charging power to help increase- or reduce their load.

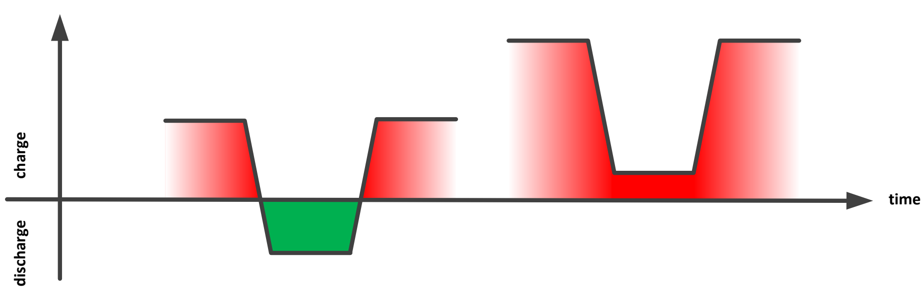

Figure 5.4: Illustration of throttled charging with- and without back-feeding.

If a non-V2G capable EV is charging at its full capacity of e.g. 22kW, it can up-regulate by 22kW but cannot down-regulate. In case of a 22kW symmetric V2G capable vehicle charging at full capacity, the ability to up-regulate doubles to 44kW while down-regulation remains impossible. Because regulation in relation to the grid, is a relative control input, a non-V2G vehicle capable of 44kW, but only charging at 22kW, will have the same potential to regulate as a symmetric V2G vehicle capable of ± 22kW, not charging.

Connector controversy

With traditional power connectors, the feeding part has always been female, primarily for the sake of safety. However, when connecting a back-feed capable vehicle the proper choice of connector becomes a bit of a dilemma. When observing the charging connectors in figure 5.1, the keen observer will notice that the plugs are male- and female respectively. The Type 2 connector handles the safety issue by having plastic capped terminals, allowing nothing larger than a small screwdriver to touch. The Type 1 connector is sunken (female), but if observed one will notice that the EV plug is then made with the same type plastic capped terminals as observed in the Type 2 connector.

One could argue that these plastic capped safeties are redundant, since implementation using either connector will not work without the remaining connectors (especially *Proximity* and *Control Pilot*), but the connectors are not always capped, which could potentially pose a safety risk in case of back-feeding.

5.5 Controlling present day EVs

Despite current advancements in charging connectivity, which is sure to bring the likes of broadband connections directly to the vehicles, there are still thousands of vehicles rolling off the assembly lines even today, which do not support communication of any kind. Among the most popular models sold in recent year, from manufactures such as Nissan, Renault and the esteemed Tesla Motors, none come with any support for smart charging built in.

Fortunately, no less thanks to the security issues touched upon earlier, they are all made to comply with the IEC61851 standard. Though mainly meant as a connectivity- and security conformance mechanism, it also allows an external party to limit the charging rate. Naturally, given an upper power limit, the EV is not required to approach it, but since most OEM vehicles are made user-centric, they will attempt to charge at their maximum allowed rate at any given time. Because of this, the upper limit dictated by the PWM signal on the *Control Pilot* write, effectively goes from simply controlling the upper power limit, to controlling the actual charging. Any deviances caused by e.g. temperatures variations or the need for cell balancing, can be modelled and anticipated. In any regard, even a centralized charging approach will suffer the same potential pitfalls when asking the vehicle to deliver a certain power flow.

The boards depicted in figure 5.5 illustration the proposed method of the patent in A3. The two boards *EV* and *EVSE* are as defined in IEC61851, with the middle board being the new addition. Two main function dictate the workings of the board, namely:

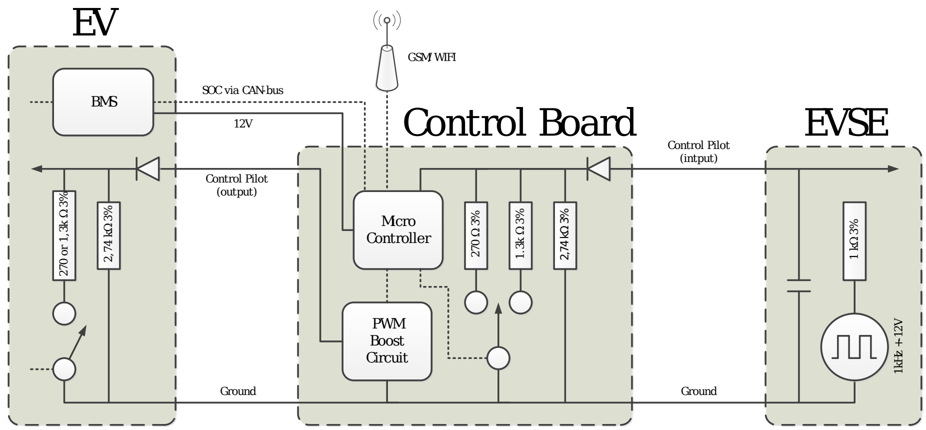

Figure 5.5: Suggested/developed circuit insert, which enabled remote control of IEC61851 compliant vehicles.

- Mirror the internal resisters in the EV, used to signal states to the EVSE
- “Hijack” PWM signal from EVSE and modify

Since the PWM signal from the EVSE is an upper limit, the board is free to re-transmit a new signal to the EV, as long as its value is no higher than the original. Due to the standards allowance for lower than dictated charging, as previously described, the EVSE will not react to the EV’s reaction to the new signal. From here it becomes a matter of externally controlling the modified PWM signal, which is proposed done by attaching a GSM module to the board. Only the PWM signal is required to control affect the charge rate, which is good enough for providing ancillary services such as regulation. For smart charging, the board also need to know the SOC of the vehicle battery. From past trials carried out at DTU, it was found that this information is most often available on the Controller Area Network (CAN) bus **?**. By connecting to this, the SOC information, and possible more values, can be read by the board. Since CAN is used throughout the automobile industry, it is highly standardized and a multitude of controllers exists.

The only remaining issues is to decode the proper CAN packages, but that is a software issue. It has already been done for the Nissan Leaf and a few other vehicles in the DTU fleet, and more will soon follow. Once decoded, the code will work with any car of the same type. To gain access to the necessary wires, the board needs to be attached close to- or on the charging cable. It is, however, advised that it be mounted along with the EV charging connector, to facilitate access to the CAN connector(s) in the vehicle. Figure 5.6 illustrates the difference in control-flow, in relation to the standard overview in figure 5.2.

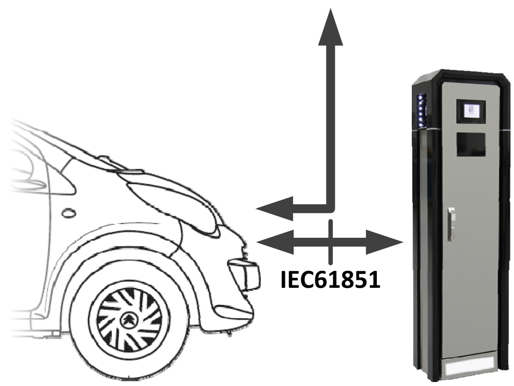

Figure 5.6: Illustration of the communication path using the suggested method.

5.6 Simulation and grid impact studies

Though the initial goal of real-time markets, such as the one in the EcoGrid EU project, is to offer consumers a more direct way of participating in grid-wide stabilizing activities, there is a second phase to this development. While the market at the top level operates in relation to region-wide day-ahead prices and various forecasts, such as market movements and the production from renewables, the behavior of consumers on a local scale can still cause problems.

Part of the work done in relation to EV grid connectivity, included development on the large scale EV simulation discussed in chapter 4. With the EVs alone, running intelligent charging experiments will be possible, but to complete the picture a grid-aware model should be included. Since grid modelling is outside the scope of this project, and has been done extensively by others, it was only natural to try to interface the EV simulation with an existing grid simulation.

Figure 5.7 offers a complete overview of the proposed simulation, including both the real-time market and the external grid simulation. Using DIgSILENT PowerFactory (PF), a model of a subset of the 400V grid on the island of Bornholm was successfully interfaced using OLE for Process Control (OPC).

While not completed, it was envisioned that the output of the grid-simulation be fed back to either the real-time market engine or VPP. Since the EcoGrid EU market is not under the control of the author, nor is the development of market mechanisms within scope, this work would be left to others more qualified. Previously research has been carried out on the use of so-called Locational Marginal Price (LMP), but it has yet to make it into the EcoGrid EU market engine **?**.

For this reason mainly, the complete grid-aware simulation remains future

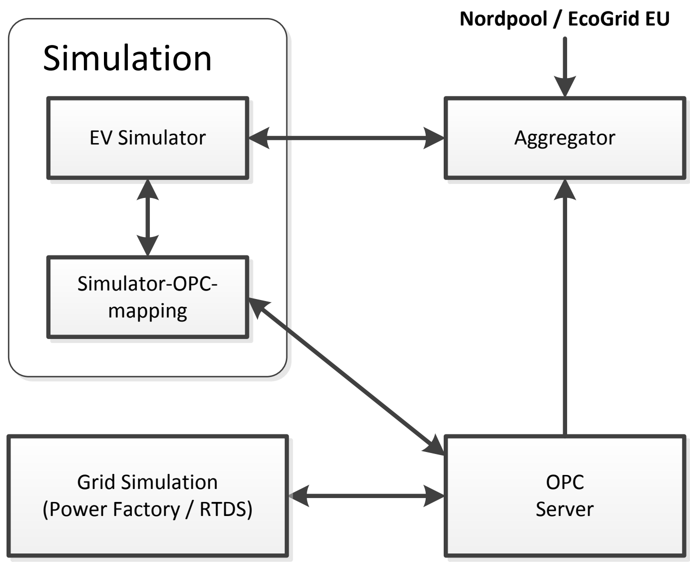

Figure 5.7: Architectural overview of proposed EV simulation

work, but from studies into the connectivity of PF with the developed software, the author found OPC to be well suited for the purpose. The transfer of even individual EV loads proved more than possible, but should it eventually become a bottleneck during large scale testing, the loads are easily bundled on a feeder-to-feeder basis.

5.7 Sub-conclusion

While there are still a few lone fragments out there, the majority of the automotive OEMs appear to have formed groups supporting only a handful of EV connectors. In North America the IEC62196 Type 1 connector remains the most popular, where the major European OEMs are still betting on both Type 1 and Type 2. In Asia, entirely different connectors are being supported, but as a whole, only the European situation presented any real problem. The solution to this came in spring of 2014, when the EU council of ministers officially voted the IEC62196 Type 2 connector as the standard to be used throughout the European union **?**.

Back-feeding capable EVs represent the cutting edge of EV-grid interaction, but has yet to make it into any of the standards. As such, the heavily used IEC61851 standard does not cover the case of back-feeding, and therefore offers no means for controlling it. If back-feed capable EVs become more predominant, the IEC61851 standard would likely have to be extended to address this.

Since the PWM signal, which is a crucial part of the methods described in the proposed patent (A3), only allows control of the upper limit, the EV is essentially allowed to back-feed uncontrollably, which could result in a whole other range of problems.

5.7.1 Future work

A project is currently under way at DTU, to develop an easily installable, universal EV data logger. While the prototypes have shown great potential, a final version has yet to be completed. This data logger has several components in common with the circuitry in A3, and is therefore closely tied to the completion of a fully functioning prototype for EV charging control. The logger is expected complete in the summer of 2014, and the control circuit should follow shortly thereafter.

The EV simulation components described in this chapter, have yet to be combined and tested as a fully working simulation platform (see figure 5.7). During the project, the OPC based grid interaction was successfully tested, but lack of a grid model with accurate feeder locations meant that is was tested against an arbitrary section of the Bornholm grid model.

Chapter 6

ICT infrastructure for EVs

6.1 Introduction

Throughout the project, the author has contributed to the genesis of several EV smart charging- and ancillary service related demonstrations, related primarily to the EDISON project. This work has led to the co-authoring of two book chapters about EVs and the related ICT A1 A5. Besides this, the continued interest in the IEC61850 standard in relation to EVs and smart grid applications, has inspired a couple of master projects supervised by the author, which resulted in the secondary publications B3 and B2.

The work contributing to the EDISON demonstrations, were in large part carried out in relation to WP7. Since the ICT was a precursor to the distributed charging optimization discussed in chapter 7, it also relates to WP6.

6.2 Communication

Previously investigated by the author, several means for communicating between back-end systems and DERs exist **?**. The illustration in figure 6.1 represents some of the more typical used; all with their individual benefits and drawbacks.

The direct internet connection (6.1 top) represents the simplest in terms of infrastructure, in that it utilizes the existing Internet connection found in most private homes today. For the most part, wired connection such as DSL, ADSL and fiber have become quite stable and represents a modest cost; since the bandwidth required for smart grid activities is very modest, the existing connection can be assumed to be sufficient and not factored into the costs. The greatest drawback is establishing the connection, which can be done in either of two ways: the EV connecting to the back-end or the back-end connecting to the EV. Most home Internet solutions come with a router with a preconfigured firewall, which would need to be configured to allow incoming connection, in which case it could render the home network vulnerable. The alternative is to have an open back-end, which poses similar security risks, not to mentioned the need to be able to handle large amounts of incoming connections.

Using a GSM connection (6.1 middle) is often favoured for its ease of installation, since no cables need to be dug down and it works out of the box. For the most part, using the cellular networks works just fine, and with modern networks allows for bandwidths sometimes exceeding that of most private homes. There are, however, like most cellphone users can attest, areas of lesser coverage and in unfortunate situation the connection can be lost altogether. There have been cases where collaborating partners, with charging spots in Copenhagen, have lost connectivity due to the charging spots being too close to a large builder or a tree. Beyond this, the price if often considered a drawback, but it largely depends on the required bandwidth.

Tunneling (6.1 bottom) is in itself not a connection scheme as such, but more a solution to the security issues arising with using a direct connection. By establishing a tunnel to the back-end, the connection from the EV is easier secured. Addressing only the security issues previously mentioned, the required encryption for maintaining a tunnel just adds more loads to the back-end.

6.2.1 Through the cloud

Common for both the EDISON and EcoGrid platforms, not to mention most- if not all others, is the inherent problems that arise when trying to reach the users through the Internet. What is required is a highly scalable solution that does not leave the end user not the back-end vulnerable.

In recent years the potentially powerful concept of cloud computing have invaded everything from social network, online office suites to nearly limitless online file storage. While fuzzy at first, what a cloud essentially is, is a computing cluster or data warehouse somewhere, that is able to scale and service whatever need the customer is willing to pay for. Instead of owning- or renting large servers, like in the past, businesses and even private individuals can now rent potentially unlimited computing power. Not only does the cloud concept solve the scaling issues of having to deal with an EV fleet of varying size depending on plug-ins, but it also solves the problem of security for both back-end and end user.

Shown in figure 6.2, a cloud service can act as a middleman, accepting incoming connection from both parties. Information can then simply be passed through, or the cloud can be utilized to perform other tasks, thereby unloading the back-end system. In **?** the authors demonstrated a IEC61850 mapping (see standard description below), which was able to accept connection from various DERs using different protocols and dynamically map them to a single standard.

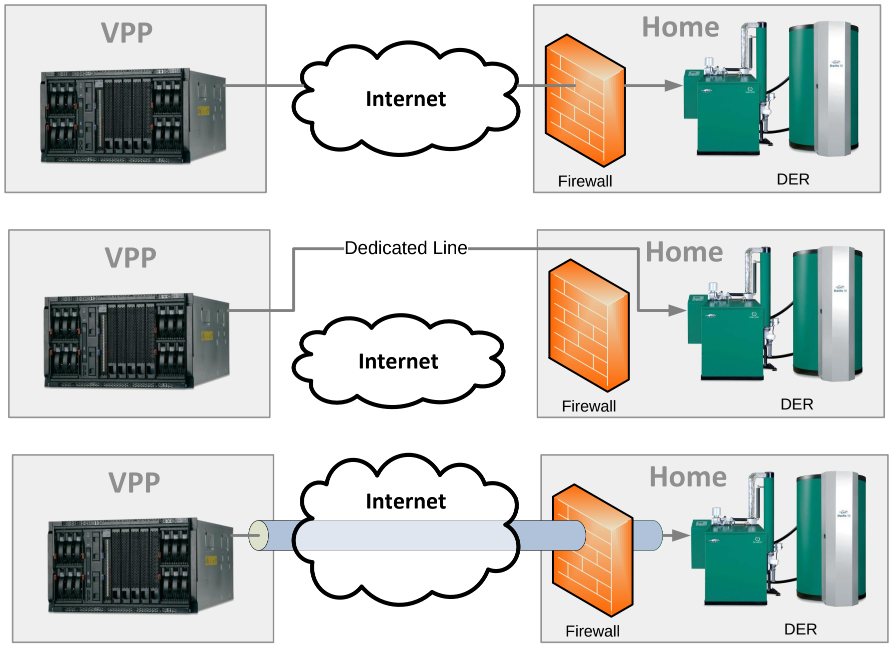

Figure 6.1: Overview of typical communication methods for linking DERs over the Internet (top: direct connection with configured firewall ports, middle: dedicated GSM line, bottom: secure connection through existing tunnel). *Source:* **?**

By further filtering the content, the back-end is then freed substantially from having to adapt and handle the load.

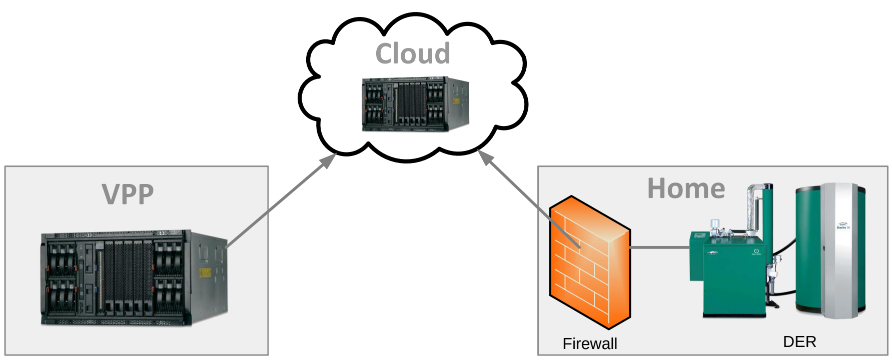

Figure 6.2: Illustration of using cloud services to scale- and relay communication to- and from DERs.

6.3 Standards

As discussed on chapter 4, standardization is important to ensure interoperability. The standards covered there, relating to EV connectivity, is the basis required to ensure safe and compatible charging of any EV at any EVSE. The IEC61681 standard is already in heavy use, ensuring exactly this. From the EVSE to the back-end systems, however, is a different story altogether. No standards have yet been agreed upon, which sadly leaves all existing charging spots under the complete control of the respective owners.

In thought future scenarios, EVs are thought to roam freely between various providers, with the charging controlled either by (likely local) aggregator or as the case of EcoGrid EU - a dynamic price signal. Besides the fact that no current standards for AC charging supports actual communication with the EV, allowing for centralized (intelligent) charging to take place, the service would have to be delivered by the EVSE owner through their, supposedly, proprietary protocols.

The standards discussed below, are among the more popular candidates for back-end to EVSE, or possible even EV, control.

6.3.1 IEC61850

The IEC61850 standard was originally developed for substation automation, but has in recent years grown far beyond its intended domain **?**. Older then the Internet we known today, its original communication mappings were not designed to work over TCP/IP; an addition that was not brought on until the end of the millenium, when Boeing revised the OSI model for Manufacturing Message Specification (MMS) (see description below).

Very popular and consequently widely used within European power systems, the IEC61850 standard was first investigated by the thesis author in 2009 for facilitating the connection of DERs to VPPs over the Internet **?**. Since then, it became the chosen standard in the EDISON project, and later even in EcoGrid EU.

The greatest advantage of IEC61850, which in itself is not a communication- but a modeling standard, is its modular approach. Using a hierarchical structure, consisting of predefined components, most existing components can be described in a logical fashion. On occasion, the hardware being modelled does not have a proper equivalent component defined in the standard, in which case it is simply defined. This was the case during EDISON, when it was decided that IEC61850 lacked the proper components to describe both EV batteries and charger along with the capabilities of the EVSE. Extension to the standard were proposed, which were consequently submitted for consideration by the technical committee responsible B1.

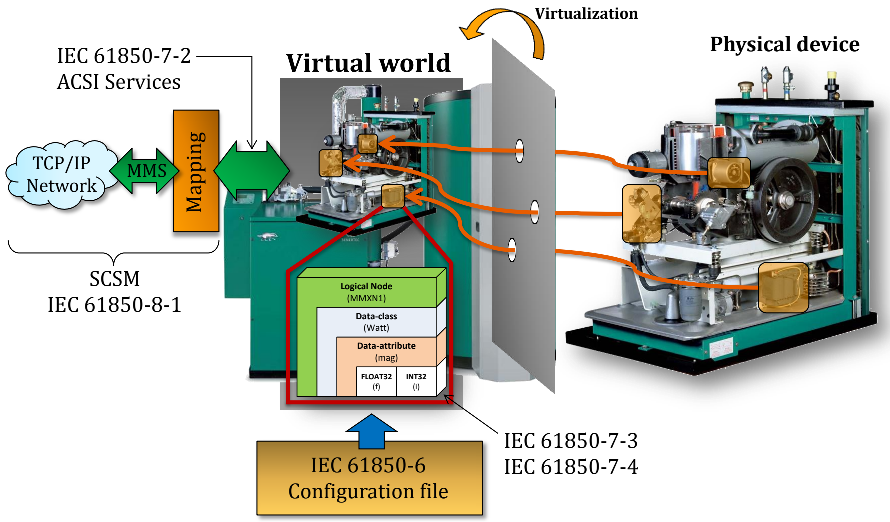

Figure 6.3: IEC61850 overview

The depiction in figure 6.3 gives an overview of IEC61850. Shown in the figure, is the transition from device to model and on the far left the communication mapping. Traditionally IEC61850 have been used with a standard called MMS (designated ISO9506), which to date remains the only fully standardization. Alternative mappings are un the process of being accepted, based among others on OPC and Web Services. In EDISON, the standard was successfully mapped to REpresentational State Transfer (REST) services, a resource oriented architectural style, but in part due to the state of the work, it was never submitted for standardization **?**.

Regardless of the chosen mapping it is, however, advised that it be well suited for Internet based communication. Since neither MMS nor the various web services in themselves offer any security, IEC61850 needs to be used together with other standards that do.

IEC62351

A standard often referenced in relation to IEC61850, is the IEC62351, which deals with the security aspects of IEC61850 **?**. In the domain of smart grids, the communication is generally assumed to happen over a public - and therefore insecure - network, such as the Internet. To ensure safe communication, IEC62351 defines a set of authentication- and encryption technologies such as Transport Layer Security (TLS), but it also defines so-called Role Based Access Control (RBAC) as we know it from e.g. computer file systems. Perhaps the greatest benefit gained from this, is the increase flexibility for accessing information on the device.

In a thought EcoGrid EU scenario, the market mechanism could be allowed write access to the nodes storing the current price-streams, while other less authorized parties would have read-only access to other data. This could be used for anything from retrieving meter readings to simply offering greater transparency to the users/owners of the device.

6.3.2 OCPP

An often references "would be" standard is the proposed Open Charge Point Protocol (OCPP), which is being developed by the Open Charge Alliance **?**. Implemented as a series of Simple Object Access Protocol (SOAP) services, it is a more application specific alternative to IEC61850, which is targeted only at back-end to EVSE communication.

Because it by and large is being developed by members with EV driving-centric interests such as EVSE manufacturers and fleet operators, it does not allow for actual control of the charging process. Most of the services defined relates to user authentication (at the EVSE) and other roaming related financial issues. Since IEC61850, on the other hand, has no support for roaming or any decent mechanism for user-authentication, the author finds no reason that the two standards cannot be use in parallel to achieve the complete objective of roamed- smart charging.

6.4 Direct vs indirect control

The primary focus of this project, has been the move from a centralized control strategy to a decentralized one. This section is meant to provide an overview, over the centralized platform of EDISON and the distributed one of EcoGrid EU. The keen observer will notice that many of the components are represented in both platforms, and that central aggregation is in fact not rules out in a distributed scenario.

6.4.1 The EDISON platform

The envisioned software platform used during the EDISON project, shown in figure 6.4, was centered around an aggregator, referred to as a the EDISON VPP. Acting on external conditions, such as the preset market prices or the need for regulation, this VPP is free to allocate its share of allotted energy among the vehicles in its fleet, while adhering to the various local grid constraints. The obvious benefit of centralized control, is the fact that the aggregator has full control of what each vehicle is doing at any given time, in a tight control-feedback loop. However, th downside to this is the increased communication flow and consequent dependence on the individual EV architecture to the VPP.

Most of the load induces by this individuality can be shifted to the cloud, as described earlier, but the cost of is will not disappear.

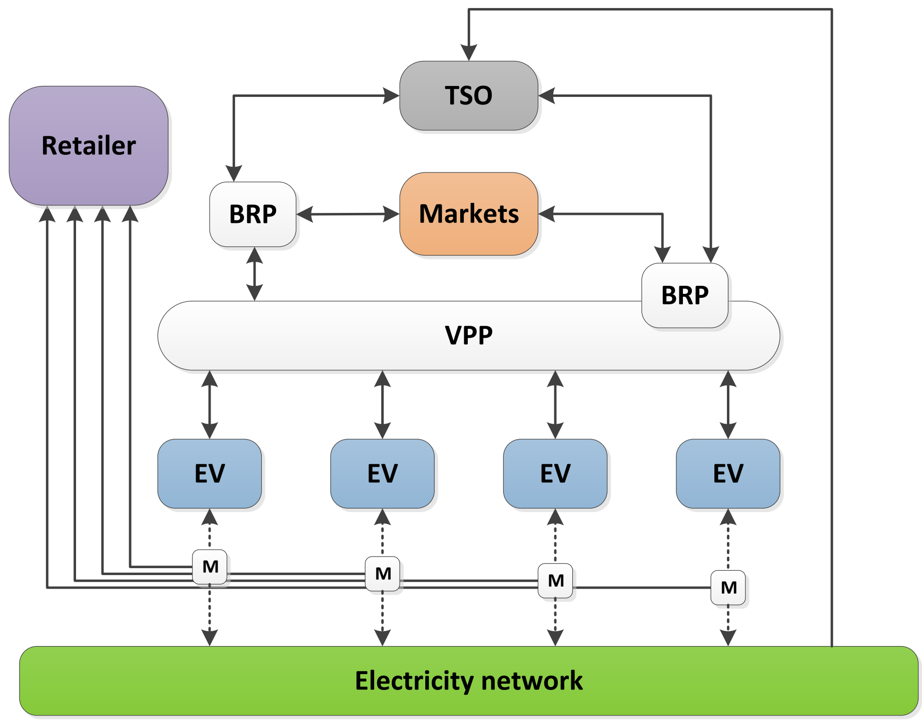

Figure 6.4: Overview of the EDISON architecture

The focus of the authors studies during the EDISON project was on the back-end to EV and EVSE and the control algorithms used. The various other components, such as the technical workings of the metering system and retailer, was not covered, especially since it was not part of the control loop.

6.4.2 The EcoGrid EU platform

The first thing to notice when viewing the EcoGrid EU platform, depicted in figure 6.5, is the unidirectional flow of information. While the centralized platform of the EDISON project had the VPP completely dependent on both the ability to control- and monitor the individual EVs in the fleet, the EcoGrid EU market concept is based on indirect control- and monitoring.

During the initial development phase of EcoGrid, the price distribution was based on a message broker architecture; a solution typically employed in enterprise level software system for providing internal component interconnection through queuing and broadcasting of data. Later, in pursuit of a broader, standardized distribution platform, the IEC61850 standard was chosen to model

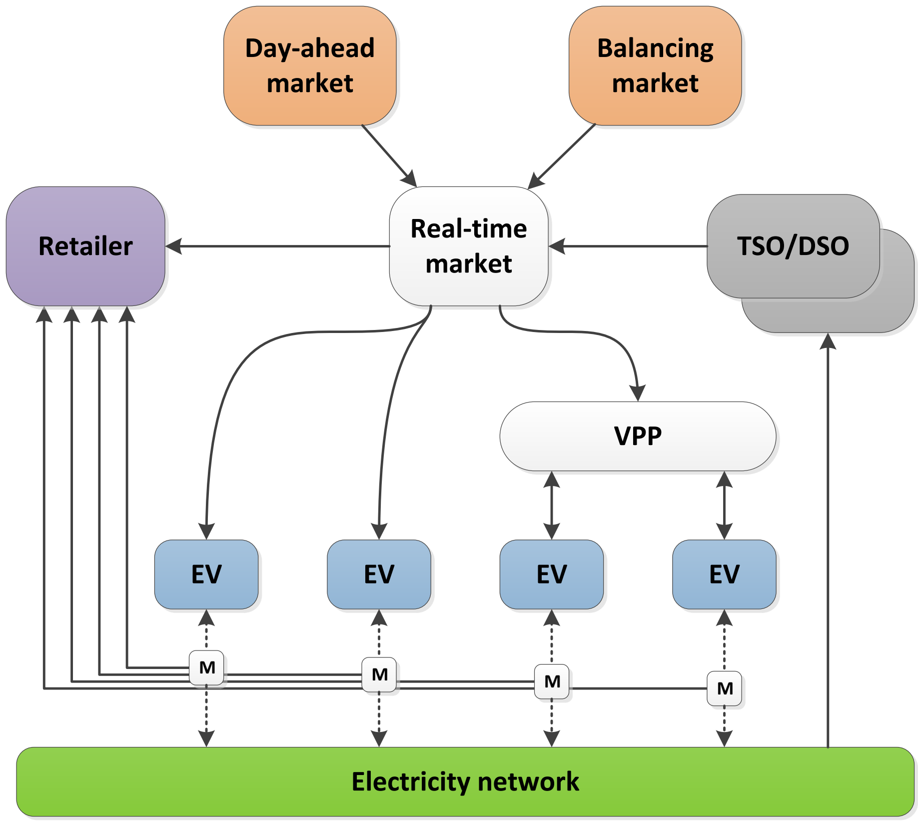

Figure 6.5: Overview of the EcoGrid EU architecture

the price streams. In parallel, the *FlexPower* project had been developing a similar price-stream mapping, though not based on IEC61850, which was given the name *FlexPrice* **?**. Unlike IEC61850, which as previously stated can be secured through the use of IEC62351, the proposed *FlexPrice* model contained no mentioning of any security mechanism.

Show in in figure 6.6 is the proposed IEC61850 mapping developed for EcoGrid EU. As discussed above, the well known IEC61850 standard provides a good base for most power system models, including, in this case, price-streams. For the sake of discussion, there are, however, a few drawbacks that could/should be changed:

- Each price note (*RTMP*) contains a unique identifier for the given price-stream, which can be used by the EV to re-trace any stored historic data. For households this works fine, since they hardly move, but for the case of roaming vehicles, back-end mechanism is required in order for a vehicle

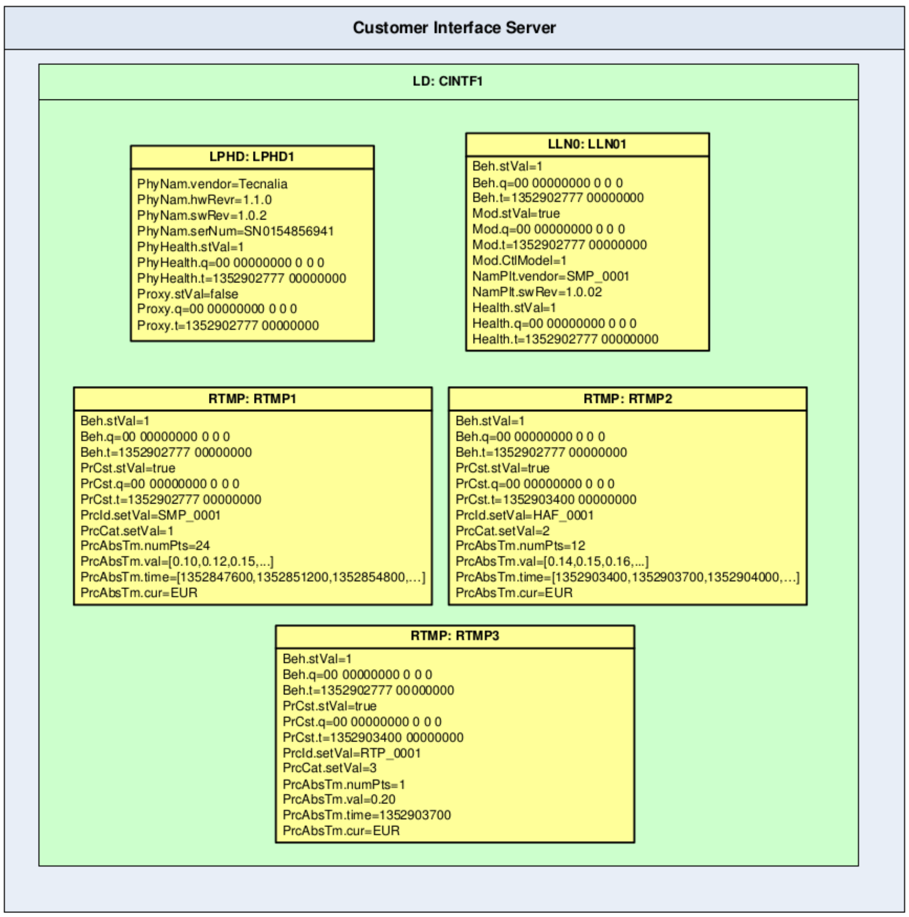

Figure 6.6: EcoGrid EU mapping to IEC61850. *Source: EcoGrid EU D4.2*

to determine the proper price stream for its given location (see chapter 5 regarding wireless communication and the parent described in A3)

- Though not clearly visible in figure 6.6, the mapping for all three price streams are defined as arrays. The need to have a single (read current) real-time price as an array, is unclear to the author. While the slight overhead in data transfer is negligible, the risk of ambiguous data (more than one current price) is avoidable by declaring the Real-Time Price (RTP) as a single element.

6.5 Demonstrations

During the course of EDISON and this project, a number of EV integration demonstrations were developed, largely in collaboration with **?** and **?**. Because the main experimental EV had not been procured at the time of the first demonstration in May of 2011, the primary demonstration platform was a battery table developed by **?**. Equipped with the IEC61850/REST based platform described above, the test was successfully carried out against the EDISON VPP reacting to a recorded regulation signal.

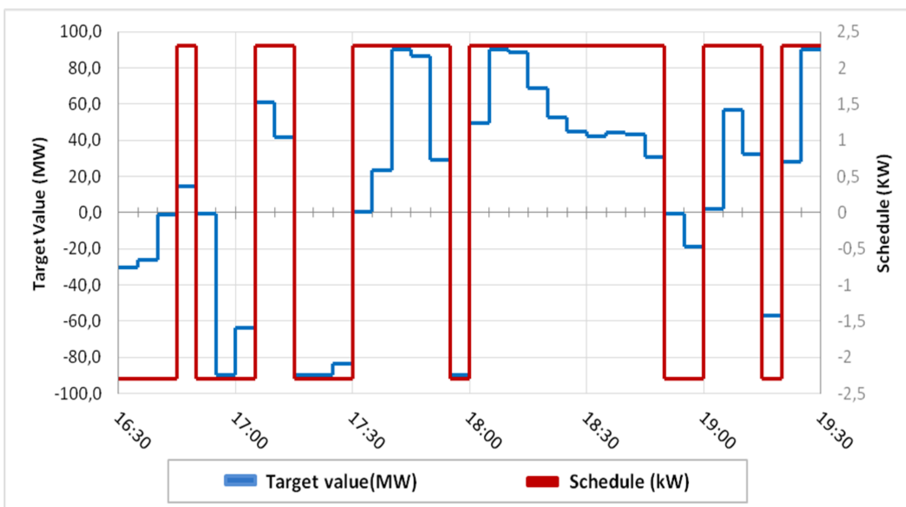

Figure 6.7: Plot of the regulation signal and the resulting (charging) schedule. A6

The plots in figures 6.7 and 6.8 were recorded during this demonstration. Figure 6.7 shows the regulation signal (blue) along with the resulting VPP response. In figure 6.8, the measured power flow from the car (purple) is plotted along side the recorded SOC.

At the time of this test, the EDISON VPP was implemented to simply follow the regulation signal. The result from this is, however, hardly visible in this plot, but with the participation in less symmetric regulation, the SOC will increase- or decrease accordingly. If the vehicles in the fleet are to reach their SOC targets by the end of the plug-in period, any participation in regulating services by the VPP would have to be weighed against the cost of the energy that has to be made up in case of a deficiency. It goes without saying, that the most lucrative scenario, would be one with mainly up regulation, resulting in free or even paid charging.

Continuous monotone regulation is, however, not that likely to occur for extended periods of time.

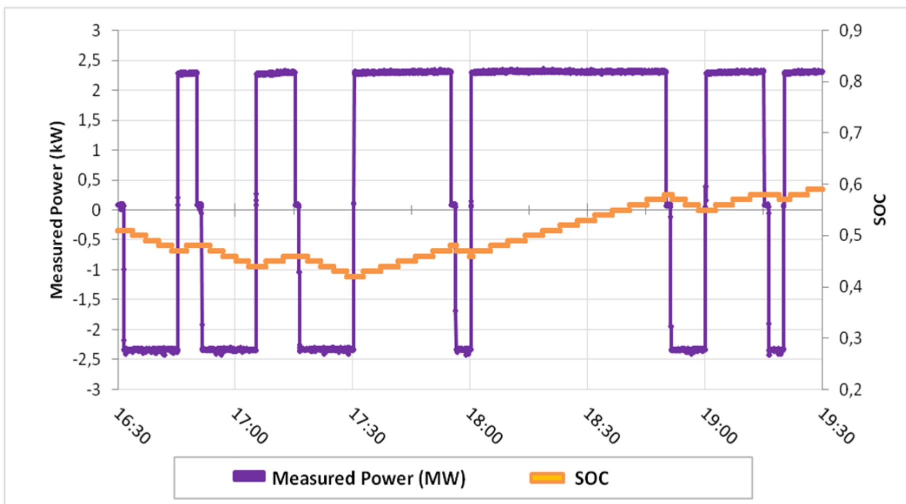

Figure 6.8: Plot showing the charging power and SOC as a result of the schedule depicted in 6.7. A6

Due to technical delays in getting the main DTU test vehicle stable and operational, no real test has been carried out against the actual EcoGrid EU market as of this writing. For a real-world demonstration, the reader is referred to the demonstration section of chapter price signal.

Since it will likely be some time, before a larger fleet of vehicles will become available for distributed charging, the completion of the proposed EV simulation platform remains the best bet for large scale testing. Unless physically distributed, the simulation will, however, not represent a realistic scenario in terms of communication over an open network such as the Internet.

6.6 Sub-conclusion

The IEC61850 standard has been extensively researched and demonstrated to be useful for centralized VPP based control in the EDISON project. It has later been adopted as the chosen medium for price signal distribution by the EcoGrid EU consortium, using a logical node mapping not too different from that of the *FlexPrice* specification, which the author briefly consulted on. Both data specification represent a reasonable- and logical format for price signal transmission but in case of IEC61850 does rely on a multicast capable delivery mechanism such as Generic Substation Event (GSE) over User Datagram Protocol (UDP) to reduce the load, not to mentioned responsibility, on the sender side. The obvious downside to this being the lack of guaranteed delivery, but on the other hand the price-signal control scheme does not guarantee any action on behalf of the consumers to begin with.

While cloud based IEC61850 based solutions have successfully been demonstrated in **?** and **?**, no large scale tests where carried out. To further the research into cloud-based smart-grid applications, extensive testing would be required.

Based on present day solutions developed- and used by most of the biggest players in the world of Information Technology (IT), from e-commerce to data-warehousing, there should be little doubt that the use of cloud computing for EV communication, could scale to handle any EV imposed load. When the security, which is one of the largest pitfalls when dealing with Internet based communication, has been verified, one of the greatest advantages is the scalability, which in the case of EVs works out conveniently with the constant load variations from cars plugging in- and out.

Chapter 7

Distributed charging

7.1 Introduction

This chapter comprises the work done in relation to WPs 6 and 7, with the partial exception that some of the tests were run against historic data. This was done primarily to speed up execution of the experiment, but also to facilitate faster and easier debugging of the code.

The final demonstration with the eBox at DTU was carried out against both historic- and the real price-feeds. It should, however, be noticed that because the IEC 61850 implementation for the EcoGrid EU market had not been completed at the time, the prices were delivered using the previously mentioned message broker(s) (see chapter 6).

The original smart charging demonstrations during the EDISON project were entirely focused on the Nord Pool Spot Elspot market, and its day-ahead hourly prices. Only towards the end of the project, was the notion of grid congestion and participation in regulating services investigated. The EcoGrid EU real-time market is, as previously described, a merger between the day-ahead- and the regulating markets.

As of the writing of this thesis, the author had not published any work directly relating to charging optimization. However, some of of the assumptions and discussions herein, does relate to the secondary publications B4 and B5

7.2 Missing the bigger picture - distributed vs centralized aggregation

The overall difference with the proposed real-time market control of DERs, especially for electric vehicles, is that the vehicles are less aware of their surroundings than a centralized aggregator presumably is. For this reason, the basic scenario for optimized EV charging becomes a bit simpler - at least from the perspective of the vehicle itself. Table 7.1 below briefly illustrates the major differences.

Centralized	**Distributed**
Direct control over every connected EV	Indirect control through price signal
Fleet level charging	Single EV optimization
Knowledge about others vehicles in the fleet (not necessarily nearby)	Independent (fleet agnostic)

Table 7.1: Table listing some of the major differences/advantages to both centralized- and distributed control

Other systems have been investigated that can best be described as hybrid solutions, where the actual strategy is devised by the EVs, only to be sent back for verification by a central entity **? ?**.

7.3 Model for distributed EV charging

The following is a basic example of optimization for a real-time market connected EV. The implementation deals solely with the price signal and the overshadowing objectives: to reach the required SOC before the predicted/announced plug-out time, while minimizing the overall cost.

The implementation was done in *Python*, using a generalizing linear-programming modeler called PuLP **? ?**. The benefit of PuLP is that the problems are expressed directly in *Python*, instead of a solver specific modelling language. Because of this, PuLP allows for dynamic switching between several popular solvers. For the listed experiments below, the GNU Linear Programming Kit (GLPK) was used (see discussion on performance in conclusion) **?**.

7.3.1 Preparing the price streams

In order to simplify the implementation, the three standard price streams (*real-time*, *hour-ahead* and *day-ahead*), which were introduced in chapter 3, have been combined into a single stream. The illustration in figure 7.1 illustrates the three streams, along with the resulting merger. As new prices updates arrive, the stream is continuously advanced accordingly.

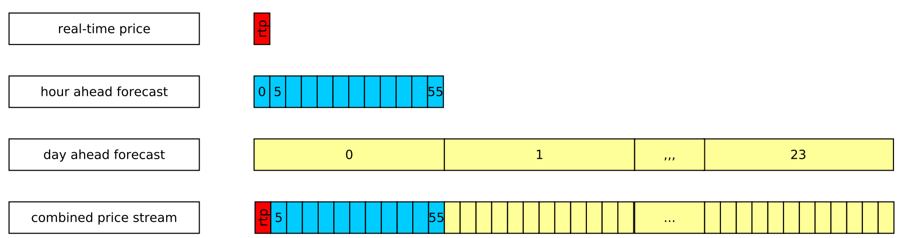

Figure 7.1: Illustration of combining the real-time, hour-ahead and day-ahead price streams.

If historic data has been collected, an estimated could be derived regarding the expected accuracy. This could be attached to the individual timeslots in the merged stream, as an indication of trust. This has not been implemented at this stage, but is discussed further in the conclusion.

7.3.2 Optimizing the charging

Centralized charging algorithms developed during the EDISON project, utilized the Nord Pool Spot Elspot day-ahead prices, which, once settled, are fixed through the charging period. Disregarding later work with ancillary services related to the regulating markets, the procedure was to generate an optimized charging schedule upon plug-in, which was then executed until plug-out.

In a real-time market scenario, any given optimization will essentially be invalid 5 minutes after it was created. Looking at the price streams above, it should furthermore be evident that like the centralized scenario, the time horizon it constantly shrinking.

For every update of the real-time price, the charging window shrinks by five minutes and the schedule is re-calculated (read optimized) based on the new prices and the latest changes to the battery.

The table in figure 7.2 shows the variables used for the optimization that generate the charging schedules. Please note that for a “regular” non-V2G EV, $p_t^{min} \geq 0$ for all t.

It should also be noted, that the use of p_t for the charging power during timeslot t is an assumption, and that a real-world vehicle can (and possibly does) change charge power in the middle of a timeslot. Furthermore, because of the way the optimization works, instead of charging fully and stopping, potentially in the middle of a timeslot, the resulting charging schedule will always use the whole timeslot, but instead charge at a lower rate to fulfill the goal.

Symbol	Unit	Description
T	$T \in \mathbb{N}_0$	Number of remaining timeslots in plug-in period
c_t	DKK/kWh	Energy price for the timeslot t
p_t	kW	Charging power for the timeslot t
d_t	hours	Duration of timeslot t
p_t^{min}	kW	Minimum charging power for timeslot t
p_t^{max}	kW	Maximum charging power for timeslot t
$e_{plug-in}$	kWh	Energy in the battery as plug-in
e_{now}	kWh	Energy currently in the battery
e_{target}	kWh	Energy required by plug-out
$e_{capacity}$	kWh	Energy capacity of the battery

Table 7.2: Descriptions of symbols used in the charging optimization

At the heart of the optimization, is the costs function, which is what all EV charging aims to minimize. It consists of the sum of all charging costs incurred in the timeslots from *plug-in* to *plug-out*. The charging costs are calculated as the product of the charging power (p_t), the energy price for that timeslot (c_t) and the length/duration of the timeslot (d_t). Earlier experiments dealt with varying duration for timeslots, primarily to accommodate the current- and hourly forecasted price in relation to the day-ahead forecast, which is in hours. As indicated, the implementation was simplified to operate on only 5 minute intervals, but for the sake of generality, the duration has been left as d_t.

$$min \sum_{t=0}^{T} p_t c_t d_t \tag{7.1}$$

For every timeslot there are a couple of natural constraints, limiting the charging performance of the vehicle. The maximum charging rate of the vehicle (p_t^{max}) is common for all vehicle, and determined the chargers capability at time t. The minimum charge rate (p_t^{min}) assumed 0 for all regular (read non back-feed capable) vehicles. For easy of implementation, and to reflect hopes for present and future EV hardware, it is assumed that p_t can take any value in the range $p_t^{min} \geq p_t \geq p_t^{max}$.

For back feeding (ie. $p_t^{min} < 0$) see conclusion below.

$$p_t \geq p_t^{min} \tag{7.2}$$

$$p_t \leq p_t^{max} \tag{7.3}$$

For a back-feed capable vehicle, the value of p_t^{min} would be set negative, to indicate “negative charging”. In the naive implementation, as is the case, the scenario that will unfold is that the vehicle will essentially start trading energy.

What this means, is that if a low price is observed for a large portion of the plug-in period, and the vehicle can easily charge to completion before plug-out, it will charge cheap, only to discharge at a higher price. Eventually, as the plug-out time draws near, it will primarily charge, in order to meat the energy requirements.

This behaviour is not necessarily undesirable, but since it comes at a cost, mainly due to wear on the battery from the increased number of cycles, it will have to be factored into the costs function (B4).

There are two primary constraints present in any EV charging scenario, namely that the battery has to be charged to a certain minimum to accommodate the energy requirements for the next trip and that the battery cannot be charged beyond its maximum capacity.

$$e_{now} + \sum_{t=0}^{T} p_t d_t \geq e_{target} \tag{7.4}$$

As previously touched upon, the SOC determination of a battery is not straight forward, and it is actually possible to “overcharge”. Since this increases wear on the battery, it should not be done too often and if a cost for overcharging could be derived, it could very well be added to the constraints B4.

$$e_{now} + \sum_{t=0}^{T} p_t d_t \leq e_{capacity} \tag{7.5}$$

Looking at the plot in figure 7.2, it can be hard to convince one self that the EV is actually following the real-time price signal. Sure it seems to be predominantly charging at times where the price is lowest, but it is difficult to tell if this trend matches the price. When analysing the result of the charging, it is again important to remember that the actual (read final) price is only known at the exact time of execution, and that the failure to generate the perfect schedule is often due to the hour- and day-ahead forecasts. If the forecasts “promises” a lower price later, which never happens, the optimization will tend to schedule for later charging, for which it will be “punished” when the price turns out higher than expected.

This can partially be remedied by optimization in relation to a stochastic weighting of the precision of the forecasts. This can be achieved by looking at historic data for the price streams, collected by the vehicle. The following optimization uses no historic data or stochastic assumption towards the forecasts, so it can be seen as the base case. In case of EV roaming in relation to nodal pricing, this would be the case every time a vehicle arrived at a new location.

7.4 Case studies

Testing the optimization was initially done on a rudimentary EV simulation, in order to control it and be able to speed it up. For the given window of price streams (recorded from the EcoGrid EU market), the vehicles are programmed to plug in at a random time between 16 and 18, with a randomized SOC of anywhere between 25 and 75%. To properly simulate a typicaly overnight stay, and to make sure ample time for charging was available, the determined plug-out time was fixed to 12 hours after plug-in.

7.4.1 Simulated

Because of the nature of linear optimization, the resulting solution (i.e charging schedule) will have the EV charge at full power for a given timeslot, or not at all. The exception is the most expensive timeslot in the schedule, where the charging is reduced to fulfil the SOC requirements. Because the vehicles will either charge full or not at all, it was an intuitive concern that the resulting load on the grid would be too binary, which was one of the reasons behind the tests. With a single ev, illustrated in figure 7.2, the binary effect is clearly evident. The vehicle managed to charge to completion, with the majority of charging in the cheapest times of the plug-in period. The observed charging before the price drop, is a result of the inaccuracy of the forecasted price stream, which is discussed later.

Since various tests have continuously been carried out on the EcoGrid EU market signal, the author chose a stable section, with no human-induced extremes. In this particular case starting Jan 1st 2014, going forward approximately 48 hours.

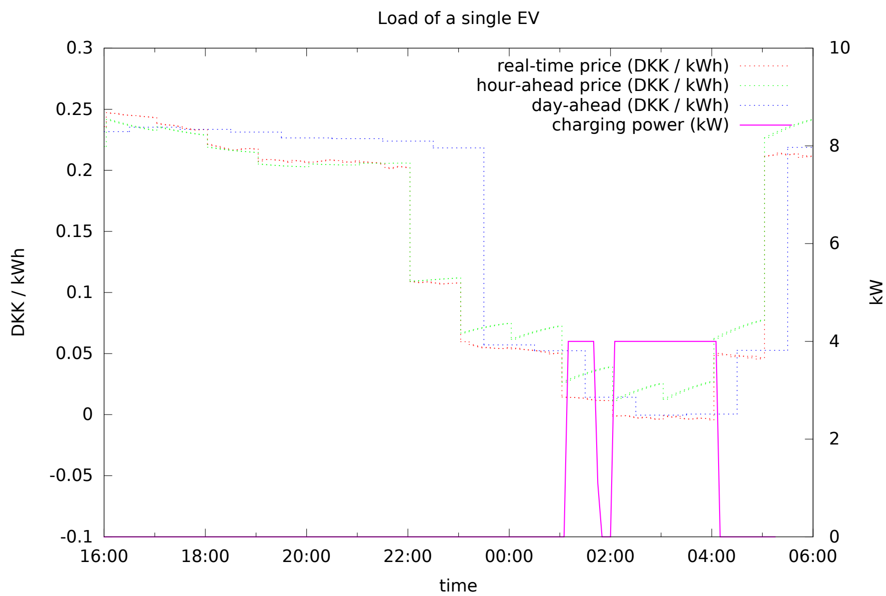

Figure 7.2: Plot showing the load of a single charging EV in relation to the real-time price.

In figure 7.3 the trial has been increased to include 100 EVs and the trend is suddenly much more clear. While is was harder to relate the load of a single vehicle to the rise and fall of the real-time price, the combined load of all the EVs can clearly be seen to follow the price-signal. Because of the stochastic nature of the vehicles, both in terms of plug-in time and initial SOC, the resulting variations in their individual requirements results in a load that more smoothly follow the price stream.

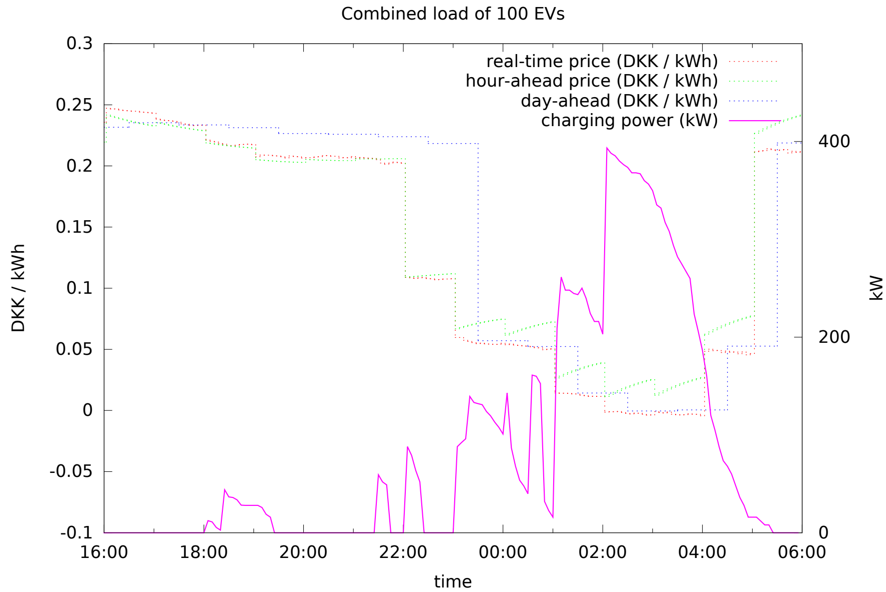

Figure 7.3: Plot showing the combined load of 100 charging EVs in relation to the real-time price.

7.4.2 Real-wold demonstration

To properly conclude the case studies in charging optimization, the same algorithm was implemented in an actual EV, namely the AC Propulsion eBox. Unlike the simulation, which had most parameters set stochastically, the parameters of this test was naturally subject to whatever state the vehicle was in. The plug-in time, which was around 17 was quasi-randomly chosen, was then projected to the same period used for the simulation.

Show in figure 7.4 is a plot of the experiment, where the vehicle had a starting SOC of approximately 55%. In order to spare the hardware, the target SOC was reduced to 85%. While not completely evident from the plot, the resulting SOC from running the test was 84%, which is a neglegable deviation likely cause by the vehicles internal conditions.

In order to properly predict the behavior of the battery for the upcoming 5-minute interval, the battery model plays a crucial role. In the described method, the model used is linear through the whole SOC range. For the AC Propulsion eBox used in this test, the SOC has proven to be fairly linear through most of the mid range (typically 20-80%), but it does level out in the low- and high end of the range, which is typical for most lithium-ion batteries.

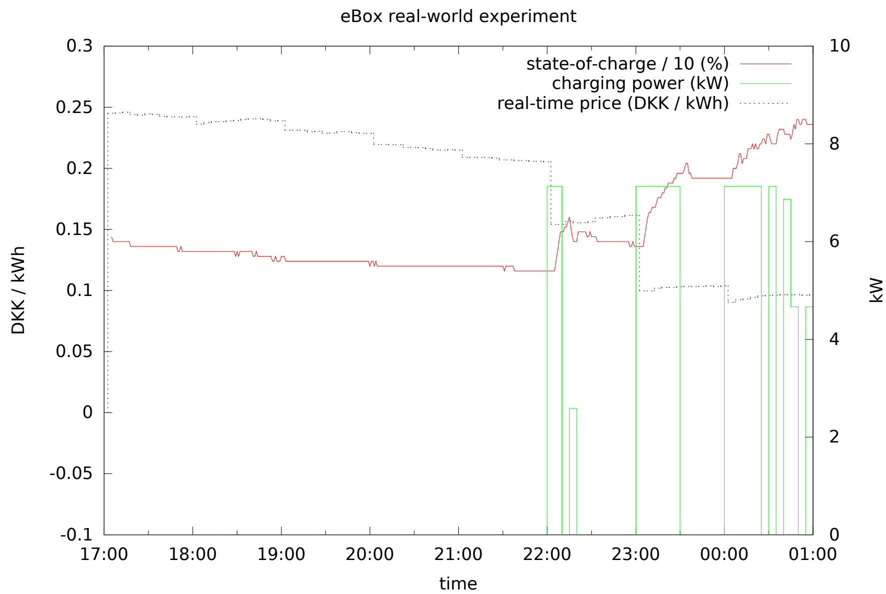

Figure 7.4: Plot of optimization running again real-world EV

To increase the accuracy of the optimization, the previously described model was tweaked with the charging efficiency of this particular EV, which is roughly 90%. Since the costs of charging is a result of the electricity going into the charger and not the battery, the efficiency only affect the SOC conditions, which become:

$$e_{now} + \sum_{t=0}^{T} p_{efficiency} p_t d_t \geq e_{target} \tag{7.6}$$

$$e_{now} + \sum_{t=0}^{T} p_{efficiency} p_t d_t \leq e_{capacity} \tag{7.7}$$

To further increase the precision of the optmization, the model could very well be replaced with a more accurate representation, such as the one described in **?**, which was modelled on the same vehicle but not converted for use in Python.

7.4.3 Performance

Unlike the centralized- or hybrid-distributed charging scenarios discussed in earlier scenarios, where the fleet operator, or aggregator, handles all the optimization, for truly distributed EV charging the vehicle itself needs to run the optimization. Not only that, but it has to re-run upwards of every five minutes and ideally finish before the next price arrives; ideally, because it can stand to miss the occasional time constraint, but it should be handles in order to ensure the cheapest possible charging.

The simulated tests were carried out on an ordinary laptop, achieving a loop time of 3.5-3.7 seconds for the 100 EV test. Using a little simple arithmetic, that corresponds to more than 7500 charging optimizations in any given 5 minute interval. Put in another way, the laptop is able to do the basic optimization for all EVs in Denmark nearly $3\frac{1}{2}$ times over.

It should therefore stand to reason, that the hardware requirements for an EV to adequately handle its own charging optimization, are negligible at best.

7.5 Sub-conclusion

The keen observer will notice that the optimization is a somewhat naively implemented in terms of the charging constraints. Here the EV is free to charge at any rate (p) at any given time (t), which is hardly realistic. The battery is, in other words, modelled to have a completely linear charge curve, which has previously been suggested to be sufficiently accurate **?**. The author does, however, feel, that to facilitate a truly realistic scenario, the use of a proper battery model should be investigated, which deals with the typical real-world constraints such as temperature and cell voltage. The potential for cell imbalance could even be included, to complete the picture, but that would likely require an entire Battery Management System (BMS) model to be implemented.

Lastly, the assumption is made that the *plug-out* time is fixed. This is of course never really the case, as the vehicle owner could decide to drive off at any given time. The perils of this scenario were discussed in chapter 4, and will therefore not be repeated. Solution using temporal- and energy buffers to account for errors in plug-out and SOC have been suggested by others, but a more flexible solution would be to represent both as stochastic variables **?**. Based on historic data collected in the vehicle, the precision of this *plug-out* prediction could be refined. In the worst case, the vehicle would have to start charging immediately, regardless of the price, in order to be sure the end requirement is met. It should go without saying, that this is hardly the ideal.

As of this writing, no publications have yet to be submitted on this subject but a conference paper is planned, which encompasses the completion and testing of the simulation framework discussed in chapter 4, allowing for large-scale grid-centric EV simulation with optimized charging. This work is expected submitted ultimo summer 2014.

Chapter 8

Conclusion and future work

This report covers the work done in relation to the PhD project *Electric vehicle integration in a real-time market*. Following the WPs defined by the project, which are listed in chapter 1, this report has attempted to cover, among others, the state of the art within EV integration, the current- and future market situation followed by challenges- and demonstrated solutions to both EV integration and related ICT systems in general. Finally a basic charging optimization for use in a real-time market scenario has been demonstrated, using both simulation and an actual EV.

What follows is a conclusion on the project along with recommendations for future work, derived from the outcome of WP8.

8.1 Conclusion

While no real work was carried out using the hybrid-distributed scenario (see EcoGrid EU description in chapter 6), controlling an EV fleet using a price-signal induced VPP, the author finds no reason why this would not work. Since centralized charging was demonstrated to work in EDISON, using a VPP that was operating based largely on the day-ahead markets, the use of price-signals merely represent a different input. Because the truly decentralized scenario is more difficult, since less information is available in the individual vehicles, the hybrid solution should have even more change of succeeding.

Naturally, since this essentially means centralizing the control of the EVs, the ICT requirements from VPP to EV remains the same as for the EDISON.

8.1.1 Contributions

During the course of this project, the author has made a series of contributions to the field of EV integration, mainly through the continued research- and developments of technologies and methods within the domain. The most essential findings, demonstrations and publications are summed up below.

Market research Through the participation in EDISON and the EcoGrid EU project, the author has researched- and familiarized himself with both the existing market mechanisms and the concept of price-control.

EV simulation Light analysis of real-world data ("Test en elbil") was carried out, in preparation for furthering an earlier developed EV simulation platform. The analysis, which also verified previously ICE-based assumptions about EV availability, resulted in a clustering methods for classifying EV charging location, which was used to developed a stochastic model for EV simulation. As a result, an EV simulation framework has been proposed, for performing large scale EV integration studies. Most components have been developed, but as of yet, no complete platform exist.

Connectivity In the work with the DTU EV fleet, the continued procurement of EV infrastructure and EVSE development and interoperability, the author has become intimately familiar with the core aspects of EV connectivity. Through research and the various supervisory roles on EVs and EVSEs alike, the work has culminated in the development of the propsed patent for IEC61851 based remote control of EV charging.

Communication Through the work with the EDISON demonstrations, the IEC61850 standard has been extensively studied and demonstrated to work well for centralized control of EV charging. The demonstrations have been run both against the hourly day-ahead spot market (Elspot) and against a danish regulation signal, demonstrating the fast responsiveness of the solution.

Via a consulting role on the development of the FlexPrice format, and consequently the IEC61850 price mapping of EcoGrid EU, the author has further investigated the requirements for price-signal distribution.

Charging optimization Lastly, the author developed and demonstrated the workings of a basic model for optimized EV charging based on the EcoGrid EU price-signal. The demonstration was carried out on both a simple simulation as well as the AC Propulsion eBox **?**.

8.2 Future work

Because the project has been run as a research- and strictly "proof-of-concept" exercise, some components developed along the way were rendered incomplete. The following recommendations serve as a guide both for furthering this study but also for completion of the various components.

The analysis work related to the "Test en elbil" data, resulting in the method for classifying charging locations used for stochastic EV modelling, remains to be merged with the suggested routing mechanism for deriving a better consumption model. In the past, during EDISON, the consumption used in earlier version of the simulation, was based on an average of the real-world vehicles at DTU. To further refine this, the simulation could very well be combined with a more sophisticated model of an EV battery along with a drive-train model that includes friction losses. Using route-mapping with variable speeds, an aerodynamic model of could be used to further refine the consumption, to the point where it accurately reflects that of a real EV driving the same route.

Chapter 7 describes a basic optimization model for charging an EV according to a real-time price signal. As discussed in the chapter, the model needs some refinement, relating to the uncertainties associated with the price-forecast streams. By using stochastic programming, likely based on the historic price-stream data recorded by the vehicle, the accuracies of the forecasts could be derived. At present, without this consideration, the optimization methods best reflects the scenario of a roaming EV arriving in a new location. In much the same respect, the uncertainty of the projected plug-out time, could be refined by combining it with the knowledge of the type of current charge, based on the clustering classification described in 4 and A2. Lastly, since most EV batteries follow a near linear curve through a large part of the SOC range, the existing model is mostly accurate. However, to make it accurate through the whole SOC range, a better battery model should be employed. Ideally the same as previously mentioned for the simulated consumption, could be used.

The use of cloud-computing is a truly interesting topic, that warrants further investigation. Even though the concept was tested in project relating to this PhD, it was never carried out using price-signal control. A combined real-time market implemented with the proposed communication mapping and price-signal broadcasting is something that should be further investigated- and demonstrated.

Whether or not the proposed IEC61850 mapping of the EcoGrid EU price signal will work with e.g. GSM based distribution remains to be seen, but regardless, the author would still like to pursue a more "web centric" approach such as the REST services proposed in B1. Not only should this be guaranteed to work, given the already extensive usage for various other Internet based services, but the development of clients to access these are far easier since the support for HyperText Transport Protocol (HTTP) is nearly universally supported.

Finally, the prototype for the proposed circuit board, used for EV control via IEC61851 (see patent application), needs to be completed and eventually hopefully integrated into the DTU fleet. This is, however, expected to happen during the summer of 2014.

8.2.1 Final remarks

The combined work of this PhD project is meant to encompass all necessary components for allowing price-signal controlled charging of EVs, from the research of existing- and the proposed real-time market, to the grid-interconnection of EVs and the necessary ICT needed to connect the two.

Through its contributions, both in terms of publications-, presentations and demonstrated solutions, it is the hope that this work will in some way have contributed to moving the integration of EVs foreword and thereby helped pave way for the realisation of a more stable electricity grid of tomorrow as well as more EVs on the roads.

Anders Bro Pedersen
May 2014

Appendices A

Publications

A.1 ICT Solutions To Support EV Deployment

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Abstract	Numerous studies and projects have proven that the electric vehicle can offer value and services that go beyond its function as a means of transportation. The value and services can, for instance, be the reduction of charging costs, adherence to grid constraints, or adjustment of charging behavior to renewable energy production. If these possibilities are considered and supported by information and communication technologies (ICT) in due time, a large potential can be exploited. Specifically, the protocols and technologies spanning the open system interconnection stack need to support the various utilization concepts for EVs and be harmonized to obtain interoperability among numerous electric vehicle (EV) and electric vehicle supply equipment from original equipment manufacturers. This chapter describes contemporary Smart Grid communication methods in terms of requirements and specific solutions and relates them to relevant standardization work and projects within the area.

Chapter 5
ICT Solutions to Support EV Deployment

Anders Bro Pedersen, Bach Andersen, Joachim Skov Johansen, David Rua, José Ruela, and João A. Peças Lopes AU1

Abbreviations

ACSI	Abstract communication service interface
AMI	Advanced metering infrastructure
AMM	Automated meter management
AMR	Automatic meter reading
AP	Access point
BPSK	Binary phase shift keying
CA	Certificate authentication
CAMC	Central autonomous management controller
CP	Control pilot
CSMA/CA	Carrier sense multiple access/collision avoidance
DER	Distributed energy resource
DMS	Distribution management system
DR	Demand response
DSO	Distribution system operator
DSSS	Direct sequence spread spectrum
EAN	Extended area network
EB	Energy box

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R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
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EMS	Energy management system
EPRI	Electric Power Research Institute
ES	Electric storage
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
FAN	Field area network
FC	Functional constraint
FDD	Frequency division duplex
FEC	Forward error correction
Gbps	Gigabit per second
GW	Gateway
HAN	Home area network
IAP	Interoperability architectural perspective
IP	Internet protocol
IT	Information technology
kbps	Kilobit per second
LW	Low voltage
MAC	Media access control
MAP	Mesh access point
Mbps	Megabits per second
MG	Microgrid
MGAU	Microgrid aggregator unit
MGCC	Microgrid central controller
MMG	Multi-microgrid
MMS	Manufacturing message specification
MV	Medium voltage
NAN	Neighborhood area network
NB-PLC	Narrowband power line communication
ND	Neighbor discovery
NIST	National Institute for Standards and Technology
OEM	Original equipment manufacturer
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiplexing access
OSI	Open systems interconnection
PAM	Pulse amplitude modulation
PKI	Public key infrastructure
PLC	Power line communication
PWM	Pulse width modulation
QAM	Quadrature amplitude modulation
QoS	Quality of service
RAU	Regional aggregation unit
RBAC	Role based access control
REST	Representational state transfer
SCL	Structured configuration language

SCSM	Specific communication service mapping
SDO	Standard development organization
SDP	Standard development organization
SG	Smart grid
SGIRM	Smart grid interoperability reference model
SM	Smart meter
SOC	State-of-charge
TCP	Transmission control protocol
TDD	Time division duplex
TLS	Transport layer security
ToW	Time-on-wire
UAN	Utility access network
UDP	User datagram protocol
V2G	Vehicle-to-grid
WAN	Wide area network
WMN	Wireless mesh network
XML	Extensible markup language

5.1 Introduction: Context and Scope

Numerous studies and projects have proven that the electric vehicle can offer value and services that go beyond its function as a means of transportation. The value and services can, for instance, be the reduction of charging costs, adherence to grid constraints, or adjustment of charging behavior to renewable energy production. If these possibilities are considered and supported by the ICT in due time, a large potential can be exploited.

Specifically, the protocols and technologies spanning the open system interconnection (OSI) stack need to support the various utilization concepts for EVs and be harmonized to obtain interoperability among numerous Electric Vehicle (EV) and electric vehicle supply equipment (EVSE) from original equipment manufacturers (OEMs).

This chapter describes contemporary EV communication methods in terms of requirements and specific solutions and relates them to relevant standardization work and projects within the area.

5.1.1 Relevant Projects and Studies

A considerable number of EV projects have been carried out throughout the world. These include the Berlin eMobility project [1], the Danish EDISON project [2], and the American V2G research program [3], just to name a few.

The experience from such projects is that the EV, as a resource, can be used for many different purposes such as smart charging, ancillary services and energy backup, as long as the communication software and hardware are made to support these.

Recognized Standard Development Organizations (SDO), such as IEEE and NIST, have made several contributions to Smart grid communication in general; much of this work is also applicable to EVs, being of particular relevance to the IEEE 2030 “Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System.”

IEC, ISO, and SAE are driving the standardization process for DER and EV communication and the appropriate protocols are either refinements and/or extensions of existing standards or entirely new candidates (IEC 61850 and ISO/IEC 15118).

Additionally, both IEC [4] and NIST [5] have produced reference guidelines on how to implement security in smart grids, also relevant for EV integration.

The chapter starts by reviewing ICT architectures, models, and requirements in Sect. 5.2. Hereafter the focus will be on the specific protocols and technologies that can meet the communication requirements as well as relevant reference models and new emerging ICT solutions, which are discussed in Sect. 5.3. Finally, in Sect. 5.4, a few practical examples of EV communication implementations, as a set of use cases, will be described.

5.2 Architectures and Models for Smart Grids and EV

The continuous cost decrease of renewable technologies along with the increase in installed capacity has contributed to a more clean and cheap electricity use. It is expected that this will allow Electric Vehicle (EV) penetration to become economically viable. The increase in the number of entities/devices interacting with the electric grid, in particular EVs, will have a significant impact on the amount and type of exchanged information (for metering, monitoring, and control) placing new challenging requirements. Novel ICT architectures will be required to support the new generation of the electricity grid, the Smart Grid (SG).

The introduction of SG concepts has brought with it the redefinition of existing players in the electric industry along with the introduction of new ones. These players have created the need for new models and architectures, along with the definition of roles and domains of action. They are intended to interact among themselves in order to improve the overall electric grid operation.

This section will introduce an SG vision of the ICT players, having in mind the definitions and models developed by the National Institute for Standards and Technology (NIST), which were devised to facilitate the integration of EV, namely in distribution grids of electricity, considering technical, market, and customer perspectives.

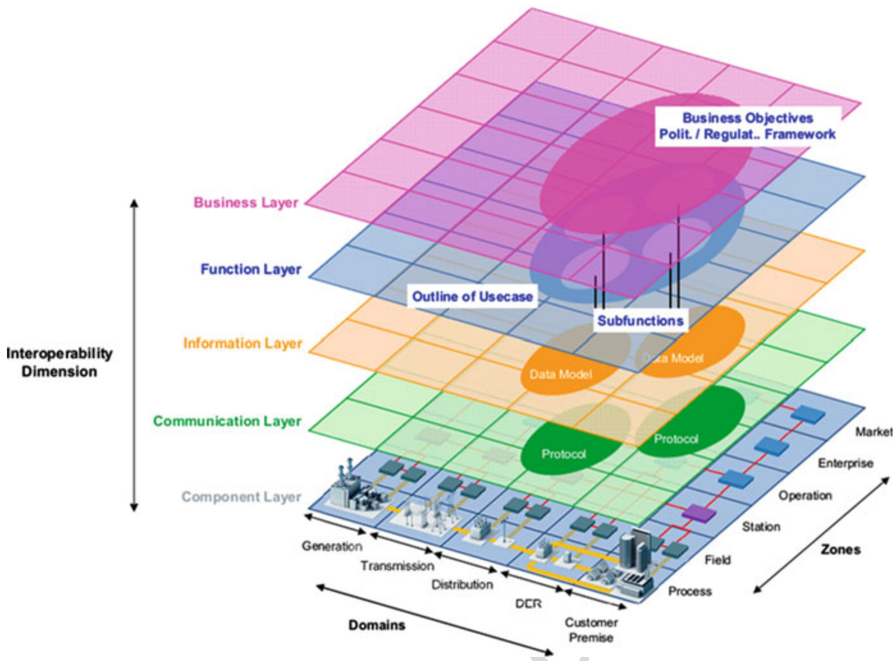

Fig. 5.1 CEN/CENELEC smart grid reference architecture (M/490 Reference Architecture WG—Framework for Smart Grid Architecture Models—2011)

5.2.1 Smart Grids: Introduction and Context

One of the base concepts used when referring to modern power systems is precisely the Smart Grid. The definition of SG can vary but at a baseline it consists of an electricity network which incorporates advanced sensing and automation mechanisms which are managed and controlled by central and distributed intelligent nodes supported by information and communication technology networks [6].

SG must integrate technology, market, regulatory issues, environmental impacts, standards, and ICT. There are still considerable challenges associated to smart grids namely in terms of communications, which will be the infrastructure that will allow the participation of different entities concerning technical and market operation. ICT will allow the implementation of different functions and business models accommodating the needs of the different participant, as depicted in Fig. 5.1.

One particular case is the integration of EV which will require the interaction between several entities concerning ICT players in SG. The importance of accommodating EV is mainly due to their mobile and highly disperse characteristic which along with the potential massive deployment in the next years will have a significant impact on SG.

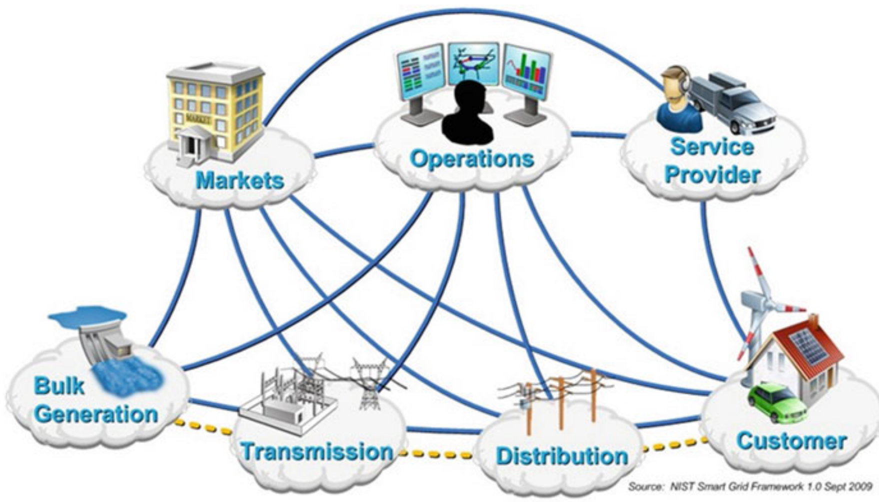

Fig. 5.2 NIST domains and interconnections

5.2.2 ICT Players in Smart Grids

One of the most active standardization bodies is NIST, the North American agency responsible for promoting innovation and competitiveness in the United States towards a better economic security and quality of life using standards and technology.

NIST has defined the main players envisaged to interact in SG using a domain perspective interconnection, as depicted in Fig. 5.2 from [7], where the lines in full define functional interconnections while the dashed lines represent electric interconnection. Internal elements inside each domain are also defined and interconnected in a functional subnetwork.

This domain-based functional architecture can be divided into:

- Markets—authorized market operators and participants
- Operations—entities directly associated with electricity flows
- Service providers—entities that provide services either to end customers or to the electric grid
- Transmission—entities responsible for the transmission of electric energy over wide distances
- Customer—end users of electricity (domestic, commercial, and industrial) that can consume, generate, store, and manage their energy

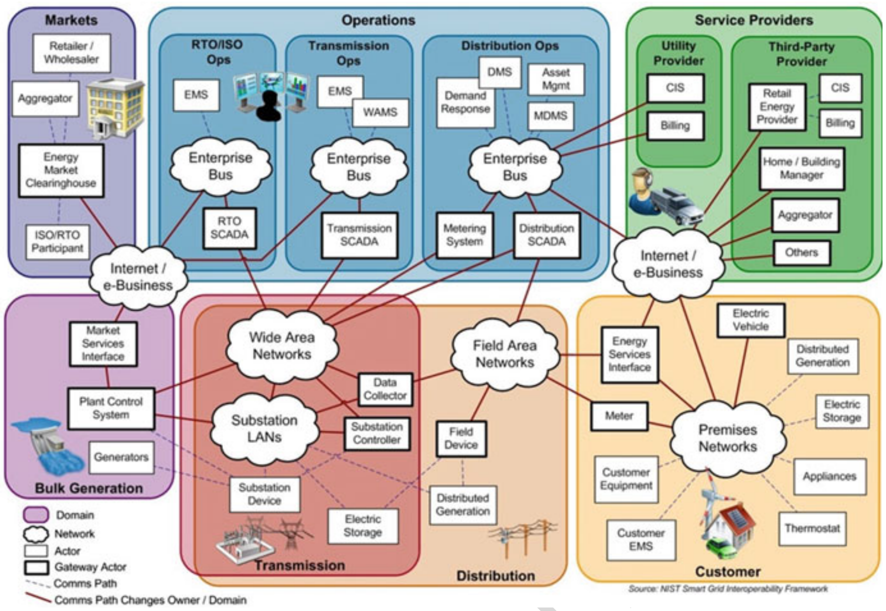

Fig. 5.3 NIST information network interconnecting domains and actors

The Electric Power Research Institute (EPRI) report to NIST [7] details the interconnection between the different domains and their respective actors, considering the most important use cases for Smart Grids requested by NIST:

- Wide area network (WAN) awareness—electric energy systems monitoring over wide areas
- Electric storage—the use of battery systems for energy storage managed individually or aggregated
- Electric transportation—EV integration as a potential flexible load and energy storage elements able to inject power into the grid
- Advanced metering systems—use of advanced metering systems allowing bidirectional information exchange between the end customer and the service provider
- Distribution grid management—electric distribution grid management and control considering the players of the previous use cases

Based on SG applications and use cases, NIST has defined a conceptual model, depicted in Fig. 5.3 [5], considering the expected information flow between actors inside each domain (intra-domain) and between domains (inter-domain). Domains are abstractions of organizations, buildings, entities, individuals, or other elements that share similar objectives and purposes. Actors can be devices, computation systems, software modules, individuals, or organizations participating in an SG. They are able to take decisions and exchange information with other actors.

Gateway actors interact with actors in other domains through information networks. In Fig. 5.3 the lines in full represent inter-domain logical connections or information paths, while dashed lines represent intra-domain connections. Information networks are composed of computers or other communication devices that form the infrastructure (technologies and resources) that allow information to be exchanged.

The EV integration will require flows within the customer domain. However, this domain interacts with the Distribution, Service Provider, Operations, and Market domains and will thus directly impact them all. The next section addresses the functional and logical models and the interaction between those domains at the distribution level. As it will be pointed out, it is considered that the Distribution Operations subdomain can be integrated with the Distribution domain into a single Technical Distribution Operation domain.

5.2.3 Reference Models

5.2.3.1 Smart Metering

Some early reference models can be pointed as the cradle that ultimately led to the Smart Grid concept and models; one of them embodies the Smart Metering concept.

The first smart metering version is associated with automatic meter reading (AMR), which is an automated mechanism to collect information initially from customers' electricity meters [8]. For that matter IEEE approved the IEEE 1377 standard, which defines a table structure for utility application data to be passed to and from end devices, although no device design criteria or specific protocol are defined to transport that information [9].

This model evolved with the introduction of the advanced metering infrastructure (AMI) concept, which is the designation for a more advanced system composed of metering, analysis, load management modules, and a bidirectional communications system. Along with AMI new concepts were defined, such as the AMI head-end, which is typically located at the control and operation system of the DSO, and the smart meter (SM), which is installed in the customer premises. An automated meter management (AMM) layer was incorporated at the SM in order to provide services to the customer.

The communications infrastructure associated with smart metering may consist of several networks, typically including a network of meters, a WAN, and backhaul networks for the connection of the metering network(s) with the utility central control/operation system.

The AMI concept was the starting point for the deployment of a communication and processing infrastructure capable of introducing services to the electric network within the smart grid vision. The definition of a smart grid is not consensual, either because of different functional model perspectives or due to specific implementation aspects. However, it is widely agreed that it is a complex system composed of interrelated systems that include the AMI or Smart Metering system.

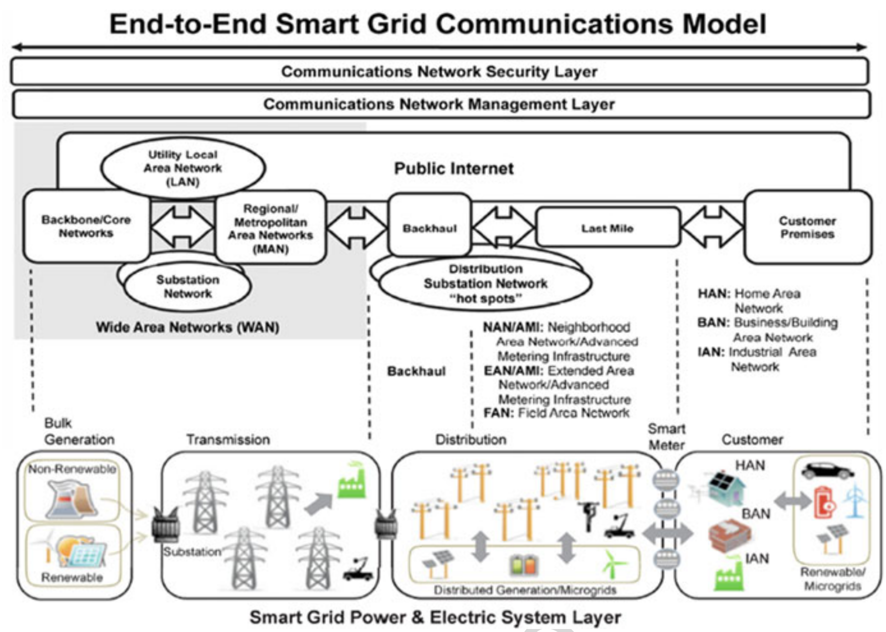

Fig. 5.4 IEEE 2030 smart grid communication model

Despite the fact that the first implementations of SG are majorly based on a sophisticated AMI, there is a concern that this approach may limit or introduce restrictions to the broader objective of progressively creating an integrated bidirectional communication system. The design of the communications system for a smart grid must take into account the expected long-term requirements, even if in the short term only a limited set of functions is necessary (e.g., monitoring or metering).

5.2.3.2 Information and Communication Models

NIST and IEEE have recently developed reference models that aim at providing an updated and detailed vision of the challenges and issues of communications in smart grid. Both models propose a segmentation of the global SG network into specific networks considering a logical separation due to functional aspects. These models incorporate requirements that were identified by several entities (governmental, standardization bodies, utilities, network operators, suppliers, etc.) and some of them are publicly documented [10, 11]. The model developed by NIST is presented in Fig. 5.3.

The IEEE standard (IEEE 2030) was based on the work developed by NIST. A smart grid interoperability reference model (SGIRM) is proposed; it is supported by an End-to-End Smart Grid Communication Model, as depicted in Fig. 5.4.

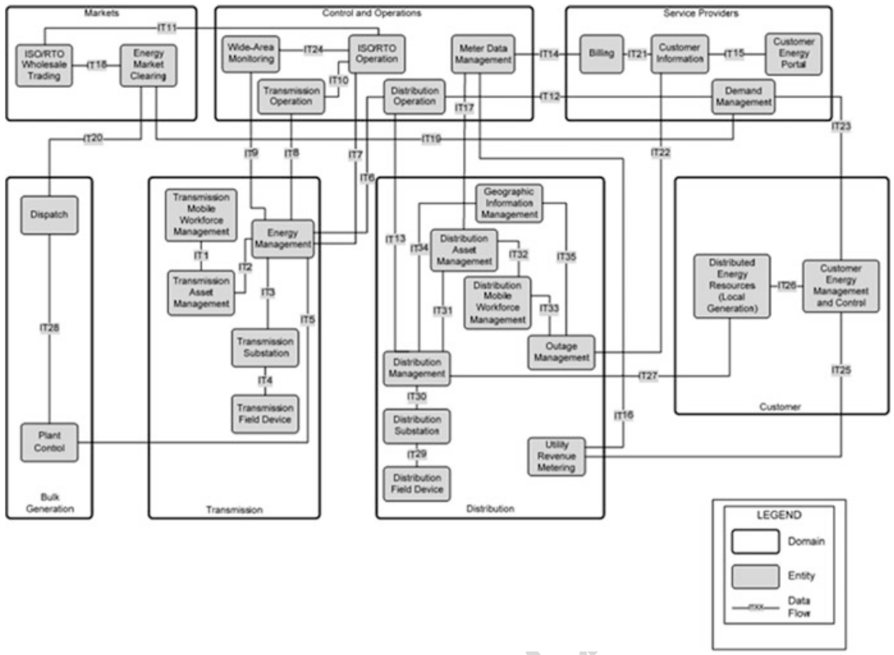

Fig. 5.5 IEEE 2030 information technology—interoperability architectural perspective (IT-IAP)

SGIRM defines three complementary views called interoperability architectural perspectives (IAP):

- Power systems (PS-IAP)—highlight the aspects of production, delivery, and consumption of electric energy. It identifies logical information to be conveyed.
- Communications technologies (CT-IAP)—highlight connectivity aspects among systems, devices, and applications. It identifies the general communication options for different interfaces.
- Information technology (IT-IAP)—highlights process control and identifies data flow management aspects.

The models used by NIST and IEEE are not incompatible, despite the different terminology and some functional differences, visible when comparing Figs. 5.3 and 5.5. There is, however, an effort to unify the terminology towards a consistent architectural framework for SG concepts.

Given the importance of the IT-IAP layer, it is depicted in Fig. 5.1. This layer gives an overview of the SG considering IT applications and associated interfaces and data flows with the goal of allowing interoperability between independently developed systems.

As previously emphasized, the interaction of EV with the SG will take place at the Customer domain, which in turn will interact directly with the Distribution and Service Provider domains and indirectly with Market and Control and Operations domains.

According to the IT-IAP model, the Customer domain has two entities:

- Customer energy management and control—it is an energy management system (EMS) (domestic, industrial, or business) that can receive management and control functions from the SM or from the service provider.
- Distributed energy resource—it is the set of generation and storage devices that may or may not be dispatchable.

Hence, the EV can be seen as an entity/device that can be managed and controlled by the SM according to the customer preferences or by the service provider. It is another DER that, according to the configuration in the SM, has the ability to participate in energy services.

On the Service Provider domain the following entities interact directly or indirectly with the customer:

- Billing—it uses the collected data from meters and is responsible for the billing of services according to tariff schemes.
- Customer energy portal—is a front-end for customers to send data pertaining to energy usage, billing, and authorization, through a universal telephone or data connection (Internet).
- Customer information—is a customer profile database with all the relevant data from the customer.
- Demand management—it is the indirect interface of the customer with the market domain. It uses customer data and negotiates service conditions in the market and with the customer, thus allowing enhanced load control strategies.

It is possible to incorporate EVs from customers in these IT entities. The billing schemes depend on the services and conditions negotiated with the customer and with the market. The EV as a load is also billable for the consumed energy. It represents extra information to add to the Customer Information entity for each customer owning an EV, like the charging rated power, since the EV is also a load. Due to the great flexibility of EVs it is very appealing to associate them with the Demand Management entity.

However, the ability to inject power into the grid also makes the EV very relevant in allowing the Service Provider entities to negotiate energy services in the Market domain. They become especially useful when managed and controlled through Aggregators as depicted in Fig. 5.3. Although the commercial aggregator of customers, in particular of EVs, is not explicitly defined in IEEE 2030, it does not conflict with the ICT architecture proposed by NIST.

The interaction of the customer with the Distribution domain may take place through two entities:

- Distribution management—it manages the distribution system operation, including load management, using information from customers, among others.
- Utility revenue metering—it is the AMI head-end for the distribution domain.

As far as the Distribution domain is concerned, the integration of EVs will be part of the load management scheme implemented in the Distribution Management entity. It will also be a target of the Outage Management entity, although indirectly through the Service Provider. As a potential element that can inject power into the distribution network, it needs to be considered as an active participant by the Control and Operations domain. For this purpose the Distribution Operation entity indirectly establishes an IT path towards the customer through the Distribution Management (Distribution domain) and Demand Management (Service Providers domain).

In the Market domain the following entities are defined:

- ISO/RTO wholesale trading—it is responsible for the trading between bulk generators, utilities, and transmission operators.
- Energy market clearing—it is responsible for conveying the market trading result to bulk generators and to Service Providers.

The integration of EV in the Market domain is also not explicitly defined in the IEEE model, but NIST suggests that it may be achieved through the Aggregator entity as a Service Provider. IEEE merely considers that aggregators, like any other service provider, are able to directly interact with the Market domain through the Energy Market Clearing to know the outcome of the energy market trading. If the Energy Market Clearing entity is able to account for bids from service providers, the inclusion of aggregators will have no impact on this ICT model proposed by IEEE.

Despite some different interpretation of the SG concept, NIST and IEEE models are very detailed and flexible and can thus ensure the proper interoperability when integrating the EV in SG ICT solutions. It is evident the importance of access networks, particularly in the Last Mile, both in terms of communication infrastructure and ICT, to enable the integration of EVs.

5.2.4 Functional and Logical Models

The functional and logical models involving the electric vehicle integration can be defined under two perspectives. One concerns the integration in models such as those proposed by NIST where the focus is placed on the interaction with the grid at a higher level with inter-domain interaction. The other concerns the models addressing the interaction of EV with the infrastructure within the customer domain.

5.2.4.1 Grid Interaction

The introduction of EV in electric grids will require changes to the SG paradigm. This will likely be a phased process that will include short- and long-term actions according to different levels of EV integration.

The Operations (in particular the Distribution Operations component) and the Distribution domains are here integrated and characterized by a hierarchical control

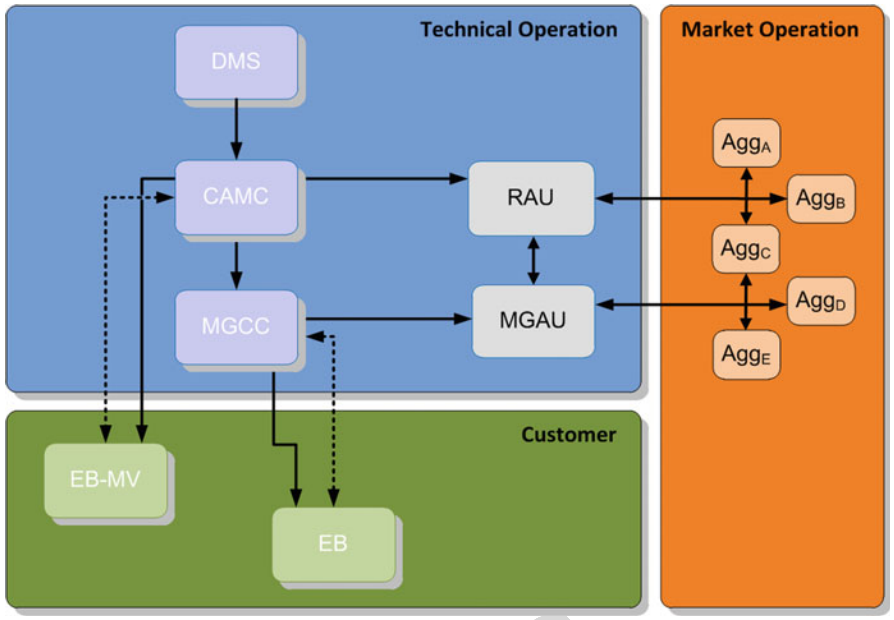

Fig. 5.6 Short-term model for EV integration

structure referred to as Distribution Technical Operation, while the Market and Service Provider domains are portrayed as a hierarchic market structure composed of aggregators. The Customer domain is defined by the Energy Box (EB) entity, which acts as an AMI and service gateway (GW), allowing the participation of customer devices, such as EVs, in energy markets.

In the short term the EV penetration is likely to be modest, but it can already have an impact on the operation of electric distribution networks, since it introduces new technical challenges. In this case the functional model of SG will mainly rely on control structures defined from the electric grid side with limited interaction with markets. Structures based on hierarchical control schemes such as microgrids [12] and multi-microgrids (MMGs) [13] will be used, allowing electric grid entities like the distribution system operator (DSO) to monitor and control different parts of the electric network, as represented in Fig. 5.6, where the market and technical operations are considered in a short-term perspective.

The Energy Box (EB) is the central actor in the Customer domain (MV or LV), since it is the interaction element with the grid. It is responsible for implementing a monitoring and metering platform (AMI) while providing a control scheme for customer devices. The microgrid central controller (MGCC) is the main actor at the secondary substation (MV/LV), which is the entity responsible for coordinating the control of associated EBs and exchanging information with a new technical management entity—the central autonomous management controller (CAMC). The CAMC is the main actor at the HV/LV substation and is responsible for the technical management of the MV grid interacting directly with MGCCs and with the distribution management system (DMS). Both MGCC and CAMC entities are associated with the DSO hierarchical structure.

On the market side, and according to the models proposed by NIST and other entities, the aggregator is one of the key actors that participate in this domain. The aggregator is as a generic commercial entity that can operate in the energy market, representing end customers, namely EV owners. Aggregators interact with the technical operation depending on the level of aggregation. At LV the interaction is ensured through the microgrid aggregator unit (MGAU) while at MV it is performed through the regional aggregation unit (RAU). Both RAU and MGAU are market interface entities that allow the DSO to ensure the participation of distributed entities such as Distributed Energy Resources (DER) and EVs in energy market services [14].

This model is based on a communications infrastructure provided by DSOs, which will allow technical entities to be aware of technical information associated with market operating conditions regarding the end customers connected to each MGCC and CAMC.

It should be pointed out that it is assumed that the distribution grid is capable of operating under two main states: normal and emergency. In the normal state the distribution network is operating without any kind of technical violation or near any operational limit. In the emergency state the electric network is operating near the technical limits or when any of the operation thresholds has been exceeded, leading or not to a violation of a technical restriction. Depending on distribution system and classification used, a given number of intermediate states may exist in between these two states.

In the normal state the electric grid operation is mainly driven by a market implementation, including the different variants, such as “day-ahead market,” “intra-day markets,” “corrective markets,” and others. The distribution network operation in normal state is mainly defined by the outcome of the market operation as depicted in Fig. 5.6 by the lines in full. However, the technical hierarchical structure is aware of the state of operation and in case it is impossible to maintain the market operation due, for instance to a technical violation, the distribution network changes to the emergency state. In this state the market operation is temporarily suspended, the RAU and MGAU stop receiving market inputs, and the technical operation takes over by activating the dashed links in the figure.

On the long-term perspective, it is expected that a more significant integration of EV will take place along with the implementation of a more dynamic energy market, which will require a different model to handle the much higher amount of information that will have to be exchanged in a Smart Grid.

With the introduction of a more complex information exchange in SG both in the technical plane and in the market, a natural segmentation of information is likely to occur. The information within an SG can be characterized primarily as having two different natures, one being technical and the other market related, as illustrated in Fig. 5.7. The customer domain now plays a central role in the model, as far as EV integration, since it has information concerning both sides.

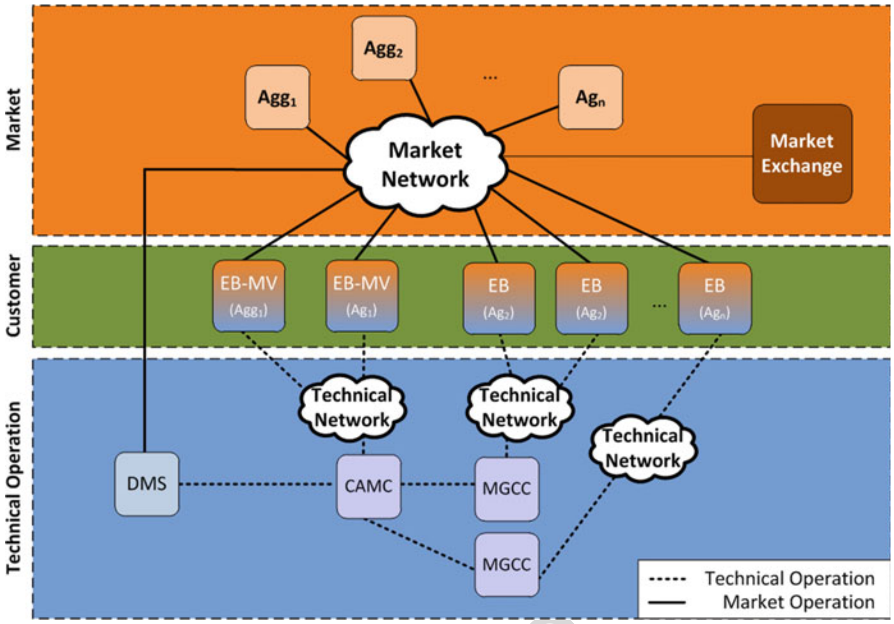

Fig. 5.7 Long-term model of EV integration

The separation of information can be supported by a physical separation using different communication networks of different technologies. It can also rely on a common communication infrastructure/technology with data and functional separation in different logical networks. One reason for information segregation is the different scopes of use. Moreover, the requirements (latency, bandwidth, and others) for the exchange of information under market operation can be quite different from those placed by the technical operation. This has obvious implications with regard to architectural and technological solutions to be adopted, especially in ensuring the proper levels of quality of service.

The separation of market and technical information is also suggested by NIST models namely through the use of Internet/e-Business networks for customer interaction with service provider and markets. The use of field area networks (FANs) is also suggested to ensure the interaction between the customer and the distribution network.

Similarly to the previous model, the lines in full in Fig. 5.7 represent the information flows when the system is operating in normal conditions and mainly controlled by the market. The dashed lines represent the technical operation information flows that are used in normal/market condition for monitoring purposes only. In case the system is not able to sustain market operation due to technical constraints the market operation is suspended and the system operator control infrastructure fully assumes monitoring and control of the distribution network.

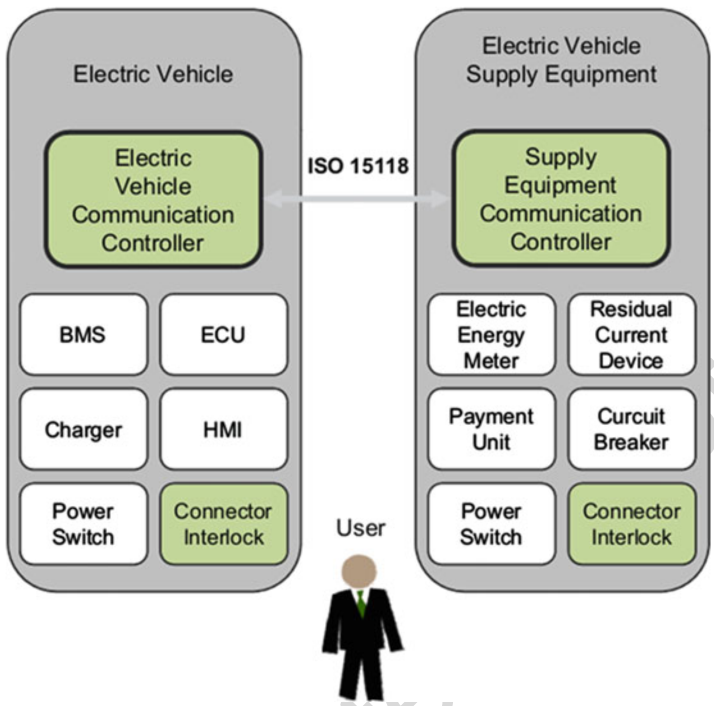

Fig. 5.8 Actors involved in EV and EVSE according to ISO/IEC

5.2.4.2 Infrastructure Interaction

In order to ensure the integration of EV in Smart Grids it is also necessary to define data models addressing the interaction between EVs and the access infrastructure. One of the most awaited standards regarding the communication model between EVs and the charging infrastructure, also known as electric vehicle supply equipment (EVSE), is the ISO/IEC 15118.

The ISO/IEC working group identified a set of actors concerning respectively the EV and the EVSE, with IEC 15118 specifying their interconnection, as illustrated in Fig. 5.8.

For a more detailed description, please refer to section "IEC 15118."

5.2.4.3 Information Flows

The flows regarding the EV integration in distribution networks can be functionally separated into technical and market information, as referred to in the previous section. However, the technical information that mainly concerns the electric operators may flow to more than one of the domains defined by NIST. The same rationale applies to market information flows.

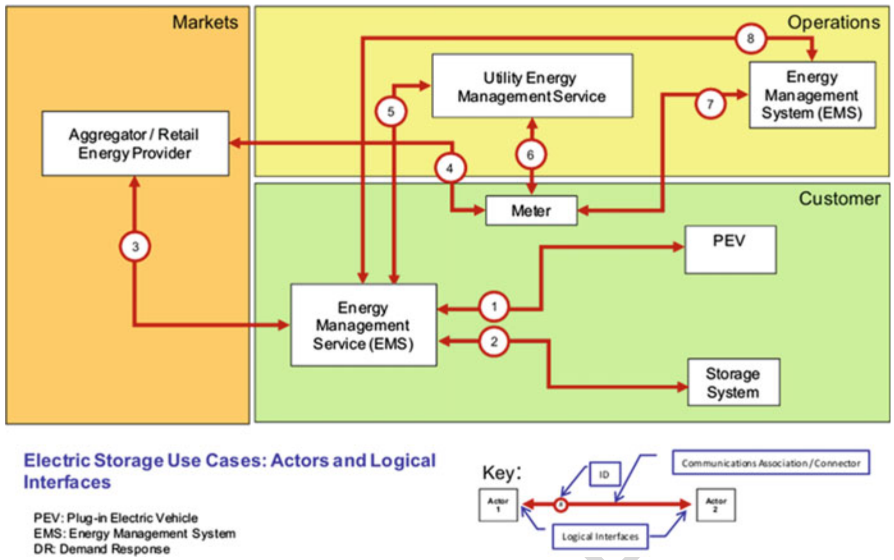

Fig. 5.9 Electric storage application

NIST has defined a set of SG applications, designating the involved entities and respective flows. As the name suggests, the Electric Storage (ES) application refers to storage devices that deal with resource adequacy and resource management. Storage devices can be deployed as bulk storage, like pump storage in hydroelectric power plants, or in a distributed fashion, like small flywheels and batteries. In the case of distributed storage, given the small scale of these systems, they can benefit from the use of market aggregators the same way as EVs can. In fact, EVs are mobile storage devices and as such can participate as actors in this application. Fig. 5.9 illustrates the domains, flows, and actors involved in the Electric Storage application according to NIST [6].

The following use cases were deemed in the Electric Storage smart grid application:

- Storage device draws energy from the grid
- Storage device supplies energy to the grid
- Storage device used in building energy optimization
- Storage device dispatched by the system operator to meet power demand
- Storage device dispatched by the utility to support intentional islanding
- Storage device used to provide fast voltage sag correction
- Impact on distribution operations of plug-in electric vehicles as electric storage

As storage devices, EVs can also participate in all of the use cases previously mentioned, especially if supported by aggregators in market negotiation, which can allow their feasible participation mostly in providing system services to the grid.

Another SG application where EVs can potentially participate is Demand Response (DR), which allows a temporary change in the consumption pattern to address market or technical constraints using Demand Resources. These are loads

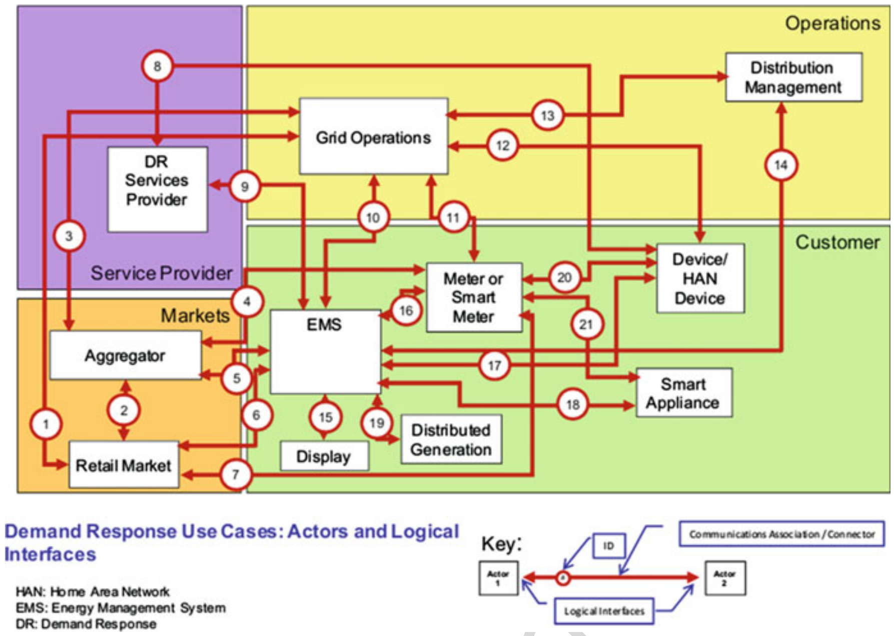

Fig. 5.10 Demand response application

or sets of loads with required flexibility to ensure feasible temporary changes in consumption levels. In SGs these Demand Resources are associated with DER, which are small scale electric energy sources that can provide temporary changes in supply, also known as Supply Management. A particular case is precisely the EV, since it can provide both services, especially when part of an aggregated set. Hence, it is common to address demand resources and DERs in an integrated fashion. Fig. 5.10 [6] depicts domains, flows, and actors involved in the Demand Response application defined by NIST.

Although the EV actor is not depicted in the figure, it is considered by NIST a participant entity in the defined use cases:

- Direct load control
- Management of DR to price signaling
- Customer reduces demand due to pricing or voluntarily
- Service provider interacts with SM/AMI to provide demand response services
- Customer implements DR strategy through the EMS
- Utilities negotiate DR with customer and settle energy market wholesale transactions
- Service providers use aggregated customer set to provide energy/ancillary services
- Voltage, VAr, and Watt control with DR, DER, EV, and ES

The characteristics of the electric vehicle make it a valuable entity that is able to participate both in demand response and supply management with no impact on ICT flows, being just another actor that can participate in both cases.

Table 5.1 SGIRM data classification[a]

Data characteristic	Classification or data range			
Use category	To be defined according to intended use and implementation			
Distance	Meters		Kilometers	
Information transfer time	<3 ms	3 ms < 10 s	10 s < mins	Hours
Data occurrence interval	Millisecond	Second	Minutes	Hours
Transmission scheme	Unicast	Multicast	Broadcast	All
Priority	Low	Medium		High
Latency	Very low (<3 ms)	Low (<16 ms)	Medium (<160 ms)	High (≥160 ms)
Synchronization	Yes		No	
Information reliability	Informative	Important		Critical
Availability	Low	Medium		High
Level of assurance	Low	Medium		High
Data volume	Bytes	Kilobytes	Megabytes	Gigabytes
Security	Low	Medium		High
Confidentiality	Low	Medium		High
Integrity	Low	Medium		High
Availability	Low	Medium		High

[a]Where the classification is stated in terms of “low,” “medium,” and “high” means that they can have limited, serious and catastrophic consequences

5.2.4.4 Characteristics of Information Flows

The IEEE 2030 standard proposes a classification of data flow characteristics that need to be considered when designing ICT solutions for smart grids. Table 5.1, adapted from [15], presents a set of characteristics that can be independently associated with different information flows. The range of each one of them depends on the real implementation of each SG application.

It should be noted though that the proposed classification for each data characteristic can be considered singly. This means, for instance, that information exchanged with an <Information Reliability> value of “informative” can have an <Information Transfer Time > of “hours.”

5.2.5 *Last Mile*

The concept of Last Mile within Smart Grids is very similar to the one usually found in communications networks. In fact NIST has defined it in [16] as being a bidirectional wired or wireless communications network overlaid on top of the power distribution network. A Last Mile network ensures connectivity between different elements within the electric distribution network and usually several different networks are distinguished, according to the type of interconnected devices and associated functions [15]:

- Feeder network—is a communication network overlaid on the electric power system for information exchange with field devices of the electric grid itself (e.g., reclosers, switches, capacitor banks, etc.).
- Neighborhood area network (NAN)—is a network connecting smart meters, field devices, distributed energy resources, microgrids, and the utility scale electric storage.
- Field area network (FAN)—is the network connecting distribution substations, feeder devices, and DER/microgrids.
- Extended area network (EAN)/advanced metering infrastructure (AMI)—is the network that interconnects smart meters with the distribution metering management systems.

These networks usually have a geographic span up to a few kilometers although this distance can vary substantially depending on whether a rural or an urban area is considered. Although all these networks are logically distinct and the information flows traversing them can originate and terminate at different systems, they can share the same communications infrastructure, in part or in full.

There are a considerable number of reasons that justify the definition of a last mile model, namely:

- A high number of devices (sensors, meters, controllers, actuators, etc.) deployed under the SG paradigm are (or will be) geographically located within the range of distribution substations.
- The expected increase in data traffic volume in SG will potentially be originated by smart devices deployed in distribution grids, which may require heavier communication mechanisms and data flow aggregation. This increase can also require complex security schemes and nontrivial traffic QoS for service discrimination.
- The availability of alternative technologies (both present and future) and the risk of adopting a unique technological solution (especially when considering the long-term evolution) may require the implementation of different coexisting communication networks over time.

5.3 Technologies and Solutions for Smart Grids

5.3.1 Interoperability

The presence of a potentially high number of different devices in SG will require an interoperable approach allowing technologies and solutions from different implementers to cooperate towards a unified smart grid.

Interoperability challenges are posed at different layers of the OSI model. At the network layer the agreement on IP-based solutions is already widely accepted as universal solution. Using IP as a common interworking layer allows using different technologies with different PHY and MACs. Higher layers concerning information models are addressed by different working groups typically using a decoupled approach regarding other layers. However it is at lower layers, which are inherently technology driven, that interoperability finds the biggest challenges.

Normative and standardization bodies as well as manufacturer alliances have a key role in defining solutions for SG and interoperability is a transversal concern that is becoming a recurring topic in their work.

5.3.1.1 Network Interoperability

The Internet Protocol (IP) is currently the de facto standard, and thus the most popular choice, of a network service that provides connectivity among end-systems attached to the same or different networks. In the particular case of smart grids, IP has an increased importance due to its interworking characteristics.

Its use is considered in current and future developments of SGs, where utilities are able to use multiple communication networks of different technologies and end devices from different manufacturers. The flexibility associated with IP networks when considering aspects such as network reconfiguration and expansion, with dynamic routing schemes and scalable design, represents an advantage for its use in SG.

In SGs, an IP end device/node is any IP-enabled device; this includes smart meters, sensors, relays, actuators, intelligent electronic devices, or any device with embedded data collection and reporting functionalities that can communicate at the IP layer [16].

IP is pointed out by NIST [5] as a central element for Smart Grids information networks and it is expected to be widely adopted. Nonetheless it is also assumed that not all devices in the SG are required to use IP, since they might not be suited to be part of an IP infrastructure.

The importance of IP as an interworking layer is more evident in the Last Mile segment of the SG, where the majority of systems, subsystems, and elements will be located. Given the high number of IP devices that potentially can operate in SGs, advantages can be found in using IPv6, despite the existing mechanisms currently used to overcome the depletion of available IPv4 addresses. The use of IPv6 over Low-Power Wireless Personal Area Networks along with Compression Format for IPv6 Datagrams in 6LoWPAN network, which addresses header compression and subnet architecture, may be also used in SGs. The IP suite with enhanced routing and QoS features, among other mechanisms, provides an appropriate interoperable layer to support the implementation of data networks in smart grids [17].

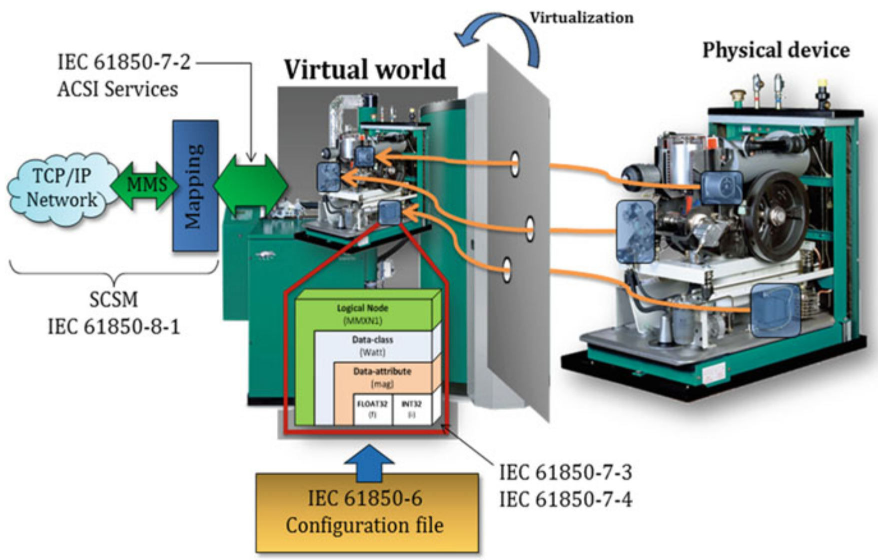

Fig. 5.11 IEC 61850 modeling approach

5.3.1.2 Information Interoperability

IEC 61850

Originally designed to allow for interoperability between different devices within a substation environment, as well as for the adaptation of future networking technologies, IEC61850 is quickly becoming a key standard within smart grid communications. Besides its versatility, one of the main reasons for this adaptation is the continuous addition to its device portfolio. One such extension is in the form of IEC61850-7-420, which specifically outlines DERs encompassing, among others, EVs. The outline is as follows:

- Logical nodes for DER management systems
- Logical nodes for DER generation systems
- Logical nodes for specific types of DERs
- Logical nodes for auxiliary systems

Fig. 5.11 shows some of the more common parts of the IEC 61850 standard and the areas they cover. Of special interest are the sections IEC 61850-7-1 and IEC 61850-7; the former gives an overview of the use of the substandard and the latter describes the common data-classes that should be used to model the vehicle. The *Virtual World* box in Fig. 5.11 shows how individual components of a substation are modeled using the IEC 61850 standard and the yellow plane marked *virtualization* represents the mapping from the physical substation environment to the logical model. The *TCP/IP* cloud and *MMS*-mapping on the left, covered by

IEC 61850-8-1, is in this case the *Specific Communication Service Mapping* (SCSM) for the *MMS* protocol—ISO 9506.

There are several key features to IEC 61850; the following are some of the more commonly used:

- Object-oriented data model (devices, nodes, data, services, etc.)
- An object naming scheme to ensure easier familiarization
- Predefined names for all data-classes (see above)
- A common XML-based substation configuration language (SCL)
- Self-describing devices (directory listing)

Other benefits include:

- Using SCL not just for configuration but also for specifying requirements
- Lower costs due to easier hardware implementation
- Expandability in using for example TCP/IP (over RS232, etc.)

Data Model

One of the primary features of the IEC 61850 standard is the data model. This has been designed to provide an object-oriented virtual representation of the physical devices within the substation.

As illustrated in Fig. 5.12, the data model is really a tree structure. At the root of the tree is the physical device, containing a server that represents the publically visible behavior of the device.

Any object within the data model can be referred to directly via its object path. Due to the fact that the data-structure is a tree, this path will resemble a file-system path or a URL. The path lists all the objects from the root of the tree to the object in question, which is illustrated in Fig. 5.13.

Where file-systems usually use a fixed delimiter between object names, the IEC 61850 references use a slash ('/') to separate the logical device from the rest of the path, which is then separated by periods ('.'). This scheme does however vary depending on its usage; the typical MMS notation, for instance, uses the dollar sign ('$') exclusively. An example of an object reference as specified by the standard could be:

EV/MMXN1.Watt.mag.f

Included in the object reference is a filtering mechanism referred to as *functional constraints* (FC). The standard defines 17 different functional constraints.

The functional constraints are used in the data-classes to divide their data-attributes into categories. Adding the functional constraint *MX* to an object reference will, for example, result in only the data-attributes containing measurements being returned. As with the delimiter example above, the functional constraints are usually at the end of an object reference, incased in square brackets ('[]'). For the *MX* example, this would look like this:

EV/MMXN1.Watt.mag.f[MX]

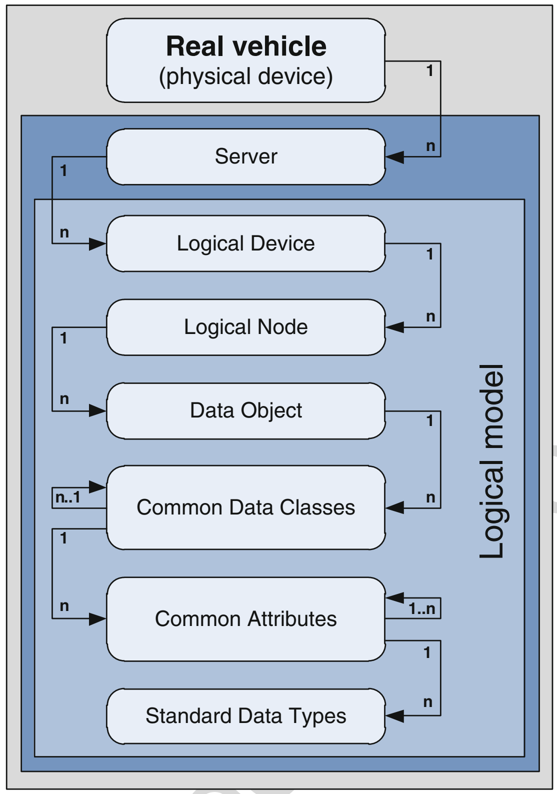

Fig. 5.12 Data model hierarchy

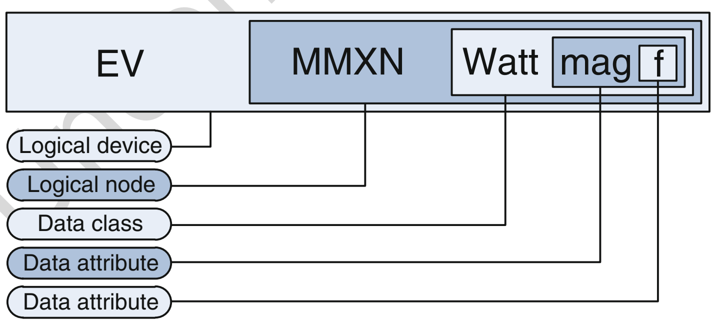

Fig. 5.13 Example of object path

Communication

IEC 61850-7-2 describes an interface called the *abstract communication service interface* (ACSI), which can be seen in the middle of Fig. 5.14, for accessing the IEC 61850 data model. *ACSI* defines a service interface for clients to inspect the

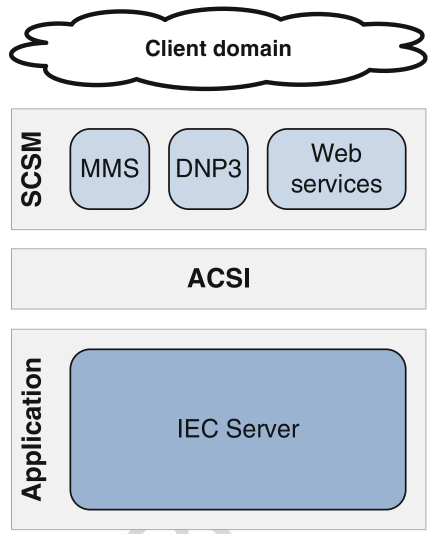

Fig. 5.14 Illustration of the *specific communication service mapping*

data model, to read and set data, to access datasets, logs, and more. As the name implies, this interface abstracts away the details of the communication protocol useful for providing a consistent interface across protocols.

For every communication protocol that is used with the standard, there is a so-called *specific communication service mapping* (SCSM). At present only a few communication mappings exist for IEC 61850, the most common of which is the MMS standard, also known as ISO 9506, which is described in IEC61850-8-1.

Where ACSI describes things on a higher, more abstract level, it is the job of SCSM to define the specifics of protocols such as MMS, DNP3 or as is the case in the Danish EDISON project, restful web services [18].

IEC 62351

In order to secure the communication, the IEC61850 standard can be paired with the IEC62351 standard that provides mechanisms such as encryption, network- and system security as well as role based access control (RBAC). Through the use of transport layer security (TLS), IEC62351 prevents eavesdropping on any communication based on the TCP/IP stack. Further measures against man-in-the-middle penetrations are ensured via either an X.509 public key infrastructure (PKI) or a token server like, for example, Kerberos.[1]

The RBAC mechanism provided by IEC62351 (depicted in Fig. 5.15) is similar to what is found in most modern computer operating systems, and provides custom roles and rights to be defined on an individual subject basis. This model is very

[1] http://web.mit.edu/kerberos/.

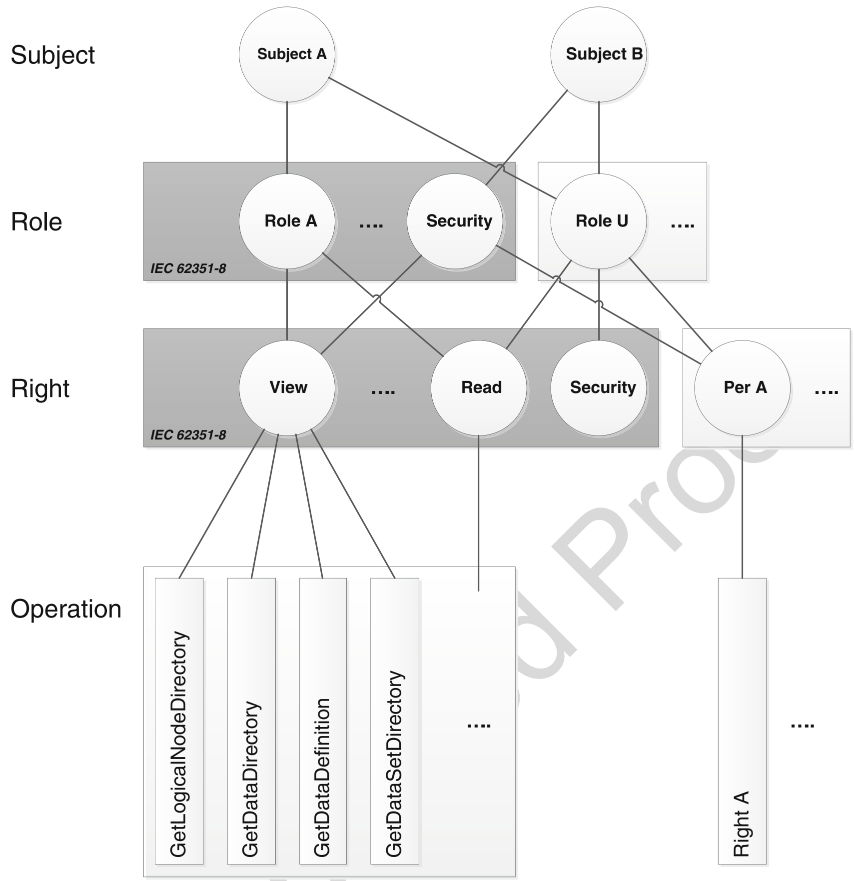

Fig. 5.15 Role based access control (RBAC)

flexible, and in a highly volatile environment allows multiple users to operate simultaneously; some with write and others only with read permissions. Due to this logical separation or responsibility, one client can safely monitor a process controlled by another without risking an accidental race condition on the control side.

Besides facilitating security within the IEC61820 standard, IEC62351 also addresses IEC60870 (dealing with SCADA systems), IEC61968 (inter-substation communication), and 61970 (EMS).

IEC 61851-1: Control Pilot Signaling

The IEC61851-1 standard is part of the IEC 61851 series, which is titled "Electric vehicle conductive charging system." The second edition of the IEC61851-1

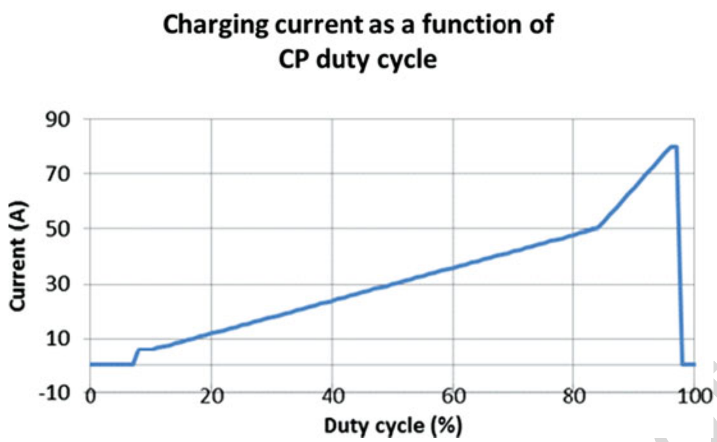

Fig. 5.16 Charging current CP duty cycle

Table 5.2 IEC61851-1 charging modes

EV charging modes	Description
Mode 1	Max 16A per phase. Directly connected to mains
Mode 2	Max 32A per phase. Connected to mains through RCD. Utilizing the control pilot function
Mode 3	Connected through an AC charging station, which contains protection equipment. Utilizing the control pilot function
Mode 4	Connected through an off-board charger, that is, DC-charging. Utilizing the control pilot function

standard was published in Q4 2010, and the scope is to describe "general requirements" for charging systems. Among other aspects, the IEC61851-1 standard provides mechanical and electrical supply equipment requirements as well as a naming scheme for identifying common charging setups, as shown in Table 5.2. The standard outlines requirements for the physical connector, for instance, that a charging station must be able to verify that a cable is plugged in.

Furthermore, the IEC61861-1 standard describes a "basic" interface for AC charging connectors. This AC connector has six wires and a proximity detection pin (used for the detection of a plugged in connector). Five of the wires are used for mains wiring, i.e., three phases, a neutral, and a protective earth. The sixth wire is the *control pilot* (CP) signal, which is used for indicating available charging current to the EV. The usage of the control pilot function is described in the normative annex A in the standard. The Mennekes AC charging cable complies with IEC 61851-1.

The signaling in the CP wire is a 1 kHz $\pm$ 12 V pulse width modulated (PWM) signal. A function of the duty cycle indicates the available charging current, as illustrated in Fig. 5.17. Furthermore, a resistive voltage division allows the EV to

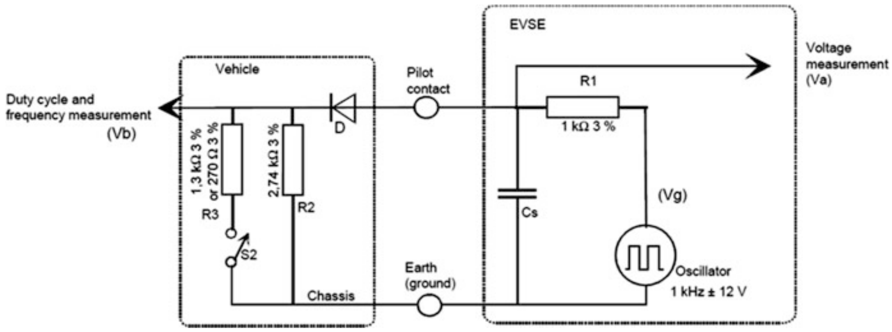

Fig. 5.17 61851-1 control pilot interface reference schematic

indicate a charging *state* to the supply equipment. The PWM signal and the resistor combinations used in the CP circuit are shown in the reference schematic in Fig. 5.17.

It can be noticed from Fig. 5.17 that the charging state is indicated by using different resistors on the EV side. The charging states indicate to the supply equipment if the EV is ready to be charged and if it needs ventilation during charging. The amplitude of the PWM signal is measured at the supply side (at *Va*), and the supply equipment can thus detect the resistor value used in the EV due to the voltage division formed by the R1 resistor and the parallel connection of R2 and R3. The wire between the EV and the EVSE will be capacitively loaded by the Cs capacitor in order to reduce EMI. This also implies that an RC filter is formed by R1 and Cs, which puts a natural limit to the slew rate of the PWM signal. However, this is not a major concern, since the PWM generator emits a relatively low-frequency (1 kHz) signal.

It is evident from the previous description that the IEC61851-1 CP PWM signaling technique cannot be used for general purpose communication, but simply provides low-level functionality in order to establish an electrically safe charging session. In the AC interface specified by IEC61851-1, no dedicated communication wires are specified, and any higher level communication must therefore be provided by other means. A strongly positioned technology in this context is power line communication (PLC), which does not require any additional wiring in IEC61851-1 compliant connectors.

IEC 15118

The ISO/IEC 15118 standard is produced by a joint working group formed by IEC and ISO.[2] It is divided into three parts. The main title of the standard is "Vehicle to grid communication interface" (V2G CI). The parts are:

[2] For brevity, the "ISO" part will often be omitted when referring to the standard.

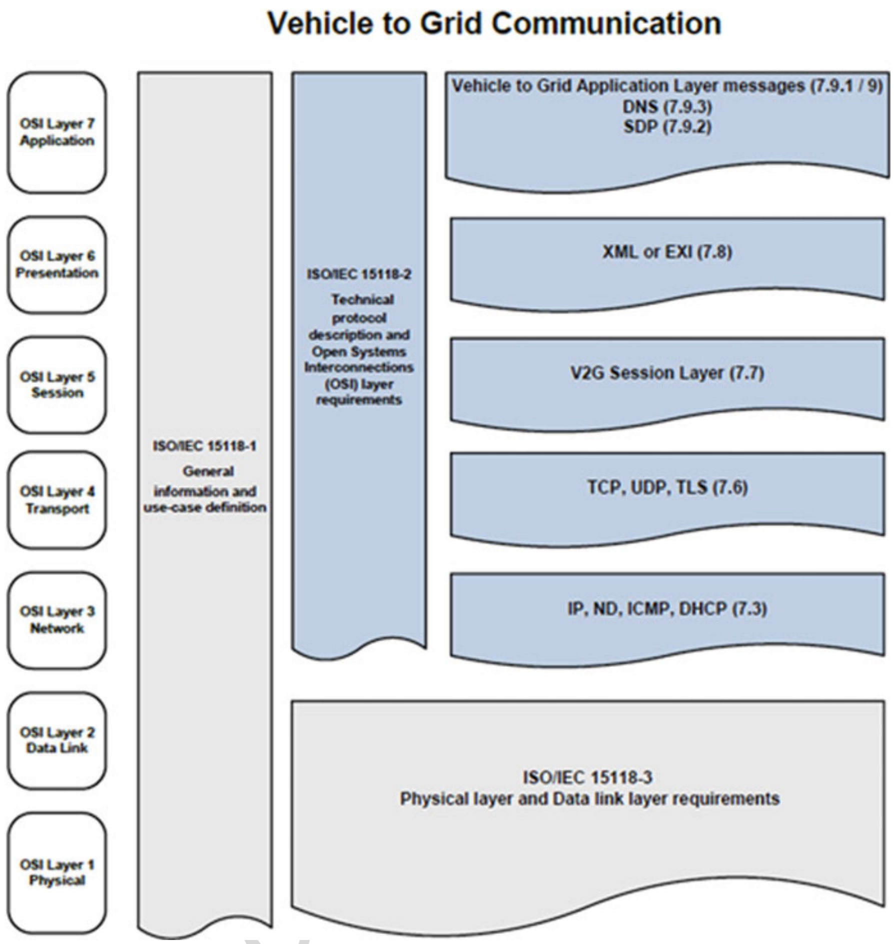

Fig. 5.18 IEC 15118 overview [44]

- ISO/IEC 15118-1: General information and use-case definition
- ISO/IEC 15118-2: Technical protocol description and Open Systems Interconnections (OSI) layer requirements
- ISO/IEC 15118-3: Physical layer and Data Link layer requirements

As can be seen from the titles of the individual parts, part 2 covers upper communication layers while part 3 covers lower layers. This is illustrated in Fig. 5.18.

The 15118-3 standard should comply with the SAE J2931. This SAE standard is divided in seven parts, and all are marked as "work in progress." Specifically, part 3 (J2931/3) covers narrowband PLC while part 4 (J2931/4) covers wideband PLC, so it seems that SAE will support both narrowband and wideband PLC [19].

The general content of part 2 of 15118 can also be seen in Fig. 5.18. TCP/IP communication is used on the network and transport layers and a binary XML format known as EXI (efficient XML interchange) is used on the presentation layer. The usage of these layers will be described further in the next section.

ISO/IEC 15118 Part 2 Overview

Because the information in this section is based on a preliminary version of ISO/IEC 15118-2, some information may have changed since the writing of this book. Also, references to specific sections in the standard are avoided. However, some of the central concepts will very likely also apply to the final version.

ISO/IEC 15118-2 specifies the use of IPv6 in the network layer along with the Neighbor Discovery (ND) protocol to avoid IPv6 address conflicts when stateless address autoconfiguration (SLAAC) is used. Also, ICMP and DHCPv6 must be supported.

On the transport layer, TCP is used for the V2G CI, which ensures end-to-end reliable data transmission. UDP is used as the underlying protocol for the SECC[3] Discovery Protocol (SDP) which is used for the EV to find an EVSE on the network when it is initially plugged in. The EV transmits a multicast UDP packet on port 15118, and the EVSE will listen for an SDP packet on this port and respond with the TCP port that the EV is allowed to connect to. In ISO/IEC 15118, the EV is always the client and the EVSE is always the server that the EV connects to. Furthermore, communication is always solicited, that is, the EV requests data from the server, which responds to the request (as opposed to unsolicited or event-based communication, where the server is allowed to initiate communication, which is valid as seen from a transport layer perspective).

TLS is used as authentication and encryption protocol to ensure secure data communication. TLS session information and certificates are negotiated after the TCP connection has been established.

The ISO/IEC15118 session layer defines three timeouts that ensure that connections are reset and TCP ports are de-allocated if faults occur (known as “Generic Inactivity,” “Initial Inactivity,” and “Alive Check” timeouts). The session layer also describes the low-level message header structure as shown in Fig. 5.19.

It can be seen from the figure that the payload following the session header can be encoded as either XML or EXI. The EXI format is a W3C-supported binary XML format and is located on the presentation layer. It provides a fast and compact way to transmit XML, while keeping the XML format functionalities intact. For example, data types can still be described using XSD (XML schema definition) and XML Security can be used to ensure authentication and encryption inside XML streams.

ISO/IEC 15118 ensures authentication and encryption of metering and billing data using, as mentioned, TLS-secured communication between the EV and EVSE.

3 Supply equipment communication controller.

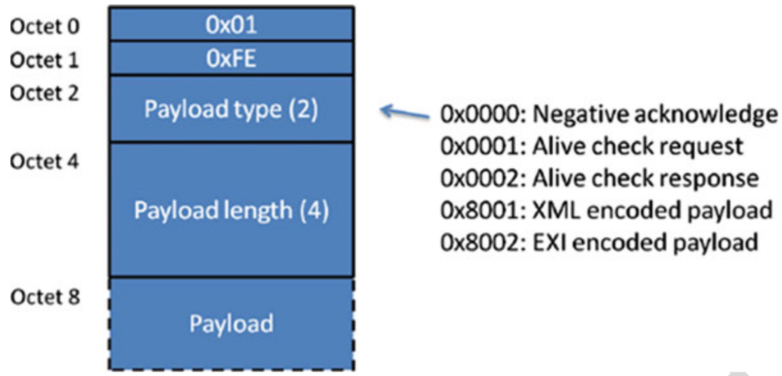

Fig. 5.19 IEC 15118 session header

Furthermore, sensitive data is encrypted and signed (that is, authenticated) inside the XML stream using XML Security. An EV must use two distinct private keys and certificates to ensure encryption and authenticity at the same time. The EVSE uses a single private key and certificate for the TLS communication establishment. All certificates must be registered with a Certificate Authority (CA). Certificates are exchanged with the EV using specific application layer certificate message types as described below.

Application layer messages (the payload) are defined in the XSD format and constructed using a header and a body in the XML stream. The header is encoded as an XML element that contains information on the current session ID. The body is another XML element, which can be one of 19 predefined message types as listed in Table 5.3. The message types are grouped in the table according to functionality. A description of each message type is also given, which should make it easier to get an overview of the functionality that ISO/IEC 15118-2 provides on application and user layers.

Furthermore, basic data types are defined in ISO/IEC 15118-2, which are used to encode and transmit data inside the application messages. Examples are definitions for price tables, certificates, response/error codes, different enumerated values, and time tags. All types are defined in a hierarchical XSD format. However, the complete list of data types is not shown here.

The OpenV2G Project

OpenV2G is a software project initiated by Siemens to support the development of the ISO/IEC 15118-2 standard. It can be retrieved from SourceForge on http://openv2g.sourceforge.net/. It is written as a console application in C and can be compiled using Eclipse CDT or using makefiles.

OpenV2G provides implementations of all application layer messages and data types as defined in ISO/IEC 15118-2 as well as message encoding and decoding

Table 5.3 ISO/IEC 15118-2 application layer message types

Message type	Description
Communication link setup	
Handshake	EV and EVSE agree on a mutually supported protocol
Session setup	Session ID is created
Service discovery and selection	
Service discovery	Find all services provided by EVSE with regard to charging the EV. Can be extended for future use
Service detail	EVSE sends specific information about a particular service
Service and payment selection	EV selects specific services and payment options. Depending on selection, EVSE provides security information for following messages
Payment details	EV sends specific payment details (e.g., contract identifier). EVSE accepts the payment method
Contract authentication	The EVSE authenticates the contract by verifying an EV signature
Charging service and metering	
Charge parameter discovery	EV sends details about needed energy and anticipated end of charge. EVSE responds with status, prices, maximum allowed power output, etc.
Power delivery	EV sends information on currently chosen price and charging profile
	EVSE responds with status
Metering status	Provides sanity checks on meter readings so that the EV and EVSE can agree on the energy drawn. Cyclically transmitted
Metering receipt	EV acknowledges the metering information from the EVSE sent previously. Cyclically transmitted
Certificate handling	
Certificate update	Updates certificates in the EV that are about to expire
Certificate installation	Installs new certificates by using an OEM certificate in the EV to ensure temporary security
AC specific	
Line lock	EV sends charging cable lock status and EVSE responds with lock status in the EVSE charging cable
DC specific	
Cable check	EVSE reports current status
Pre-charging	Adjusts EVSE output voltage to the EV battery voltage
Current demand	Cyclic exchange of requested current from EV during charging
Welding detection	Requests a detection of a welded breaker in the EVSE
Terminate charging	Separate termination of charging for DC

using EXI (located in the codec folder[4]). Function calls are provided which simulate the transmission of IEC 15118 messages from the EV and the responses from the EVSE.

[4] A large part of the OpenV2G source code seems to be auto generated by various EXI tools that are not provided along with the code. The use of auto generated code makes sense, however, because it could become quite cumbersome to define all types manually in C when they are already defined using XSD in IEC 15118.

However, the OpenV2G code is still at an early stage (current version is 0.5) and lacks a lot of features when compared to the complete ISO/IEC 15118 standard. OpenV2G "only" defines the application layer messages and no lower layer functionality is provided such as socket-based TCP communication, session layer timeouts, SDP, TLS, certificate management, XML Security, and related functionality.

5.3.2 *Communication Technologies*

5.3.2.1 Network Segmentation

Both the NIST and the IEEE communication models consider different network segments within the scope of smart grids. One possible criterion for segmentation can be based on the functional areas of the electric power system: generation, transmission, distribution, and end customer.

A WAN is typically defined integrating all entities participating in the transmission segment, which may include bulk generators, HV/MV substations, and transmission operations entities. Similarly, a FAN is defined aggregating entities participating in the distribution segment, including HV/MV substations, MV/LV secondary substations, and End Customers. A local area network (LAN), typically in-building, can be associated to customer premises (Premises Networks), interconnects devices, which may include loads, microgeneration, and EVs. These LANs can have specific designations such as home area network (HAN) or even industrial area networks (IAN) due to their usage in domestic or industrial buildings.

It is also usual to aggregate part of the FAN, specifically the segment below the MV/LV secondary substation, and the HAN/IAN, defining what is also known as Last Mile or utility access network (UAN), as illustrated in Fig. 5.20. This aggregation is mainly due to the number of nodes that potentially can participate in exchanging information. This segment covers a geographic distance generally below 2 km.

Besides functional reasons, network segmentation may also take into account geographical, administrative, physical, or logical criteria, which have an impact on technological choices and solutions. It is usual to consider the need for back-haul networks that bridge the gap between access/last mile networks and a WAN backbone. The boundaries between such networks is not always clear, since in some cases they may share a common infrastructure and interworking systems may operate at different protocol layers, acting as repeaters, data concentrators, routers, or even application gateways. In the access or last mile segment the distinction between different networks (according to the type of devices they interconnect or the applications they support) may be enforced at the physical level, by using separate infrastructures (possibly of different technologies), or by a logical separation over a shared infrastructure.

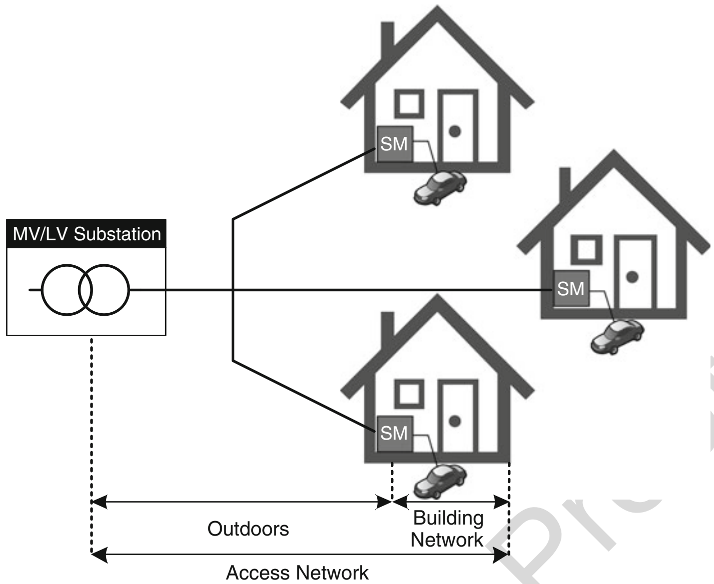

Fig. 5.20 Access network

5.3.2.2 Communications Technologies and Services: Main Options

Since the deployment (and evolution) of such networks may occur at different evolutionary steps of the electric grids, coexistence of different communications and networking technologies is not only natural but maybe even necessary, provided that seamless interworking is planned from the outset.

For the scope of this analysis, the choice of communications technologies and services may be classified along two axels: on one hand, the use of public or private networks and services and, on the other hand, the use of wired or wireless technologies.

The use of services provided by telecom operators (over their copper, fiber, or cellular networks) is usually a matter of concern for the electric utilities, since they do not have any control over the service provided, which may not guarantee security, availability, reliability, and performance levels required by critical applications. However, since these are commercial services, they may be subscribed to fulfill specific objectives (for example, for some noncritical applications or as a back-up solution).

On the other hand, the deployment by the electric utilities of private networks in the backbone and back-haul segments has been common practice over the past years—using either optical fibers, copper or, more recently, wireless technologies (such as WiMAX) in point-to-point or multipoint configurations.

For the above reasons this debate is focused on the use of private networks in the last mile segment, for which the solutions are still quite open, in terms of research challenges as well as opportunities for the different players involved.

The option for wired technologies reduces, in practical terms, to using the existing power lines as the communications medium, since deploying a new private infrastructure (fiber or copper) seems unfeasible, at least in the short to medium term, and there is no evidence that such an option is being considered by the utilities.

PLC is already being used in the narrowband variant, which offers modest rates (up to a few dozens of kbps). Although this may be acceptable for smart metering, the adverse characteristics of the PLC channel may introduce severe limitations even for this application (particularly in dense urban areas with hundreds of meters attached to the same broadcast channel), let alone for future smart grid applications. The recently approved IEEE 1901 standard (BPL—Broadband over power line) promises throughputs in the order of hundreds of Mbps, and thus is a new candidate to be considered and evaluated for medium-to long-term adoption, as the technology matures.

In the meanwhile, wireless technologies have started to emerge as a feasible alternative to PLC, as reflected in a number of initiatives led by standards bodies, research projects, utilities and manufacturers, as well as in pilot trials that have shown promising results. However, when short range wireless technologies are used, extending the coverage area requires relaying data over multiple hops and thus deploying multiple access points (nodes), organized as a wireless mesh network (WMN).

Both PLC and its variants and the currently available wireless technologies and solutions like WMNs will be addressed in the following sections.

5.3.2.3 Power Line Technologies

PLC has been used for decades in the utility industry for remote metering and load control applications [20]. In recent years, smart grid activities as well as advances in building and home automation have brought a lot of attention to PLC technologies as an alternative to unwanted or impractical wiring. Also, PLC technologies are becoming more advanced and promise to achieve data rates up to 1 Gbps [21].

However, the objective might not always be a matter of applying advanced modulation technologies to achieve higher data rates. Power lines are inherently exposed to time-frequency-varying noise, unmatched loads, and interference from similar equipment. At the same time, national legislation puts an upper limit to the allowed transmission power and accepted frequency bands. For these reasons, a large number of PLC technologies have evolved; each addresses different applications and specifies different target throughputs, frequency bands, and channel access mechanisms.

This section will address PLC from a technological point of view approaching the different implementations (narrow, wide, and broadband) and the targeted segments of application within Smart Grids. The supporting standards will be mentioned along with the major characteristics of each PLC application.

Narrowband Power Line Communication

The narrow band PLC (NB-PLC) is typically distinguished between low-speed and high-speed versions. The narrow-band high-speed version is also referred to as medium-speed implementation.

The narrowband frequency range is typically between 3 and 500 kHz while the wideband region ranges from 2 to 30 MHz. The narrowband region can be further divided into legally allowed frequency bands depending on continent or country:

- In Europe, CENELEC has standardized the allowed use and width of the frequency bands from 3 to 148.5 kHz. This is described in EN50065-1. The bands are further subdivided, which are generally known as "CENELEC bands"[5]:
  - Band A: 3–95 kHz. Only utilities are allowed to use this band.
  - Band B: 95–125 kHz. All may use this band.
  - Band C: 125–140 kHz. All may use this band when using CSMA.
  - Band D: 140–148.5 kHz. All may use this band.
- In USA, the FCC has established the use of band ranges from 10 to 490 kHz.
- In Japan, the ARIB defined band ranges from 10 to 450 kHz [22].

Besides the allowed frequency ranges, there is also a maximum allowed transmission power in each range that must be respected.

The first generation of PLC implementations made use of single or double carrier transmission schemes with simple modulation schemes like PSK and FSK to achieve only a few kbps towards usually remote metering applications.

G3 and PRIME are two non-SDO second generation NB-PLC technologies that focus on smart meter communication. They both use an OFDM-based modulation technique, but subtle physical layer details make the two technologies differ a bit [23]. As a general rule, PRIME achieves higher data rates while G3 has a more powerful error correction algorithm that increases reliability [23]. As seen from a higher layer perspective, the two technologies are similar. Data rates for the CENELEC A band are maximum 33 kbps for G3 and 128 kbps for PRIME.

G3 is maintained by the G3-PLC Alliance,[6] whereas PRIME is maintained by the PRIME Alliance. Both G3 and PRIME are available as open industry standards.

Even though G3 and PRIME are targeted at smart meter communication,[7] EV communication is also a valid application. As stated earlier, one of the main advantages of using narrowband communication is the usage of a dedicated "utility frequency band" and physical and MAC layers implemented in DSP software. For

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[5] A total frequency range from 3 to 148.5 kHz is available for utilities whereas for end-user application the 95 to 148.5 kHz band is available.

[6] http://www.g3-plc.com.

[7] Recall that EVSEs typically contain an energy meter, which might be relevant to communicate with using G3 or PRIME. This communication might be completely separated from the EV to EVSE communication link.

this reason, companies have implemented point-to-point variants of G3 and PRIME, which are designed to communicate between two nodes, for example between an EV and an EVSE. The frequency range used in G3 can also be extended beyond the CENELEC A band to achieve higher data rates.

However, neither G3 nor PRIME was originally designed for EV/EVSE communication and they are not SDO-based. These two facts render it uncertain that they can be used without modification to the standardization work in ISO/IEC 15118-3. The IEC Smart Grid Standardization Roadmap report [24] published in June 2010 states that several communication media are being evaluated for ISO/IEC 15118-3, including G3, PRIME, HomePlug GP, and others. Therefore, it is still uncertain which PLC variant will be chosen for EV/EVSE communication.

The International Telecommunication Union (ITU) defined G.HNEM project to address home networking for energy management using high-speed OFDM NB-PLC. One of the objectives of ITU Telecommunications Sector (ITU-T) in this project was to develop a unified next generation NB-PLC. It integrates some features from PRIME and G3 which are complemented with coherent reception, enhanced protection against power line impulsive noise, multiple bands for worldwide compatibility, adaptive medium access rules, and support for multiple network protocols [25]. In this project the ITU-T targets applications such as AMI (residential or business), in-home automation and energy management (DR and Smart Appliances), and EV charging. Recommendations G.9955 and G.9956 are part of G.HNEM and define respectively the physical layer and data link layer. At the physical level CENELEC and FCC bands are supported, with up to 16QAM subcarrier modulation that enable rates up to 1 Mpbs. Forward error correction (FEC) codes are used to improve robustness against noise. The medium access method used is a prioritized CSMA/CA. Automotive support is provided allowing operation over main and pilot wires [26].

An emergent standard for narrow band PLC is P1901.2 being developed by IEEE since 2009. Defined as a low-frequency OFDM-based narrowband power line standard for smart grid applications, it is set to use frequencies below 500 kHz and data rates up to 500 kbps, supporting indoor and outdoor communications. In the outdoors scope this standard targets the use of MV and LV distribution networks for both urban and long-distance rural feeders, defining a communication medium for the WAN and FAN segments, ensuring connectivity between the electric grid and the end customer (through the smart meter). In the indoors scope the standard is an alternative technology for HAN applications. One particular application targeted for P1901.2 is the electric vehicle charging, for potentially charging stations and charging infrastructure.[8] One particular key aspect seems to be the coexistence philosophy, defined by NIST in Priority Action Plan 15, being adopted by IEEE. It aims at providing the required mechanisms to allow this technology to coexist with PRIME and G3, similarly to ITU-T within G.HNEM (G.9955 and G.9956).

[8] http://standards.ieee.org/develop/project/1901.2.html.

Broadband Power Line Communication

The cradle of broadband PLC implementations was the domestic environment as a technological alternative to enable Internet services to end user customers through existing power lines. The use of Broadband over Power Lines has been employed using different technologies and approaches and recently has been considered to be used outside the building environment, in what was previously referred to as Access Network.

The wideband frequency range is generally available worldwide for all purposes except in Japan, where it is illegal to use PLC in this frequency range. Technically the upper limit to wideband communication is usually dictated by the minimum communication distance and the use of TV broadcast signals above 80 MHz. Some wideband solutions use a frequency range up to 60 MHz. Naturally, a larger frequency band permits a higher number of OFDM subcarriers and thus yields higher theoretic data throughputs, although this also depends on the modulation format in the individual subcarriers. For wideband PLC a high number of subcarriers in a frequency bandwidth of 28 MHz (2–30 MHz) can be used, depending on the standard [23], compared to a narrowband where the typical number of subcarriers in the CENELEC bands is around 36 [23].

A particular implementation of BPL is HomePlug which is targeted at the domestic environment. Developed by a non-SDO industrial grouping, the HomePlug Power Alliance is responsible for the development of different versions. HomePlug defines MAC and PHY layers.

In 2001 HomePlug 1.0 was made available using DBPSK and DQPSK modulations with different FEC mechanism to achieve data rates near 14 Mbps [27]. The variant HomePlug AV [28], released in 2005 and targeted at high quality multi-stream data over power lines, uses flexible modulation schemes ranging from binary phase shift keying (BPSK) to 1024-QAM. Using FEC mechanisms along with ROBO or Adaptive Bit Loading, it enables up to 10 and 200 Mbps data rates at physical level. The HomePlug Green PHY (GP) [29] released in 2010 is a recent version that targets PLCs for in-home smart grid applications. HomePlug GP is basically a scaled-down version of the HomePlug AV, since for domestic smart grid communication context a high data throughput is not paramount. The objective is not to achieve high-performance audio/video streaming or similar applications but rather to ensure reliable and good coverage communications. HomePlug GP does not support adaptive bit loading using only QPSK as ROBO modulation scheme, to ensure high reliability, achieving up to 10 Mbps [23]. The simplifications introduced in GP make it lightweight in terms of processing power, memory, and power consumption requirements when compared to HomePlug AV.

Since GP and AV use the same frequency band, they will naturally have to share the available time-on-wire (ToW). Both technologies use CSMA and can thus access the wire if no other devices transmit. This can lead to conflicts since consumer HomePlug AV equipment will then adversely affect HomePlug GP throughput and vice versa. The HomePlug GP specification tries to solve this issue by only allowing GP devices 7 % ToW, which equals an effective data throughput of 700 kbps (at 10 Mbps base rate). This is a compromise that must be accepted when using the GP technology.

On the other hand, the sharing of bandwidth and compatibility between HomePlug AV and GP enables smart grid communication to be a part of the HAN. Some auto manufacturers see this is an opportunity to easily connect EVs to the Internet and thus provide convenient features such as GPS map updates, car software updates, intelligent call for service, etc.

Another implementation of BPL, from an SDO, can be found on IEEE 1901 standard, which defines the MAC and PHY layer for high-speed communications over power lines (>100 Mbps). The standard defines two MAC layers, targeting respectively in-home and access networks (over MV and LV distribution lines), with different requirements and potential applications. It defines two PHY layers based on different modulation schemes: one based on FFT OFDM (FFT-PHY) and another on Wavelet OFDM (Wavelet-PHY). These two implementations are not compatible and manufacturers can implement only one of them or both. The FFT-PHY can use up to 1974 carriers from 1.80 to 50 MHz with different subcarrier modulation from BPSK up to an optional 4096-QAM. The Wavelet-PHY uses 512 subcarriers within the 1.8–28 MHz band using M-PAM modulations (up to 32-PAM). Robust signaling schemes and FEC mechanisms are used to ensure resilience over the transmission medium [30].

ITU-T has also defined in 2010 a broadband PLC for home networking (G.hn) with the purpose of supporting smart grid applications such as AMI and energy management for electric vehicles. This technology can be used for robust in-home or in the last mile of the access network. It comprises the definition of the physical layer, in G.9960, and data link layer, in G.9961. It defines an OFDM transmission technique and two frequency bands: one ranging from 2 to 100 MHz with up to 1 Gbps data rate at the physical layer; and another band between 2 and 25 MHz within a Low Complexity Profile definition with data rates between 5 and 50 Mbps. Robust transmission schemes, FEC mechanisms, and repetition encoding are used to address the power line medium [31].

PLC for Smart Grids

In a smart grid context, both narrowband (high-speed) and broadband PLC technologies can be used. Both versions use multicarrier-based[9] encoding formats, the predominant being OFDM that use different modulation schemes for the subcarriers.

[9] Many (older) technologies are single-carrier based, but these are not applicable in an SG or EV context [20].

Despite implementations of wideband PLC, there are still some reasons to use a narrowband implementation[10]:

- Narrowband communication has a much larger geographical coverage than wideband, and some narrowband technologies are capable of passing through local distribution transformers. This is a huge advantage in, for example USA, where only a few households are connected to each (pole-top) transformer. This essentially deprecates wideband communication for smart meter communication. Currently, around 100 million narrowband PLC smart meters have been deployed [20] and the future potential is huge.
- Regulations limit the use of wideband PLC in some countries, e.g., Japan. The only worldwide available frequency band is the CENELEC narrowband.
- Narrowband has dedicated frequency bands not used by consumer PLC electronics in the HAN. This comfortably ensures that consumer PLC products do not adversely and unpredictably affect noise and data throughput for smart grid-related communication purposes.
- Narrowband solutions are still cost-effective when compared to the broadband counterpart since in general they require less demanding HW implementations.
- Not all applications require high data throughput.

On the other hand, wideband solutions can be preferred for the following reasons:

- Achieves higher data throughputs when the data is only transmitted over a short distance, e.g., in a HAN. In general, wideband PLC is the only practically acceptable solution for a HAN (other than wireless and dedicated wiring).
- More than 45 million devices use HomePlug-based devices [23], so it is almost as widespread as narrowband PLC solutions and the future potential is huge. A large number of wideband PLC devices are available off-the-shelf.
- There is generally less noise in the 2–30 MHz frequency range. One reason is the low-pass filters in, for instance, switch mode power supplies that attenuate high-frequency noise. This makes it easier to achieve high data rates.
- Using recent wideband PLC advances in, e.g., HomePlug GreenPHY, robust modulation formats (known as ROBO) have shown to increase transmission reliability at the expense of lower data rate. However, the data rate can still be up to 10 Mbps [23].

This shows that the choice between narrowband and wideband PLC is not straightforward and must be assessed on a case-by-case basis.

For the particular case of EV/EVSE PLC communication, it is obvious that the communication distance to the HAN is small and thus a wideband solution might be viable, which will also yield high data rates. On the other hand, EVs and EVSEs should clearly be a part of the future smart grid communication infrastructure and

[10] Adapted from [20].

thus a narrowband solution that is separated from consumer (wideband) PLC solutions and that is able to communicate directly to utilities or aggregators might be preferable.

5.3.2.4 Wireless Technologies

We start by briefly analyzing the main advantages and limitations of using wireless technologies in the last mile segment, which includes devices located in critical points of the electric grid, such as sensors and controllers, and in end-users premises, such as smart meters, as well as traffic aggregators and concentrators located in transmission and distribution substations.

Among the main advantages we can mention the low cost and ease of installation, maintenance and future expansion, support for mobility and interoperability, as well as flexibility, since the location of access points (nodes) that provide wireless access to end devices is not constrained by an existing physical infrastructure, as in PLC. However, the location and number of such wireless nodes may require a careful planning to overcome potential problems that typically arise in WMNs, as will be discussed.

The main disadvantages of adopting wireless technologies are related with the adverse characteristics of wireless channels (bit error ratios are much higher than in guided media), which are aggravated by the time varying conditions of the channels and interference.

On the other hand, different technologies are quite different as far as cost, coverage (which, among other factors depends on the maximum allowed emission power), spectrum (free or licensed bands), available bandwidth, and how it is shared (which impacts the useful throughput, both aggregate and per user). Some of these problems are aggravated in WMNs, as said; nevertheless, WMNs also have some interesting properties that make them suitable for smart grid environments. Moreover, there are also some challenges as far as performance, interoperability, and security that have to be addressed.

IEEE 802.11/Wi-Fi

The IEEE 802.11 group has specified over the past years a set of standards [32] for low cost wireless LANs with the aim of providing a service similar to wired Ethernets. Two modes of communication are possible: in the infrastructure mode the stations communicate through an Access Point (AP) typically connected to a wired network, while in the ad hoc mode the stations communicate directly without the intervention of an AP.

Multiple alternatives are available at the Physical Layer, either employing direct sequence spread spectrum (DSSS) or orthogonal frequency division multiplexing (OFDM) in the 2.4 and 5 GHz non-licensed ISM (industrial, scientific, and medical)

Table 5.4 IEEE 802.11 variants

	802.11	802.11a	802.11b	802.11g	802.11n
Bandwidth (MHz)	20	20	20	20	20/40
Frequency band (GHz)	2.4	5	2.4	2.4	2.4/5
Number of channels	3	12	3	3	Up to 13
Modulation	BPSK, QPSK DSSS, FHSS	BPSK, QPSK MQAM, OFDM	BPSK, QPSK DSSS	BPSK, QPSK MQAM, OFDM	BPSK, QPSK, MQAM
Maximum rate (Mbps)	1.2	54	11	54	600
Maximum range (m)	–	30	75–100	75–100	150–180
MAC Protocol			CSMA/CA		

bands. At the MAC layer a carrier sense multiple access with collision avoidance (CSMA/CA) protocol is adopted. The IEEE 802.11n amendment [33] introduced improvements at the Physical layer that allow a higher throughput and coverage than its predecessors. Other IEEE 802.11 documents address specific aspects, such as security improvements (802.11i), support for Quality of Service (802.11e), WMNs (802.11s), and vehicular communications (802.11p).

The IEEE 802.11standard is promoted by the Wi-Fi Alliance [34], which has favored the widespread availability and deployment of this technology, at low cost; it is thus becoming ubiquitous in traditional LAN environments, hot spots, and making progress into wider areas that may include traditional last mile scenarios.

The principal characteristics and differences of the IEEE 802.11 variants are summarized in Table 5.4.

IEEE 802.15.4/ZigBee

The IEEE 802.15.4 standard [35] was specified for low-data-rate, low-power, and low-complexity short-range radio frequency transmissions between devices in wireless personal area networks (WPAN). These networks include full-function devices (FFD) that may operate as coordinators (which are devices capable of relaying messages) and talk to any other device, and reduced-function devices (RFD), which are intended to run simple applications, may have power constraints, and can only talk to an FFD.

The standard specifies the physical and MAC layer functions and protocols. The physical layer is based on the DSSS technique combined with different modulation schemes, on different bands. In particular, in the ISM 2.4 GHz band, offset quadrature phase shift keying (O-QPSK) is employed, achieving a rate of 250 kbps. At the MAC layer, CSMA/CA is adopted.

The standard defines two topologies. The star topology is established between RFDs and the PAN coordinator, which is an FFD. In the distributed peer-to-peer topology devices can communicate directly, provided they use the same radio channel; this allows more complex configurations, such as mesh structures, which are useful for example in sensor networks or in monitoring and control applications (interconnection of smart meters falls in this category).

The ZigBee Alliance [36] is promoting the use of networks based on this standard, having defined a complete stack on top of the IEEE 802.15.4 Physical and MAC layer services.

IEEE 802.16/WiMAX

The IEEE 802.16 standard [37] specifies the Physical and MAC layers of the radio interface of combined fixed and mobile point-to-multipoint broadband wireless access (BWA) systems.

The MAC layer is structured to support different Physical layers suited for particular operational environment, in two frequency bands.

In the 10–66 GHz band, line-of-sight (LOS) is required; single carrier modulation is adopted, typical channel bandwidths are in the order of 25 MHz, and raw data rates in excess of 120 Mbps are possible. Both frequency division duplex (FDD) and time division duplex (TDD) modes are supported.

In the frequency bands below 11 GHz LOS is not required and different alternatives are specified, both in licensed and license-exempt bands. In the latter case the 5–6 GHz range is primarily used and additional interference and compatibility issues and radiated power constraints are taken into account. Both OFDM for fixed wireless access and OFDMA (orthogonal frequency division multiple access) for fixed and mobile systems are specified, with both duplexing alternatives (FDD and TDD), and typical channel bandwidths of 10 and 20 MHz. The maximum channel rates depend on various factors (radio technology, duplexing mode, channel bandwidth, distance) but values in the order of 140 Mbps are achievable. Channel rates more than double with improvements at the Physical layer and antenna design, according to IEEE 802.16m amendment that is intended for an advanced air interface.

The WiMAX Forum [38] certifies and promotes the compatibility and interoperability of broadband wireless products based upon the IEEE 802.16 standard.

Wireless Mesh Networks

Among other possible applications, WMN are used as a means of extending the wireless coverage of single hop networks and provide access to infrastructure networks (either wired or wireless). The requirements of last mile smart grid networks may fall in this category and thus WMNs are currently being considered as a feasible and promising alternative to PLC.

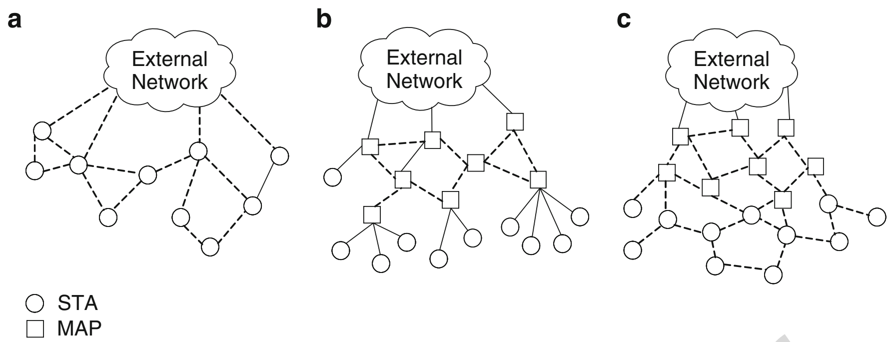

Fig. 5.21 Wireless mesh networks topologies

In the simplest case, a WMN may be formed by end-stations (STA) only. However, a more structured, robust, and scalable solution is possible if the wireless network is organized in two tiers: at the higher level a set of mesh access points (MAP) are interconnected in a mesh fashion, forming a wireless mesh backbone, while the end-stations reside at the lower level and communicate with a neighbor MAP to gain access to the network. The higher level is in fact a cooperative mesh network that enables information to be relayed between source and destination nodes; one or more MAPs act as gateways to external networks. As a third alternative, MAPs and end-stations may form a hybrid mesh network. These three arrangements are depicted in Fig. 5.21.

When WMNs are used as an infrastructure extension, the internal traffic between MAPs is limited since the main services are usually provided by external networks, with a considerable amount of information exchanged through a gateway MAP. In smart grids the expected traffic patterns seem to be compatible with such type of WMN—traffic aggregation is performed along the path towards a gateway MAP, which is the concentrator point for the traffic exchanged with external networks.

Since these networks are meshed by nature they offer a degree of redundancy and thus robustness in the data path in case of a node loss or link quality degradation, either temporary or permanent. As such, routing algorithms must take into account the proper metrics to deal with these issues, by dynamically adapting to topology changes or varying channel conditions in order to determine the best routes. The use of complex routing schemes at the network layer can have a beneficial impact, especially in the case of non-homogenous data traffic patterns, but at the cost of introducing additional overheads, when compared to its implementation at the data link layer. In the latter case, the use of bridging techniques implies that packets are simply forwarded by mesh nodes along a logical tree; this simplification comes at the price that the routes followed by some packet flows may not be the best ones. However, this drawback does not arise when most of the traffic is exchanged between end devices and external networks. This is the typical situation in smart grids and thus the use of bridging techniques may be an advantage in case WMNs are adopted in this environment.

However, WMNs also have some drawbacks that must be solved or mitigated through additional mechanisms on top of the native MAC service provided by the specific wireless technology adopted.

In shared medium wireless networks such as IEEE 802.11 and 802.15.4 competition among end devices is handled by the CSMA/CA contention-based mechanism. However, collisions may still occur and trigger retransmissions that cause additional delays; under heavy traffic this may lead to serious throughput degradation, uncontrolled delays, and even losses.

The multi-hop nature of WMNs introduces new challenging problems. In the first place, the existence of multiple hops in the data path means that delay increases with the number of hops; moreover, when most of the traffic is exchanged through a gateway, competition for wireless resources and the risk of congestion are higher in nodes closer to the gateway, because they have to forward all aggregated traffic generated by upstream nodes. This not only causes additional throughput degradation but also unfairness among nodes, since nodes farther away from the gateway have to contend for the channel a higher number of times—besides a higher delay, they may suffer severe throughput degradation and even starvation, since successive collisions on each hop contribute to a higher probability of packet loss. These problems may be attenuated if it is possible to reduce the number of hops by means of carefully planning the location of mesh nodes.

But WMNs introduce an additional problem, not found in wired store-and-forward networks. Besides inter-flow interference, collisions also occur due to intra-flow interference; spatial contention extends beyond one hop distance and thus only one packet of a given flow can be successfully transmitted within a neighborhood region of the sending node. This contributes to further reducing the capacity of a WMN and thus requires exploitation of spatial reuse techniques to optimize the use of wireless resources, which is not trivial.

The practical exploitation of WMNs thus requires solving a number of problems deeply analyzed in the literature, such as fairness [39], scheduling schemes (with, for example, fair sharing [40, 41] or resource optimization [42] as the main goal), cross-layer mechanisms (that combine scheduling with congestion control [43]), etc.

The use of WMN in a smart grid context has a few characteristics that can simplify the implementation. First of all, there is no mobility inside this kind of networks; once an end device or mesh node is deployed for the first time it is very likely to stay at the same position for a long time. Second, since most of the end devices are part of an electric network there are almost no constraints regarding power supply, although a blackout might require a battery backup even if for short periods of time. Third, the adoption of a two-tiered approach may require a limited number of mesh nodes and a moderate number of hops in the data path and thus the need for less complex overlay mechanisms than those required in large WMNs. Fourth, it requires the roll-out of simpler and less costly infrastructures (for instance, based on IEEE 802.11, possibly combined with IEEE 802.15.4), when compared with other solutions, such as WiMAX, for example, which is best suited for point-to-multipoint communications in back-haul networks.

5.4 Conclusions

This chapter addressed ICT solutions and supporting communications for Smart Grids that will enable the integration of different players and entities such as the EV.

It is clear that the ICT foundation already exist to start supporting diverse SG concepts and applications tailored for EVs. ICT implementations need to account for the requirements for different applications and consider different models and scenarios as described in this chapter. Despite the lack of a general solution for SG, the combination of existing technologies for different segments, paired with specific solutions, is already able to address SG communication requirements.

The deployment of smart grids is an evolutionary process and the planning, design, deployment, and operation of ICT solutions for smart grids must take into account the full scenarios even if only a subset of functions are initially supported.

The importance of interoperability between devices from different manufactures is also clear, in order to ensure expansion capabilities in the future, with seamless integration of new systems and applications.

Except for very specific cases, the rule should not be designing and optimizing solutions for specific applications, but rather a globally integrated approach should be taken into account—sharing information and communication resources is not only more efficient but also eases interoperability in integration, thus saving costs.

Interoperability at the IP level is the current trend—in particular IP is agnostic to the underlying communication technologies and supports a wide diversity of applications.

It is likely that in a smart grid environment, in particular in the last mile segment, a diversity of communications technologies will be adopted since:

- Diversity minimizes risks.
- Different technologies may coexist and complement each other, benefiting from their abilities to handle specific problems (e.g., different technologies and solution may be adopted in rural areas as opposed to dense urban zones).
- Emerging and future technologies will be introduced as they mature, either coexisting with legacy ones or replacing them.

Currently there is a need for pilot trials to evaluate and compare solutions based, among others, on performance, cost, scalability, flexibility, and robustness, to better understand open issues and to help defining a roll-out strategy.

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A.2 Generating Geospatially Realistic Driving Patterns Derived From Clustering Analysis Of Real EV Driving Data

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***Abstract*—In order to provide a vehicle fleet that realistically represents the predicted Electric Vehicle (EV) penetration for the future, a model is required that mimics people driving behaviour rather than simply playing back collected data. When the focus is broadened from on a traditional user-centric smart charging approach to be more grid-centric, it suddenly becomes important to know not just when- and how much the vehicles charge, but also where in the grid they plug in. Since one of the main goals of EV-grid studies is to find the saturation point, it is equally important that the simulation scales, which calls for a statistically correct, yet flexible model. This paper describes a method for modelling EV, based on non-categorized data, which takes into account the plug in locations of the vehicles. By using clustering analysis to extrapolate and classify the primary locations where the vehicles park, the model can be transferred geographically using known locations of the same classification.**

I. Introduction

One of the driving forces behind the Danish EV effort is the idea of using the batteries in the vehicles to balance out the fluctuations in the production, which is caused by a growing amount of wind power being produced in the country. The current wind penetration has already exceeded 30%, but with the government aiming for a fossile free production by 2050, the wind penetration is expected to reach 50% already by 2020.

Past projects like the danish funded EDISON project has already investigated Electric Vehicles (EVs) in relation to increased wind penetration, and currently the larger EcoGrid EU demonstration project is aimed at showing exactly this; a prototype powersystem with 50% renewable production [9][10][11].

The primary mechanism in the EcoGrid EU project is a socalled real-time electricity market, with a resolution of 5 minutes. In its most basic sense, an intelligent automated algorithm receives information about the current consumption from smart meters throughout the grid. Based on the current electricity price and the grids perceived need for up- or down regulation, it transmits a price to the customers that is meant to induce the necessary reaction. The general case works on a larger segment of the grid, but the next step would be to have locational prices [14].

Since EVs have yet to start selling in numbers that will cause them to rival existing Internal Combustion Engine (ICE) vehicles, it has been necessary to develop simulations to try to predict their impact on the grid. Since most, if not all, of these simulation have focused on the combined load, the EVs have often been modeled in a cumulative fashion. This technique works well for determining things like the day-to-day load imposed by a vehicle fleet, but does little to help determine the low-level impact such as the congestion you would likely see on a local feeder, should too many in the neighborhood decide to invest in an EV. The main purpose of a vehicle will always be transportation, hence it is also necessary to model the locational side of this behavior, if one wishes to realistically determine the local grid loads that result from an increased EV penetration. Knowing not only the daily consumption of a vehicle, but the detailed movements thereof, is a good platform for investigating both congestion preventive charging algorithms but also more user-centric services, such as route prediction, which could aid in facilitating e.g. automatic reservation of charging stations etc.

Many existing EV simulations, besides being cumulative, calculate the consumption based on an average efficiency and an expected daily driving distance. The method propsed in this paper uses recorded EV charging locations, which, through a clustering analysis, is partitioned into typical categories such as *home* and *work*. When identified, the identified locations can either form the basis for the simulation, or be translated elsewhere using existing databases of categorised addresses. Because the model incorporates actual locations, it is possible to create feasable routes using existing routing engines as is known e.g. from GPS navigation. This can provide a more realistic, not to mention flexible, consumption pattern. For example if a vehicle owner lives and works close to a major freeway, the vehicle will more likely be travelling along at a higher average speed, which results in an increased consumption compared to an inner city commuter. Once the vehicles have been modeled in the geospatial domain, the next step would be to attach them to a grid- model to simulate the actual impact. This is, however, slightly outside the scope of this paper, but will briefly be touched upon in the final conslusion. Section II describes the dataset from the Danish “Test-en-elbil” project, on which the method in this paper is based. This is followed by a generic analysis of the data, looking into the availability of the EVs compared to findings of previous EV studies carried out on data obtained from ICE vehicles. Section III discusses the clustering of charge locations and the algorithms used along with various classification rules to obtain the desired result. Section IV describes the generation of the model(s) based on the clustering analysis. Section V wraps with a conclusion and a discussion of the next steps.

II. Data analysis

The Danish “Test-en-Elbil” (“Test-an-EV”) project, which lays claim to the title of Europe’s largest EV research project, was founded in 2010 by Clever A/S and is still ongoing [3]. The purpose of the project is to gain a better understanding of ordinary peoples driving styles and -habits when using EVs, and therefor puts great emphasis on logging how- and where the vehicles travel as well as charge. About 180+ Full Electric Vehicles (FEVs), predominantly belonging to a group of models commonly referred to as the “Triplets” (Peugeot iOn, Citroen C-Zero or Mitsubishi i-Miev), are currently used by the participants of the project. Everyone is free to requestion participation, but the ideal users for the project are families that fits the following profile:

- They must already own at least one vehicle.
- They must, to the extent permitted by the range etc., use the EV to cover all their everyday driving needs.

The chosen families are given the an EV for a duration of three months, after which the vehicle is returned. A multitude of measurements from the EVs are collected during the trials, some as fast as once per second, which are stored in the onboard computer before being uploaded to a server. Because some data, such as that from a Global Positioning System (GPS), is logged in a “raw” state, a certain amount of post-processing is required to partition this, so as to determine when the vehicles are driving, charging or just parked. This pre-analysis process is very helpful, since it allows the clustering analysis to easily focus on just the charging locations.

A. *Comparitive analysis*

In the past, other data collection projects have been carried out in Denmark which have been focused on ICE vehicles, since it was the only thing on this scale available at the time [2]. Interesting questions like consumption in relation to EVs would be speculative at best, but one question that was sought answered was how much time the vehicles stayed parked throughout the day. These numbers are very important from the grid side perspective, since they directly speak of how available the EVs are to potentially participate in balancing. Time parked is of course only an indicator to the true availability, but since an EV’s battery is only accessible for balancing when it is plugged in, this is very important. While the data did not allow for the distinction between merely plugged in and actually charging, it was not possible to determine how often the vehicles in fact were grid connected. For this reason, the assumption was made, that when parked (i.e. not driving), the vehicle is grid connected. Many ideas, projects and businesses are addressing ways to incentivise users to plug in the vehicle whenever parked for a longer duration, but this is outside the scope of this paper. Before staring the clustering analysis an initial analysis of the pre-processed data was carried out, primarily to uncover whether there were any major differences between the previously analyzed ICE datasets and this, the first larger all-EV data set collected in Denmark. Previous studies carried out have found that the ICE vehicles were on average parked more than 90% of the time, and nearly all were parked during the critical night hours where the wind is usually most predominant [1][9][10]. The illustration in figure 1, which was borrowed from one such study, shows an overall availability of no less than 94%. This is presumably a result of most of the trips being of a relatively short duration, with little discernible overlap. The figure paints a picture of a typical commuter, with a morning trip to work around 8:00 and a homebound trip again around 16-17:00.

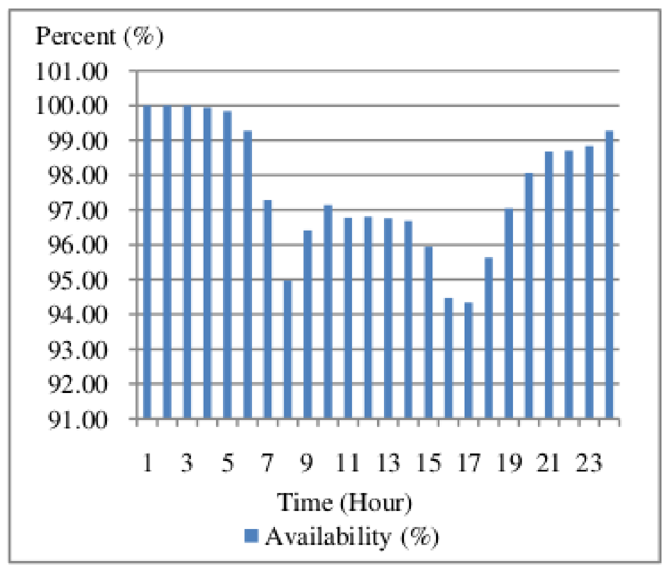

Fig. 1. Illustration of availability from ICE vehicle study (borrowed from [1])

To compare, the same analysis was carried out on the EV data from the “Test-en-elbil” project and the result, as seen in figure 2, shows an overall availability of at least 89-90% with an average of more than 96%. Not only is this in line with the previous findings for ICE vehicles, and because the availability it is not noticably higher, it seem to suggests that the test-drivers did in fact managed to utilized the EV to cover their regular driving needs. When looking at the weekday availability, two dips are clearly visible, resulting from the larger number of trips in the morning and afternoon, which are typically for people going to- and coming *home* from *work*. Since people generally go straight from *home* to *work*, but have a tendency to run other errands afterwards, the afternoon dip is noticeable larger.

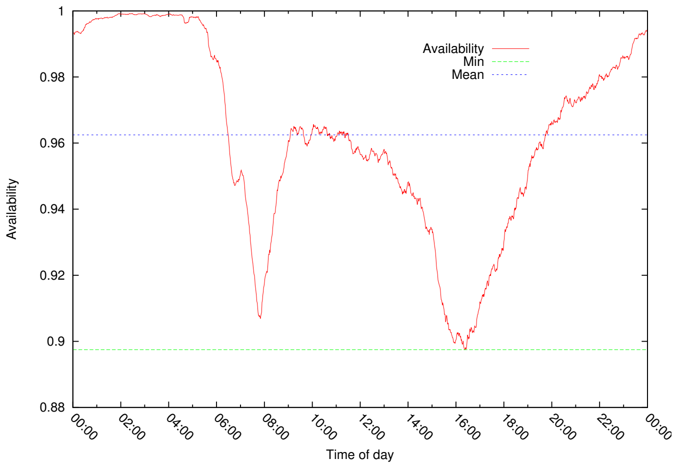

Fig. 2. Illustration of the overall availability on a weekday.

When observing the weekdays individually (not shown here), there is also a clear difference between Monday through Thursday and then Friday. Not surprisingly the weekend looks different, though still with an equally high availability. Since people are not going to *work*, but instead run errands throughout the day, there is only a single larger dip to be observed starting from around 10:00 and slowly leveling out throughout the late afternoon. As seen in Fig 3, which shows the weekday- and weekend availability overlaid for the sake of comparison, another noticeable difference is that weekday ends with a slightly higher availability. Considering that many people tend to visit friends, family and in general run late social errands, this is perhaps not surprising.

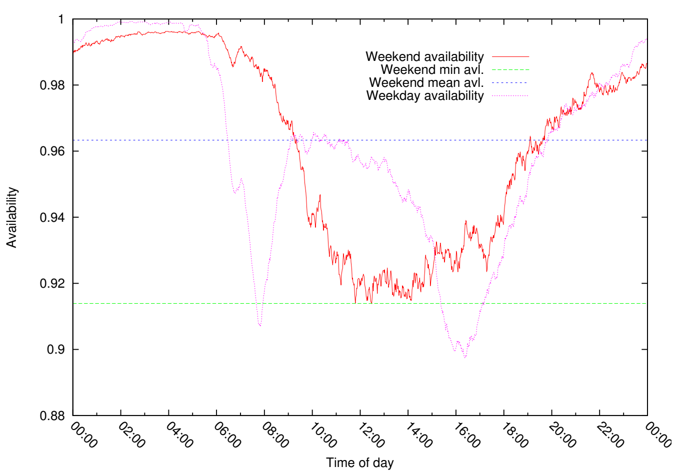

Fig. 3. Overlay comparing the weekday- and weekend availability.

B. Conclusions

Generally, the trends observed from the EV data seems to support that of previous ICE studies. Because the availability is nearly as high as for the ICE vehicles, the EVs appear to be able to cover most of the regular driving needs for the users. On the other hand, with the avialability being so high, it also bodes well for their reliability in relation to grid balancing. Since the vehicles in the project change hands every three months, it can be difficult to filter out any initial "enthusiastic" driving, which would differ from the normal routine. There is not much that can be done about that at this stage, but a record of their normal driving behavior, prior to receiving the keys for the EV, could be beneficial to work as a baseline. An interesting observation from the initial analysis of the dataset, was a somewhat large number of very short trips, lasting as little as e.g. 10 seconds. Initially it was thought to be a data-logging error, but when noticing similar trends in the logs for other EVs on the local campus, it was discovered that the likely reason is people briefly turning the ignition key to see the State Of Charge (SOC). Not counting online access, like what you will find in e.g. a Nissan Leaf, perhaps other OEMs should consider adding a function for retrieving this information without having to turn the key.

III. Geospatial clustering

In order to be able to efficiently map the derived model to known addresses, the locations from the dataset have to be classified in order to identify if it is *home*, *work* or *other*. A dataset for a real-world vehicle will inevitably contain a lot of noise. In the case of GPS, assuming tracking itself is accurate, the noise in the data consists of scattered locations, which the vehicle visited few- or sometimes just once. figure 4 shows a sample of data for a vehicle, which has visited the same location several times.

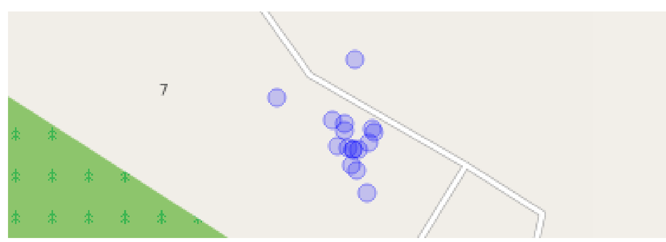

Fig. 4. Sample showing the error in precision typically observed in GPS measurements.

Because of this error induced dispersal it is necessary to perform an additional cluster analyses in order to determine which measured locations are really part of the same true location.

A. Clustering algorithms

The initial approach for deriving the number of clusters, i.e. the number of classified locations in the set, was to utilize the K-means algorithm [4]. The problem with the K-means algorithm is that it tries to force data into a pre-specified number of clusters, which is not ideal when this number is unknown. The resulting process is a brute force attempt at solving the problem, whereby testing for different numbers of clusters while observing an error-function, eventually results in the actual number. Suffice to say this process can take a little time, especially when looking at larger dataset. K-means has another downfall, which is that it is not very well suited for classifying clusters of data that are not uniformly separated. This should, however, not constitute a problem when attempting to classify groups of GPS coordinates, as they will usually be grouped in a uniform manner. As a better alternative to K-means, the DBSCAN algorithm, was considered, which has a somewhat different approach to identifying clusters [4]. The algorithm, which is a so-called density based algorithm, takes two parameters: the base clustering radius (usually denoted ϵ), which defines when locations belong to the same cluster, and the minimum number of points required to form a cluster (hereafter referred to as *MP*).

B. Choosing the parameters

Ideally, a location like e.g. *home* would always be represented by a unique location, but unfortunately the nature of GPS tracking is that it is somewhat imprecise and sufferes from a variying degrees of error. A typical example of this can be seen in figure 4. One way to go could be to derive a standard spread from recorded coordinates for a stationary real-world object and use that to derive ϵ. However, to make things a little easier and assuming that clusters have a certain degree of separation, ϵ was fixed to 0.1 (100m) since the main clusters like *home* and *work* are unlikely to be located that close to each other anyway. The basic assumption is that people will choose not to drive between locations that are in such proximity.

TABLE I
RESULT OF DBSCAN ANALYSIS ON CHARGING LOCATIONS FOR DIFFERENT CLUSTER MINIMA (*MP*).

DBSCAN clustering example			
	$\epsilon = 0.1$ *MP*=5	$\epsilon = 0.1$ *MP*=15	$\epsilon = 0.1$ *MP*=25
Classified noise	246	395	433
Cluster #0	209	199	195
Cluster #1	164	164	159
Cluster #2	44	40	33
Cluster #3	31	22	
Cluster #4	15		
...			
Cluster #18	5		

With ϵ chosen, a series of trials were carried out to determine a suitable *MP* that would result in the largest clusters. Depending on the chosen ϵ value, a larger *MP* could be restricting the formation of smaller initial clusters, which will then not have the opportunity to merge and become even larger clusters. Table I shows the number and size of the clusters for various values of *MP*, which seems to support this hypothesis. As expected, the smaller *MP* value results in a larger number of clusters. If the value of *MP* is too great, the number of clusters shrink, since more locations are not allowed to form clusters and are instead labeled as noise. Because the goal is to identify *home*, *work* and *others*, it is ideal to have at least two dominating clusters. Looking at table I, the smaller *MP* seems a better fit. After the clusters have been formed, a heuristic is employed to select- and classify the desired clusters. Figure 5 illustrates the intended goal, namely to classify the largest clusters. The left of the figure shows the unfiltered locations, the middle the result from clustering and the rightmost the largest clusters.

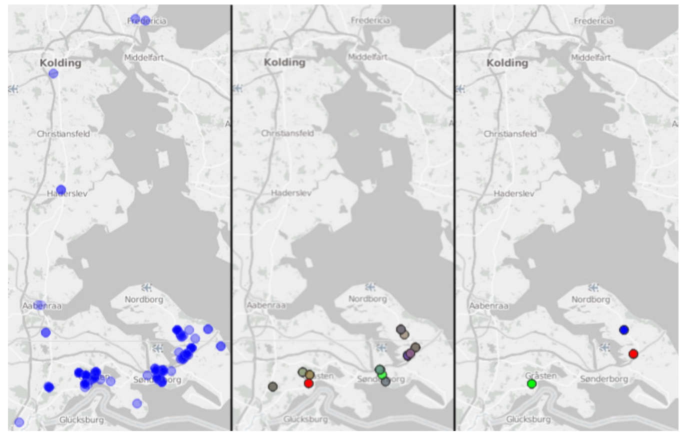

Fig. 5. Illustration showing first no clustering (left), then clustering with too small minima (middle) and lastly with suitable minima resulting in three distinct clusters (right).

Once the clustering analysis has been completed, the identified clusters have to be classified according to type. The heuristics used are as follows:

- The largest cluster and the one with the most stops spanning midnight is said to be *home*. If the two criteria results in different clusters, the dataset is abandoned in favor of better ones.
- The second largest cluster with an average stop-over starting time before noon is declared to be *work*. Of course some people work according to a non-A type schedule, but since it is tricky to verify the assumption here is "work before noon".
- The remaining cluster are characterized as *other*.

More complicated heuristics, to determine e.g. daycare were considered, but were left for future works to easy the initial implementation.

C. Conclusion

As seen in TABLE I, the scans with the smaller *MP* value seem to yield not only the greatest number of clusters, but also the largest individual clusters. The former is perhaps not that surprising, but one could be forgiven for expecting to see larger clusters for greater values of *MP* and not vice versa. Since a set of heuristics are employed for the final classification of the clusters, the smaller clusters will likely be filtered out, while the larger clusters remain. Because of this, the number of clusters is not as important as the size of the largest clusters, which is why a small *MP* is preferable.

IV. GENERATING THE MODEL(S)

A cumulative simulation often focuses on e.g. the total daily consumption and therefore settles for addressing when-and how much the vehicles are driven and not where. The proposed method takes a slightly different approach; since one of the main goals is the ability to provide virtual loads as inputs to a grid simulation, the vehicles need to transition between their typical plug-in locations. The basic model is based on a three state Markovian inspired stochastic process, with the two main states being *home* and *work*. Initial attempts have thus far failed to yield a good heuristic for individually classifying the remaining clusters, so for now they have collectively been labeled *other*. Activities that could belong to this group are shopping, sports, visiting friends etc. Given the nature of the data, it would be intuitive to model the state transisions based on the probabilities for the real-world vehicles to move between the identified clusters. This does, however, have one or two drawbacks. Because the aim is a simualtion that behaves not just statistically correct, but also mimics real driving behavior, adhering strictly to using the transition probabilities could result in undesired behavior.

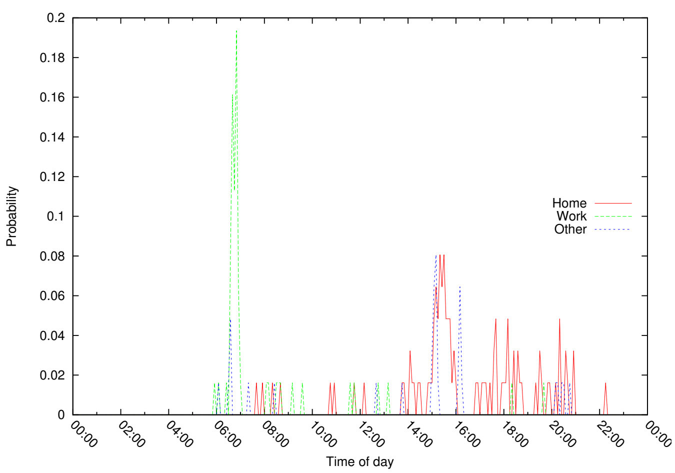

Fig. 6. Plot showing the probabilities of driving to the three primary locations.

Looking at figure 6, which shows the probabbilities of driving to the three different states respectively, one will observe a peak probability for driving to *work* in the morning. Later in the afternoon the probability of driving *home* increases, but starts to diminish from around the same time as the peak for driving to *other*. The behavior typically observed in real-life drivers is one that starts at *home* and ends at *home* again. With the probability of driving to *home* fading, so is the probability of the vehicle returning at the end of the day. For the real-life vehicles there are only a certain number of trips recorded on a daily basis, and most of them are recorded during the day. In fact, using the driving probabilities as basis for the model, it would become statistically unlikely that the vehicle would return *home* after approximately 22:00. Another less than realistic behavior that can arise from using the trip probabilities, mainly due to the greater fluctuations, is that the vehicle is more likely to jump eradically between locations. For example most people will arrive at work in the morning, will stay there for 7-8 hours and rarely leave to go shopping for an hour at random times during the day.

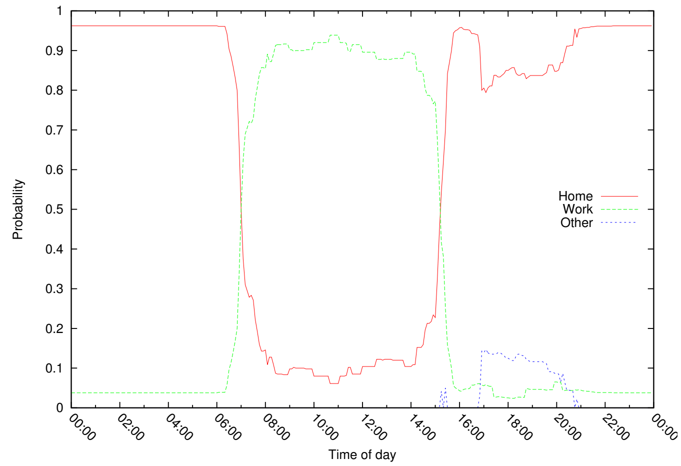

Fig. 7. Plot of the probabilities for being in the state of *home*, *work* and *other* for any given time during an average weekday.

As a more dependable alternative, the probabilities for being in a certain location at a given time of the day, were considered. The plot in figure 7 shows this probability for the three main states and compared to that of figure 6, it better reflects the intended behavior. The likelyhood of the vehicle being home in the beginning of the day is very high. At roughly 7-8:00 there is a shift from *home*- to *work* being the most dominant. In the late afternoon the probability of going elsewhere is highest and finally there is a much higher probability of the vehicles returning *home* at the end of the perceived workday. Since nearly all drives in figure 7 result in the vehicle returning *home*, it works much better as a basis for the model.

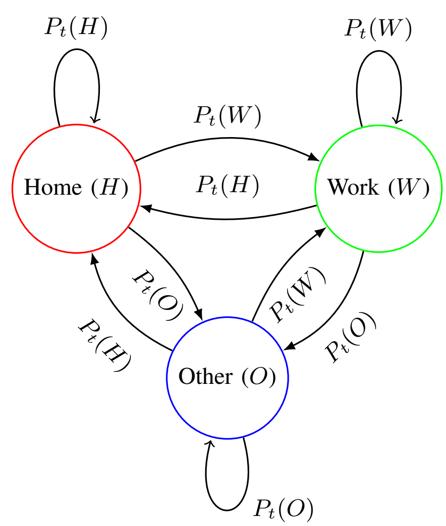

Fig. 8. Illustration of the stochastic model for the vehicle based on state likelyhood.

By using the state probabilities, the vehicle is essentially forced to return to *home* and is much less likely to stay out overnight. Because of a few observed late night trips to work in the original data, there is still a chance of a late night stay at *work*, but it is negligible. Figure 8 shows the three state model based on the state probabilities, where $P_t(S)$ denotes the probatility that a transition to state S will occur at time t. Once a decision has been made to transition to a certain state, a route should be calculated, along which the vehicle can start to drive. The route provides speed and duration and it is not until the vehicle arrives at the destination, that it should be allowed to once again transision. A way, to reduce computational overhead when simulating large amount of vehicles, could be to determined the duration of the given stop-overs and essentially stop the simulation for that period. This could be done stochastically based on the density distribution for the given location, arriving at the given time. It does, however, not help with the stranding issue as the needed transisional probability could have decreased during the stop-over.

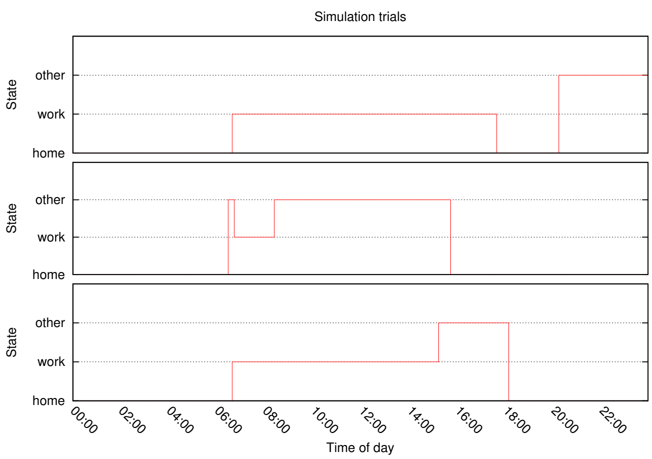

Fig. 9. Output of a random selection of weekday simulation trials.

The plot in figure 9 shows a series of simulation trials for the probabilities plotted in figure 7. With the exception of the end of the first trial, where the vehicle seems to stay out past midnight, the observed patterns appear to reflect a realistic behavior.

V. Conclusion

This paper suggests- and discusses a method for deriving a more realistic driving pattern, with the purpose of individually simulating large amount of EVs and their respective position throughout the day. This is achieved by cluster analyses of existing EV driving data, to group and classify the most typical types of stop-overs. Following this, a statistical analysis of the data is used to feed into a Markov inspired stochastic model used in the simulation.

A. Future work

Grid models have already been developed for the island of Bornholm, which has been the Smart Grid focus point in Denmark for a while [9][10]. Linking those models with the EV simulation would make for an ideal framework for large scale testing of everything from charging algorithms to grid-centric ancillary services. Another topic, that is rarely tested in practice, is the true scalability of existing- and proposed communication solutions for smart grid applications. Many projects and studies have dealt with various control algorithms, but few tried to tackle the pratical issues that arise with growing penetrations [5][12][13]. In a cumulative simulation the consumption would normally be determined by random trials of driving and parking, likely coupled with an average, EV consumption over distance. Several EV studies have been carried out, mostly arriving at 150Wh/km as a good average but this may not be ideal when simulating individual vehicles. Early trials used online routing services such as the Microsoft Bing Service [8]. While excellent and easy to program against, a dependence on an online service is not feasible when the simulation will result in thousands of route queries being made again and again. A promising alternative is the Open Source Routing Machine, which as the name suggests is a free routing solution [7]. It is based on the Open Street Maps [6] from which its highly optimized algorithm can find a way from A to B in mere milliseconds. While routing on a global scale is definitely possible, a lighter alternative is to simply download a subsection of the map representing the simulation area.

VI. Acknowledgement

The authors would like to thank Clever A/S for use of the data collected during the “Test-en-elbil” project. Since an initial filtering had already been performed by Clever A/S, the needed processing time was reduced, freeing time to focus on more essential areas of the analysis.

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A.3 Enabling smart charging of electric vehicles by remote control of PWM signal via modem

Year: 2014

Status: Strictly confidential - pending submission

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Enabling smart charging in any electric vehicle by remote control of PWM signal via modem

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Fulde navn:		**Stilling:**	
Email (arbejde):		**Tlf. (arbejde):**	
Nationalitet:		**Privat adresse:**	
Ekstern opfinder 3		**Andel af opfindelsen (%)**	
Fulde navn:		**Stilling:**	
Email (arbejde):		**Tlf. (arbejde):**	
Nationalitet:		**Privat adresse:**	

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Beskriv opfindelsen

(Beskriv opfindelsens hovedtræk og det teknologiområde, opfindelsen angår, på en alment forståelig måde. Kopier gerne figurer og grafer ind, vedhæft gerne yderligere materiale og udvid skrivefeltet hvis nødvendigt)

The idea, hereafter referred to as "Device X", is exploiting a well-known man-in-the-middle concept, where a third party is placed on the communication channel in between the two parties that are supposed to communicate directly with each other.

Smart charging is defined as the ability to externally control the timing and size of power and energy exchanged between the electric vehicle supply equipment (EVSE) and electric vehicle (EV).

Note: The method relies on the EV and the EVSE both properly implementing the IEC61851 communication standard.

- **Typical EV charging setup and process**

  While the EV is not connected to the EVSE, the charging circuits of both are in standby mode. Once the vehicle is connected to the charging spot via the charging cable the following happens: vehicle detects the cable by sensing Proximity Pilot (PP) pin and changes the status on the Control Pilot (CP) pin to ready for charging (Shown in the by Voltage drop from 12V to 9V). The EVSE detects the vehicle by sensing the voltage drop on the CP pin and starts generating the PWM signal to indicate the allowed charging current to the vehicle. The EV lowers the voltage on the CP pin to 3- or 6V to indicate its' readiness to charge. When EVSE senses this drop it closes the power relays providing the power for the EV to charge. Once the EV gets the power, it starts charging. If the duty cycle of the PWM signal is changed while charging, the charging current will always adhere to the new limit set by the EVSE (as seen in Figure 5 and Figure 6). The charging is ended if the battery is full or, case of the SAE 1772 standard, the switch on the charging plug (see Figure 1 and Figure 2) is pressed on the charging plug to disconnect the charging cable from the EV. In this case the voltage on the CP line is pulled up to 9V and the chargers stop charging the battery. Afterwards the plug is disconnected and charging electronics comes back to the standby mode.

  The default behavior of the EV is to charge immediately after plugging-in with the maximum power taking into account:

  - Cable current rating
  - EVSE charging current limit indicated by CP PWM signal duty cycle
  - EV AC charger limit

  Most contemporary and older vehicles do not have intelligent algorithms to control charging. The existing standard electronic setup of the CP communication is shown in .

- **EV charging with Device X in the car, process and purpose (novelty)**

  The proposed invention would enable any electric vehicle that supports IEC61851 to be remote controlled for use in smart charging. This is accomplished by remotely modifying the Control Pilot PWM signal duty cycle according to the control signal from any smart charging controller or aggregator, and since the device is inserted between the existing components specified by IEC61851, none of them are aware- that they are not directly communicating.

- **How Device X works**

  The device would ideally be placed in the EV, intercepting the CP signal line from EVSE as shown in . This could be done immediately behind the charging connector, in a non-intrusive manner. The device would be transparent from both the EV and EVSE point of view.

  Default operation would involve reading the PWM signal coming from EVSE and reproducing it to the vehicle. In the scenario of smart charging, the device would take into account charging current restrictions from EVSE and SOC of the battery and would produce the appropriate PWM signal for the vehicle to charge the battery. The original PWM signal from the EVSE would define the upper limit at all times .This way direct charging power control and scheduled charging are possible.

Because the device is comprised of only low power circuitry, it could therefore be powered solely off the incoming EVSE CP 12V signal or 12V vehicle aux-battery.

To properly facilitate the charging of the vehicle, it is often required to know the SOC of the vehicle. For many (if not most) vehicles, this can be read from the CAN bus. Retrieving the correct package, containing the battery information, from an unknown vehicle model, usually required a little investigatory work, but is entirely a software issue. The CAN bus is standardized and a multitude of decoders can be found (see prototype description further down).

- **Safety**

  To continue to provide a safe operational environment, the device could be mounted in parallel to the CP line. In the default scenario allowing the original signal from EVSE to come directly to the EV. When activated the device would reroute the line trough itself to modify the CP signal.

  Naturally, any limitation dictated by the EVSE needs to be replicated to the EV, in order to comply with external safety factors.

Figure 1 – Typical AES 1772 charging cable with adapter rated for a 13A wall plug (e.g. used with Nissan Leaf)

Figure 2 – IEC 62196 Type 2 charging cable with adapter, along with control box allowing manual setting of current (6, 8, 10 and 13A)

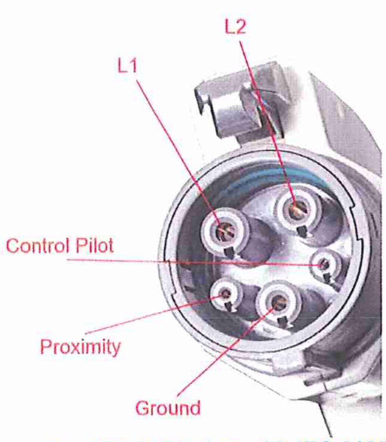

Figure 3 – AES 1772 plug with IEC 61851 compatible PWM on the "control pilot"

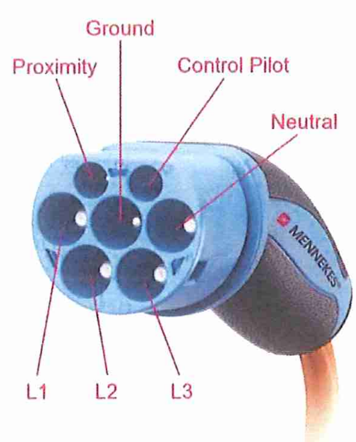

Figure 4 – IEC 62196 Type 2 plug, with IEC 61851 PWM on the "control pilot"

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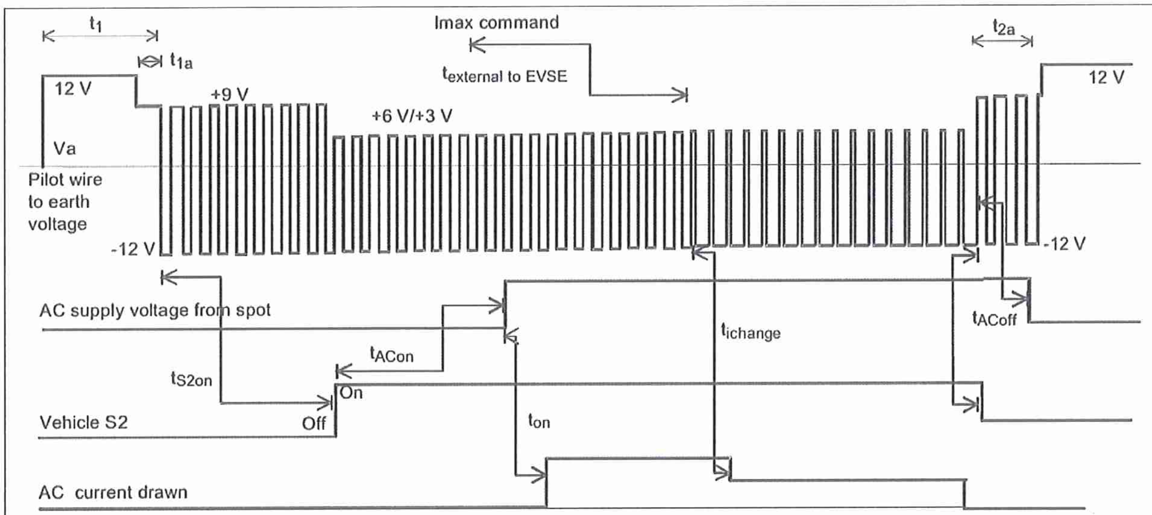

Figure 5 – Control pilot PWM signal during stages of the charging process (IEC 61851)

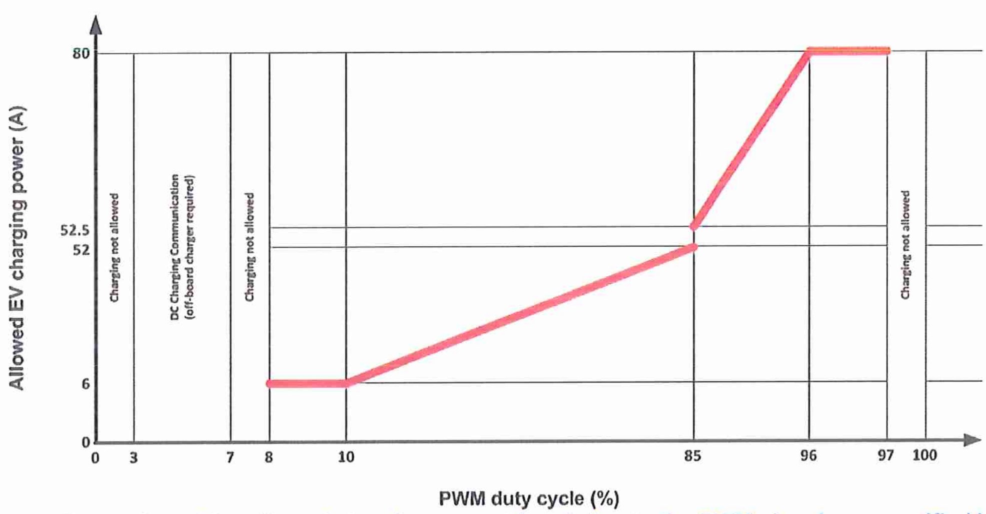

Figure 6 – Illustration of the allowed charging current in relation to the PWM signals as specified in IEC 61851

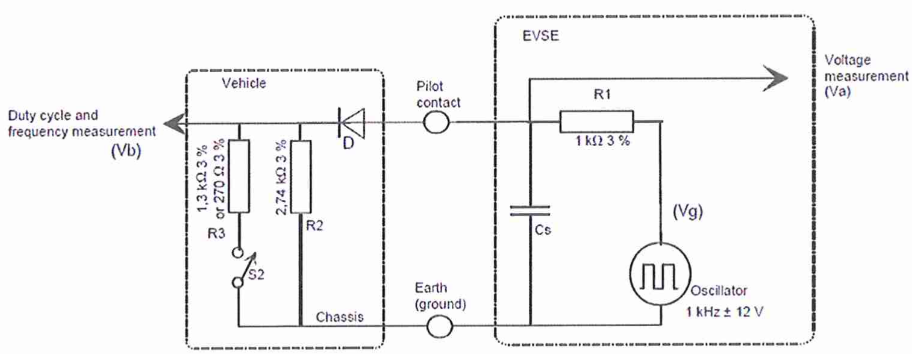

Figure 7 – Existing control pilot circuit as illustrated in the IEC 61851 (figure borrowed from standard documentation)

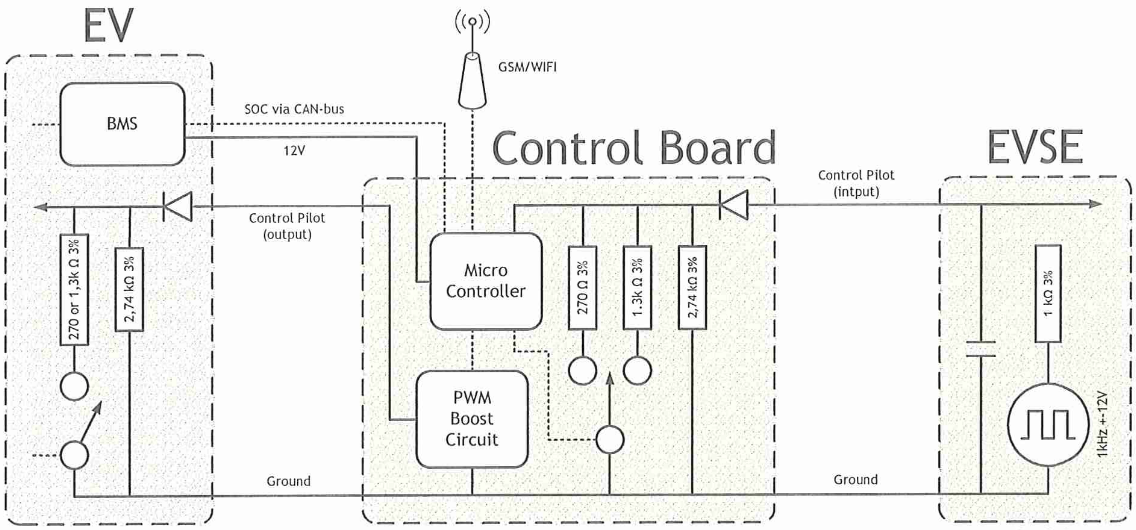

Figure 8 – Control pilot circuit with Device X inserted in the middle, enabling remote control of the charging, by varying the PWM signal on the Control Pilot on the EV side

Beskriv udviklingsstadiet
(Er der f.eks. en fungerende prototype, er nogle delelementer blevet testet, eller hvilke indikationer er der på, at dette ville kunne fungere)

A prototype is currently under development

A Bachelor project that resulted in successful development of the data logging solution from the EVs CAN-bus will be extended to control the PWM signaling from EVSE.

CAN bus data acquisition of SOC data is already implemented and tested. The PWM control section of the board is under development and is expected to be finished soon in 2014.

Interpreting the CAN-bus data requires the knowledge of the CAN message frame data descriptions, which is specific to the vehicle manufacturer/model, moreover it is typically not easily accessible, but can be reverse-engineered. Once relevant data messages are identified and decrypted for one car manufacturer, they can be applied to most other vehicle models of the same manufacturer.

Measuring and generating a Pulse-Width Modulated signal (PWM), is a trivial task at the frequencies specified by IEC61851 (~1kHz) even with cheap off-the-shelf DIY electronics kits. The board that was used for development of the prototype is of more professional quality; therefore most of the problems of low quality electronics are avoided.

Beskriv det kommende års forventede resultater inklusiv forventede udfordringer
(Hvilket forsknings- og udviklingsarbejde forventes at gøres som styrker opfindelsen teknisk eller kommercielt, og hvor ser I de største udfordringer?)

The above mentioned Bachelor project finished in summer 2013, and a full prototype of the device is expected to be implemented and tested by summer 2014.

In the first tests it is planned to use different smart charging algorithms. Tests would be done as both ad-hoc setups and with relation to the bigger research project, where a 5-min real-time price is sent directly to the vehicles, or NIKOLA EV integration project.

A plan to roll this out to the remaining DTU Elektro EVs and to expanding the tests to use the EVs available at other departments, have been discussed with CAS and DTU Transport.

Litteratursøgning

(I denne sektion skal du angive referencer til litteratur, som du mener ligger tæt på din opfindelse og derfor kan være begrænsende mht. patentering. Du kan bruge patentdatabaser og andre søgemaskiner for at finde informationen)

Kopier referencer til de relevante publikationer, der er fundet

(Vedlæg gerne de mest relevante publikationer til denne anmeldelse)

Artikler og andre publikationer (inklusiv jeres egne):

Patenter (brug f.eks. følgende links: Derwent Innovations Index (via DTU), freepatentsonline, eller Espacenet):

Method for charging battery of vehicle e.g. electric car, involves computing time segmented base load profile based on selected charging mode, and maximum rated power of charging station
(Patent # DE 102011109422-A1)

Smart charging system for mobile vehicles and method of operating the same
(Patent # US 20130020992 A1)

Intelligent charging cable for electric vehicles
(Patent # WO 2011147391 A2)

Beskriv hvorledes din/jeres opfindelse adskiller sig fra den eksisterende publicerede teknologi

(For at kunne patentere en opfindelse skal den være ny og have såkaldt opfindelseshøjde. At den er ny, dækkes af at opfindelsen aldrig tidligere er blevet beskrevet før. At opfindelsen har opfindelseshøjde betyder at opfindelsen ikke er "oplagt", dvs. man skal ikke kunne kombinere anden kendt teknologi og få samme idé. "Oplagt" kan være svært at definere, men udfordringer er at argumentere for at opfindelsen er forskellig fra en simpel kombination af eksisterende viden inden for teknologiområdet.

Other existing solutions use- or simply propose the use of digital communication over the charging cable, which required substantial work in terms of standardization. It is much more complex solution and requires matching communication transceiver in both vehicle and charging spot, not to mention that existing vehicles still need to be retrofitted.

Device X instead duplicates the existing PWM signal, with a varied duty cycle, and requires no changes to the charging spot or the vehicle itself. The device would be installed in the vehicle for easier access to the SOC information transferred via CAN bus. This can be done by plugging into the vehicles OnBoard Diagnostics (OBD) port or by plugging into the any other place on the CAN bus in the EV. A multitude of off-the-shelf consumer products for reading from the OBD system already exist, so connecting this way would hardly constitute a problem. For a more permanent installation, a CAN bus connector in the engine bay would be used, which could still be done in a non-intrusive and reversible manner.

The PWM modification board could be directly mounted on the AC charging socket, requiring little or no modification to the socket. As the CP signal is rated at +-12V DC, it could be done with almost no security risk and could be reversed if the device was later to be removed.

Kommercialisering

(I denne sektion skal de kommercielle overvejelser beskrives. DTU har brug for at vide hvilke tanker du/I har omkring kommercialiseringen af teknologien)

Har du/I bud på virksomheder/brugere som kunne være interesseret i opfindelsen, og er der er kontakt til disse?

(Beskriv gerne hvorfor disse virksomheder/brugere kunne have interesse i denne opfindelse)

All over the world, both in the academic arena and in private industry, the Evs are predicted to offer a wide array of services and assistance in bettering the stability of the electrical grids. These instabilities already exist, but are predicted to worsen with the continued increase of renewable (read less predictable) energy resources, such as wind and solar. Since the existing regulatory mechanisms are both expensive to aquire and maintain and Evs, like regular existing vehicles, spend the majority of their time parked, represent a growing buffer, which, with a little added intelligence and communication could be made to respond with a moments notice.

Despite unfavourable sales of EVs in Denmark, other regions around the world are seeing much greater demand for electric transportation and the number of so-called "full" EV or plugin hybrids are on the rise. None of those, however, come with support for intelligent charging/services.

(Example of US sales numbers)
http://www.electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952

All EV fleet operators along with the distribution companies have an interest in such a product, since there are no other established solution to controlling EV charging. It should be noted that the distribution companies may not directly be interested in doing so, but since it represents a important commodity to them they help add to the value-chain which will spur on other middle-men. I Denmark we had Better Place, whos primary reason for failure was the low EV sales numbers, and Clever A/S.

If control is not built into the EVs from the factory, it will up to the individual owner/customer to have it done to participate- and thereby receive compensation from aggregating operators. Despite the fact that the largest eaernings are to be found in participating in electricity- and regulating markets, there is also ample room for doing business based soly on the manufacturing and installation of devices in the vehicles.

Hvad opnås i forhold til eksisterende konkurrerende teknologier/produkter?

(Hvilke kommercielle produkter eksisterer allerede på markedet? Hvilke fordele forventes ved brug af denne nye opfindelse?)

As outlined above, intelligent charging is a heavy focus area in many communities around the world, and has played a corner stone in several industrial- and research projects. Common to all is a focus on future solutions such as fast digital communication via the charging cable or wireless means.

The closest product is Mennekes I-9000002-09 charging adapter, seen in and Figure 4. However, it only allows the user to control the charging current manually in big steps and via direct manual manipulation (using buttons on the device). The primary benefit and goal of this device, is judged not to be smart charging, but simply adaptability to varying house-hold electricity installations. The adapter itself has no ability to receive any information from the vehicle, such as SOC, or from anywhere else.

Most mass manufactured EVs from recent years, with support for the IEC 61851 standard, should be compatible with Device X and eligible for retrofitting.

Hemmeligholdelse og rettighedsforhold

(I denne sektion skal du/I beskrive om opfindelsen er hemmeligholdt, og om der er brug for at offentliggøre opfindelsen i den nærmeste fremtid. DTU har brug for at vide dette, da det indvirker på en eventuel patenteringsproces. Desuden har DTU brug for at vide, om der eksisterer f.eks. en samarbejdsaftale, eller anden aftale som gør at DTU ikke alene kan råde over opfindelsen)

Er dele af opfindelsen blevet offentliggjort, eller er der en offentliggørelse på vej?

(Er dele af opfindelsen f.eks. blevet delt med folk uden for DTU eller offentliggjort? Er der blevet indsendt abstract/artikel eller skal opfindelsen præsenteres ved et forsvar i den nærmeste fremtid?)

Nej

Vil der være problemer forbundet med evt. hemmeligholdelse i op til 4 mdr. efter denne anmeldelse?

(DTU har ofte brug for ca. 4 mdr for at få vurderet opfindelsen og indleveret en patentansøgning)

☐ Ja ☑ Nej

(hvis ja, beskriv hvorfor):

Indgår opfindelsen i et samarbejde med eksterne parter hvor der ligger en aftale om fordeling af rettigheder til opfindelser?

(Findes eksempelvis ved medfinansiering fra PSO, EFP, EUDP, HTF, DSF, EU m.v. Få eventuelt hjælp af instituttets kontraktansvarlige)

☐ Ja ☑ Nej

(hvis ja, angiv navn og samarbejdsparter i projektet og vedlæg aftalen):

Er der andre oplysninger du/I mener, der bør indgå i grundlaget for DTU's beslutning om overtagelse af denne opfindelse?

(Indgår opfindelsen f.eks. i et af instituttets strategiske forskningstemaer. Har instituttet i forvejen en patentklynge indenfor området?)

Smart Grids is one of the primary focus areas at the Center for Electric Power and Energy (CEE) at DTU Elektro and in the heart of this area you often find EVs. This is also reflected in the still broad portfolio of EV related projects, both past and present.

This is also reflected in the continued electrification of not just the CEE/Elektro fleet, but also that of CAS, the DTU administration and possibly others.

Det overståede EDISON projekt løb i tre år og fokuserede udelukkende på elbils integration in relation til den voksende vind produktion i Danmark. Efterfølgende er EcoGrid EU startet op, spænnende endnu bredere end elbiler til at dække alle former for distribuerede energiresurser; alle sammen styret af det nye real-tids markeds koncept der er målet. Det nyligt opstartede NIKOLA projekt omhandler kun elbiler, hovedsageligt med fokus i de services de kan yde for både nettet og brugerne.

The now finished EDISON project ran for three years, and focused exclusively on EV integration in relation to the growing wind penetration in Denmark. Following EDISON, the EcoGrid EU project launched, spanning an even broader range of distributed energy resources (DERs); all controlled by the new real-time electricity market concept, which is the goal of the project.

Recently the NIKOLA project started, which will focus on the various ancillary services that are possible when the vehicles are remote controllable.

In parallel with the various research activities, there is the NEVIC center (Northern Electric Vehicle Interoperability Center) at Risø DTU, which has worked on stream-lining standardization of various EV and EVSE interoperabilities such as plugs, electric compatibility and communication aspects.

NIKOLA
INTELLIGENT ELECTRIC VEHICLE INTEGRATION

NEVIC

EDISON

EcoGrid eu
www.eu-ecogrid.net

Yderligere opfindere

Indtast yderligere opfindere, hvis der ikke var plads i starten af skemaet – husk privatadresse og nationalitet

A.4 Identification - Requirements on central ICT platform and software

Year: 2012

Published: EcoGrid EU project - Task 3.1 deliverable

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EcoGrid EU – A Prototype for European Smart Grids

Deliverable 3.1

Identification - Requirements on central ICT platform and software

January 2012

Executive Summary

April 2013

Task Leader: DTU-CET

Project full title: Large-Scale Smart Grids Demonstration of Real-Time Market-based Integration of DER and DR

EU Project no: 268199
Instrument: Collaborative project
Thematic Priority: ENERGY

Executive Summary

Generation of electricity from renewable sources such as wind and solar power creates a challenge for the power grid since although production from these sources can be forecast, it cannot be controlled. Even if the energy produced follows the forecast perfectly, it still may not match the needs of consumers of electricity. Therefore, compared to existing power systems in which generation can be carefully controlled, more must be done to balance the supply and consumption of electricity.

The focus of the EcoGrid EU project is to exploit flexibility in particular also in the consumption of electricity in homes to help provide balancing power. Flexibility in this case is normally associated with heating, either for hot water or to keep the house warm. There is flexibility since the heat can be stored and there is normally a range of acceptable temperatures. There may be additional sources of flexibility in homes if an electric vehicle is used or if a stationary battery is available.

In order to exploit this flexibility the house must be "smart". It must have the capability of acting on external input to either consume more or less electricity than planned in a particular time period. The house must also have a "smart meter" that is able to provide real-time feedback on its consumption to the "smart grid" so that stability in the overall system can be achieved.

The EcoGrid approach is to deploy a real-time market-based platform to enable distributed grid balancing. In this case real-time means that information is provided to the smart homes so that they are able to react to the needs of the grid within minutes. A market-based platform ensures that information is provided to all active parties, who will be able to react according to their needs and constraints, and who will benefit according to how much they are able to help balance the overall system by adjusting their consumption. This approach is feasible since it has the following characteristics:

- The balancing power available from a single smart home might be quite small, but the impact of involving a large number of homes is significant. The system is robust since it does not rely on the response of any single home, but on the ability to change the aggregate consumption of a large number of houses.

- A simple mechanism – a price signal – is visible to the individual houses. No complex monitoring is required nor is there a complex process to bid or otherwise indicate how a house will participate. Each house will simply react to the price signal according to it's current state (e.g., temperature), the expected weather, and the needs of it's occupants (e.g., depending on if the people living there are at home or not, and on the comfort they need).

- The mechanism is also scalable since the price signal can be sent to a large number of homes in parallel. The techniques developed to ensure stability (for example the smart homes should not over react to a change in the price signal) need to work well for configurations of all sizes.

The benefit to consumers is the chance to help achieve a lower overall cost for electricity by using existing flexibility (their own consumption) to provide balancing instead of having the utilities build more expensive infrastructure which the consumers will pay for in the end. They will also benefit directly by paying less for energy if they support the distributed balancing market. The benefit to electric utilities is the availability of a new source for balancing the grid that does not require a significant capital investment compared to alternative solutions, such as water reservoirs or flexible gas-powered generation. In addition all players benefit from the long-term stability provided through the increased use of renewables.

The technical challenge to make this work in a simple way for all of the participants is to hide much of the complexity in the real-time marketplace. The marketplace receives input from two key sources. On the one side, it has information from existing power markets regarding the forecast and actual needs of the power grid. On the other side, it monitors the consumption of smart homes to understand their current state and also to be able to continuously improve forecasts for how these homes will react to the markets price signals in the future. Through the use of good algorithms for forecasting, the marketplace will be able to select the right price in every situation to help achieve the maximum benefit for the power grid. Development of these algorithms is covered by WP1. The mechanisms developed in WP1 will be designed and implemented in a modular, flexible manner, thus making it easy to test many different mechanisms as a part of EcoGrid.

To make all of this work, the system needs to communicate with the appropriate stakeholders in order to get the necessary information and provide feedback such as price signals. Communication is required with existing entities involved with the generation and distribution of electricity, including the utilities, TSOs, DSOs, other parties responsible for balancing the power grid, as well as existing markets for electricity. On the other hand there is communication with both individual houses as well as houses that may be aggregated by virtual power plant solutions (this consumer-side communication is covered in WP4).

The EcoGrid EU project is a demonstration project, and as such the developed technology will be implemented and tested in practice, in collaboration with real electricity market participants. Prior to implementation of the proposed real-time market, to be carried out in subsequent WP3 tasks, the goal of Task 3.1 is to define the information and communication technology (ICT) scope and requirements to achieve this. The use cases developed in T1.7 that outline business models, requirements and the architecture specification have provided the basis for this work.

In this document the resulting requirements are presented in a clear and concise manner, in the form of a series of business scenarios. The business scenarios have been categorized, separating the specific software requirements from the general market operation and accompanying user interfaces.

The first set of business scenarios focus on the real-time marketplace covering the following aspects:

- Price forecasts are important for supporting the EcoGrid marketplace since they allow the consumers (smart homes) to plan their consumption. Assuming the flexibility of a consumer is sufficient, smart homes will plan consumption for low price periods. Price forecasts for the real-time market are derived based on forecasts obtained from the existing Spot Market and distributed to the smart homes or the smart home aggregators.

- The response of the consumers to the price forecasts needs to be predicted based on the current state of the system and historical data on prices and responses. From the predicted response the system will determine the degree to which it will be able to help balance the overall power grid. Based on the predicted response, the real-time market price is computed and distributed.

- On an ongoing basis the real-time market must also have updated information on the consumers that are participating in the market, since this will determine the overall capacity of the system for balancing. As an example, if the number of participating consumers and the resulting overall capacity grows, the marketplace will need to moderate the price incentives that it provides, to avoid having the system over-react to the needs of the grid.

- Information from the smart meters at each consumer is also collected and made available to the parties that need it. The real-time marketplace benefits from this data since it allows the market to continuously improve its understanding of how consumers react to pricing information. On the other hand, since consumers are rewarded for providing flexibility to support balancing the grid, this data is required in order to credit them appropriately.

- The protocol to distribute the real-time price information will be defined and implemented in a flexible way so that the scheme can be adapted based on experience gained with the system.

The EcoGrid solution is flexible, and in particular it supports houses that are integrated with the marketplace in different ways. There is a set of business scenarios focused on the integration of houses according to the methods specified by IBM, one of the project partners, as follows:

- When a house is selected by the local retailer to be part of the IBM-EcoGrid system, the necessary hardware and software systems are installed in that house. An operator system is available to assign houses that are ready to the IBM system and to provide configuration information on those houses. In particular information is provided on the devices in the houses that can provide demand response. Information on the IBM-EcoGrid houses is available on the EcoGrid portal.
- An interface is provided to the house residents so that important user-specific parameters such as the acceptable temperature range can be specified and made available to the IBM system. In addition measured data on the current temperature and other parameters is collected. Based on this data, the demand-response capacity for the house in question can be determined. The home owner is also provided with feedback on the operation of the system (e.g., savings to date) so that he will be able to better tune the parameters he controls (e.g., due to understand the relationship between a larger temperature range and savings). Mechanisms are also defined to allow the home owner to report problems with the system and to override the automated controls.
- Based on the price received from the real-time market along with the configuration and status information, the control system in each house will determine if the house is active (e.g., heating) or not for a given period. The control system will use analytics based on historical data to determine its actions. Since this computation is distributed, the scheme is scalable (this can occur at a virtually unlimited number of houses in parallel). The control system also interacts with the DSO such that local grid congestion can be avoided.
- Based on the operational experience from EcoGrid, and input from existing parties (operators of existing markets, regulators, etc.) a plan for integrating this scheme into the existing electric power system will be developed.

Siemens manages a second set of EcoGrid houses and other loads, and a set of business scenarios focused on these houses has also been defined. The basic processes are similar to those of the IBM-EcoGrid houses. The key difference is that the Siemens solution includes an aggregation element, the Decentralized Energy Management System (DEMS) that operates together with a smart controller in each house to optimize the provisioning of balancing power.

The ICT platform itself is described as a set of business scenarios. The central component for implementing the Real-Time Market and interfacing between the existing markets and the EcoGrid homes is an IBM BladeCenter server, which is installed at an Oestkraft facility on Bornholm. Availability of a dedicated local server ensures that the solution is robust. In addition to hosting the EcoGrid Real-Time Market, this server hosts the EcoGrid billing application, which is adapted to the

The research leading to these results has received funding from the European Union
Seventh Framework Programme under Grant Agreement no 268199

Real-Time Market price interval, database and asset management subsystems, user administration, as well as central components of the IBM (GreenWave Reality server software) and Siemens (DEMS server and licensing software) solutions. The server is network connected with appropriate security mechanisms, including user authentication and firewalls.

In addition to the functional requirements described above, the ICT platform also supports several non-functional requirements. All required data is stored and made available to the EcoGrid applications. The data is backed up to ensure that data loss is avoided. Furthermore the data is protected by access control schemes to ensure that it is only used for the intended purpose. The ICT platform also supports software change management processes to allow smooth rollout of a high-level of anticipated updates as the EcoGrid algorithms are developed and refined.

The ICT platform supports a number of user interfaces to allow the various actors to interact with the systems. The pilot users (home owners) are given access to a portal to view the current status of the houses, including control parameters and temperature readings. Specific portals are also provided for the IBM houses (GreenWave Reality platform) and the Siemens houses (DEMS). A second user portal provides access to billing information, including a view of their EcoGrid benefits. Finally, a portal is provided for the users to access their EcoGrid-related contract information.

Several portals are also provided to support EcoGrid administrators and investigators. A portal is provided to EcoGrid users to allow them to see all aspects of price information including historical, current, and forecasted values. A second portal provides an overview of all households including both current status and the overall state of the system. The Siemens system also provides a GUI to allow the operator to monitor data collected by the system related to energy consumption. An overall Web page is provided to show summary results of the project to date.

A set of interfaces and tools is provided to the EcoGrid system administrators to allow them to manage the ICT systems and software. This supports managing the server itself, network connectivity, the systems software, EcoGrid virtual machines, and hosted applications.

To support development of the complex EcoGrid system by a distributed team of experts with very diverse roles, including people focused on system software and hardware, energy markets, and power systems, the Rational Requirements Composer is used to manage system requirements, including the complete lifecycle of requirements management (create, modify, finalize). The system also allows the requirements to be linked to ongoing development and test of the overall system.

The research leading to these results has received funding from the European Union
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A.5 Smartly Charging the Electric Vehicle Fleet

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SMARTLY CHARGING THE ELECTRIC VEHICLE FLEET

Peter Bach Andersen, Einar Bragi Hauksson, Anders Bro Pedersen, Dieter Gantenbein, Bernhard Jansen, Claus Amtrup Andersen, and Jacob Dall

15.1 INTRODUCTION

The Danish EDISON project [1–3] has been launched to demonstrate how the charging and possible discharging of *electric vehicles* (EVs), if handled intelligently, can yield benefits to the EV owner, the grid, and society. EDISON is partly publically funded through the Danish transmission system operator (TSO) Energinet.dk's research program FORSKEL. The total budget is approximately EUR 6.5 million, with EUR 4.5 million thereof coming from FORSKEL. The consortium consists of the Danish energy corporations DONG Energy and Østkraft, the Danish Technical University (DTU) CET and Risø, as well as IBM, Siemens, EURISCO, and the Danish Energy Association (DEA).

While the more progressive concepts such as using the EVs as energy storage or for regulating services using V2G show great promise, the EVs potential as a controllable load could be seen as the low-hanging fruit in EV integration. The smart

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charging concept, where the charging of EV batteries is delayed or advanced in time based on energy costs, grid constraints, or renewable contents, has great potential and is the initial focus of EDISON. The success of smart charging, however, relies on a suitable and standardized ICT architecture. This chapter documents the suite of contemporary communication technologies, components, and standards, which helps to facilitate smart charging in the EDISON project. The chapter is organized as follows. First, Section 15.2 describes the integration scenario used in the EDISON project and introduces the fleet operator as a new stakeholder in the power system. The objectives of the fleet operator will be described along with the requirements of the ICT architecture that supports its operation. Next, Sections 15.3 to 15.5 describe the standards and standardization work relevant to the project, a set of EDISON-developed hardware and software components and the communication technologies used to interface the main entities.

The final parts of the chapter, Sections 15.6 and 15.7, present a set of demonstration interfaces and draw conclusions on the utilization of communication technologies in EDISON.

15.2 THE FLEET OPERATOR AS A NEW CONCEPTUAL ROLE

The conceptual role of a fleet operator, which can be taken by different commercial players, is introduced to allow groups of EVs to be actively integrated in the power system. Toward the grid and market stakeholders, the fleet operator will operate as a *virtual power plant* (VPP). The virtual power plant concept describes an aggregated system in which distributed energy resources (DERs) are partly or fully controlled by a single coordinating entity. In this way, DERs can be actively integrated into the power system and market, for which individually they would be too small, in terms of power output and availability, to participate in. The concept has been demonstrated in the European FENIX project [4] and studied by Shi You et al. [5].

In the case of EDISON a fleet operator could mimic a traditional power plant by aggregating a group of electric vehicles. The fleet operator would also need to interact with each individual electric vehicle to optimize charging. The technical implementation of this concept is called the EDISON VPP (EVPP) and would be used by a fleet operator as shown in Figure 15.1.

15.2.1 Fleet Operator Interaction with Grid and Market Stakeholders

A first step in EV integration is identifying the stakeholders, old and new, that will have a role to play in interfacing the EVs with the power system and market. The composition of stakeholders depends heavily on the business models and market environments under consideration.

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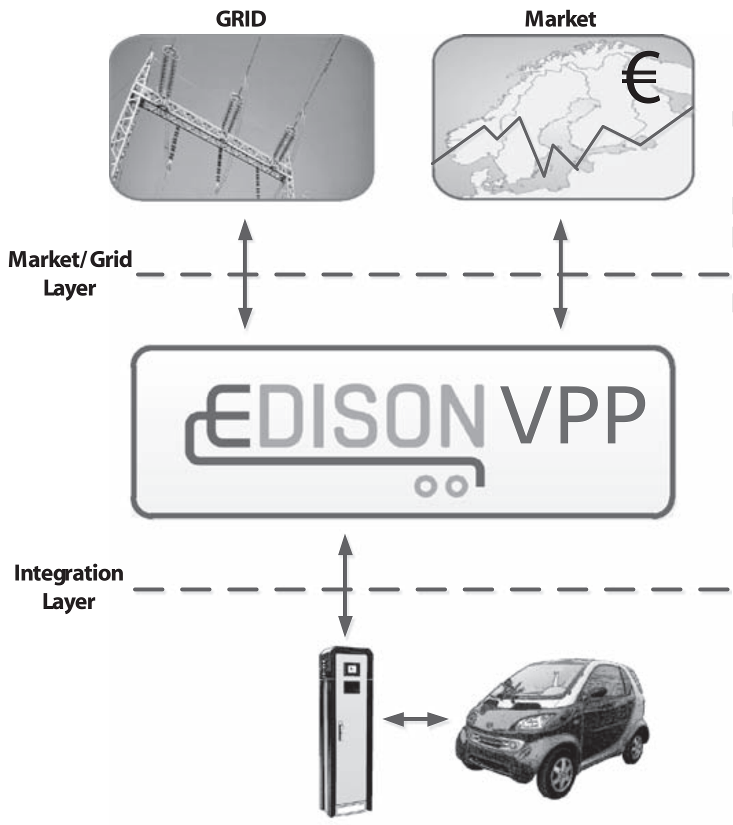

Figure 15.1. EDISON conceptual architecture.

The EDISON fleet operator integration scenario is based on the current Nordic power system and market configuration. There are obviously many other integration concepts such as near real-time markets, frequency response, or price signals in which the vehicle acts as autonomous and intelligent agent. While such concepts are within the research scope of EDISON, the phase-1 scenario will focus on conditions as they are today and is a pragmatic first approach to EV integration. Figure 15.2 shows the market domain model in which the fleet operator interfaces the EV with the power market. Among the stakeholders in this domain is the *transmission system operator* (TSO), which controls the transmission grid and maintains the overall security of electricity supply, and the *distribution system operator* (DSO), which manages a part of the distribution grid and handles local metering. The fleet operator must maintain the appropriate balancing responsibilities when acting on the markets.

As illustrated, the fleet operator could participate either in the energy market or in ancillary services. The first project phase, however, will put its emphasis on the former and indirectly connect the EVs with the day-ahead spot market by controlling the charging in correspondence with hourly energy prices.

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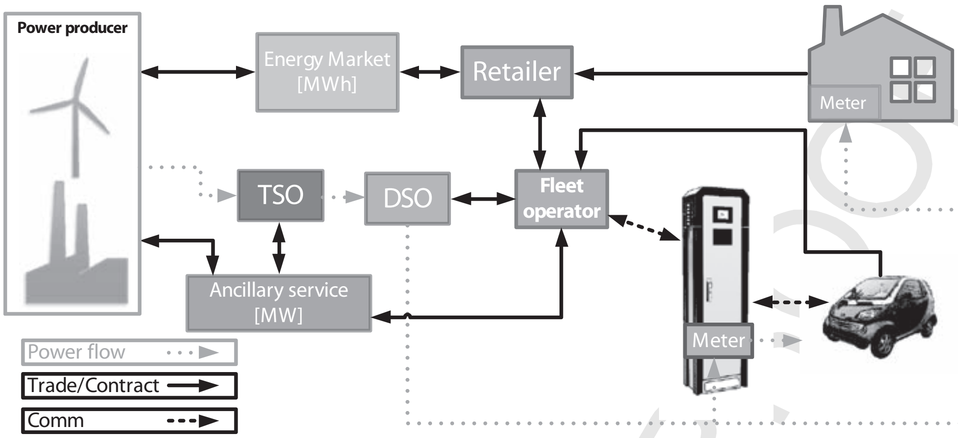

Figure 15.2. Market domain model.

15.2.2 The Objective of the Fleet Operator

Based on the market integration and stakeholder setup, as described above, the primary objective of the EVPP fleet operator is to facilitate smart charging. Under smart charging, we understand the computation of a per EV charging schedule, which is computed using some predetermined optimization targets as well as a set of constraints. The objectives of the charging schedules are primarily to ensure that sufficient energy will be delivered to the EVs such that future trips can be carried out. Sufficient energy can be further refined into energy objectives, that is, an 80% full battery or a more precise, per-trip, energy objective.

Aside from the primary objective of supplying energy for the use of driving, other objectives can be defined:

- *Minimizing Energy Costs.* Charge at the time periods with the lowest energy prices.
- *Respect Grid Constraints.* Adjust charging to capacity limitations of the distribution grid.
- *Renewable Contents.* Charge during periods when underutilized renewable energy is produced.

This results in a multiobjective optimization problem where a solution requires that a compromise between the objectives is found. For example, optimal use of renewable energy will not guarantee a minimization of charging costs. This optimization is done in the EVPP software, which is described in Section 15.4. The mathematical techniques used by the EVPP are addressed by Olle Sundström and Carl Binding in the paper "Optimization Methods to Plan the Charging of Electric Vehicle Fleets" [6], where linear and quadratic optimization methods are investigated for charging schedule generation. The paper "Planning Electric-Drive Vehicle Charging Under Constrained Grid Conditions"[7], by the same authors, add distribution grid considerations to the optimization.

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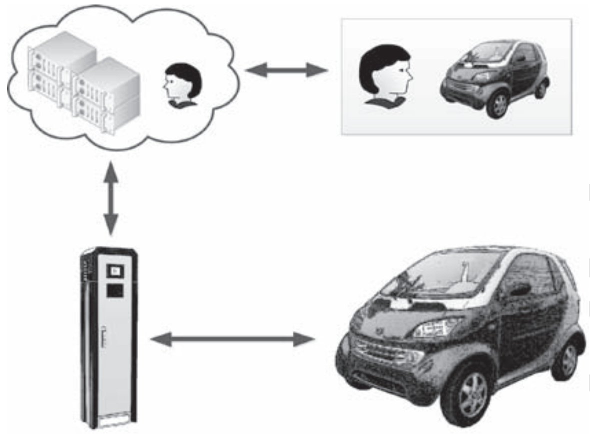

Figure 15.3. The EDISON setup.

15.2.3 ICT Architecture Setup and Requirements

A fleet operator will require a suitable ICT architecture that can connect the stakeholders and let them exchange the information necessary for smart charging. The ICT architecture in EDISON is based on the setup shown in Figure 15.3.

The figure shows the four entities directly involved in *electric vehicle* (EV) smart charging. In this setup the *electric vehicle supply equipment* (EVSE) facilitates the connection between EV and fleet operator. The EVSE will extract information from the EV and share it with the fleet operator. The EVSE will then receive a charging schedule from the fleet operator and follow it in the charging of the EV. Since the charging decisions are delegated to the fleet operator and communication is handled by the EVSE, this setup will support most "simple" EVs with limited computation and communication capabilities. As future EVs evolve into more autonomous and intelligent agents, the setup will most likely change. Based on the above setup the following requirements of an ICT architecture have been defined.

- *Adherence to Standards.* EDISON attempts to identify, and to some extent implement, the standards most relevant to its architecture. The chosen standards are IEC 61850 and IEC 61851 as well as the coming ISO/IEC 15118, which will be described in Section 15.3.
- *Implementation of Smart Charging Components.* EDISON must develop a set of hardware and software components that support smart charging for demonstration purposes. This includes software running on the EVSE and fleet operator platforms and the I/O components necessary to connect the EV to the EVSE. These components are described in Section 15.4.

- *Interfaces that Satisfy Basic Communication Requirements.* The protocols connecting the main entities in the EDISON setup must satisfy such requirements as interoperability, scalability, and security. Since the EVSE acts as a proxy for the EV toward the fleet operator, the main focus is on the communication between EVSE and fleet operator. The communication protocols and techniques chosen for the architecture will be described in Section 15.5 along with arguments for including them. See Chapter 10 for an overview of Smart Grid protocols.

The rest of the chapter will attempt to describe how the above requirements have been meet.

15.3 EDISON AND THE USE OF STANDARDS

The EDISON project should produce technical components that are reusable and applicable across different projects and geographies. This requires that the components, as far as possible, conform to a set of standards. By using and supporting standards, the project may also offer input and recommendations for the continued standardization process.

This section describes contemporary standards on which the EDISON ICT architecture is based. As seen in Figure 15.4, these standards can be split into two groups: the ones used for performing (1) EV-to-EVSE and (2) EVSE-to-fleet operator communication, respectively.

IEC 61850 is the communication standard used by EDISON. This standard is not specific to EVs, but supplies the necessary components to describe and send relevant data between EVSE and fleet operator. The IEC 61851 focuses on the

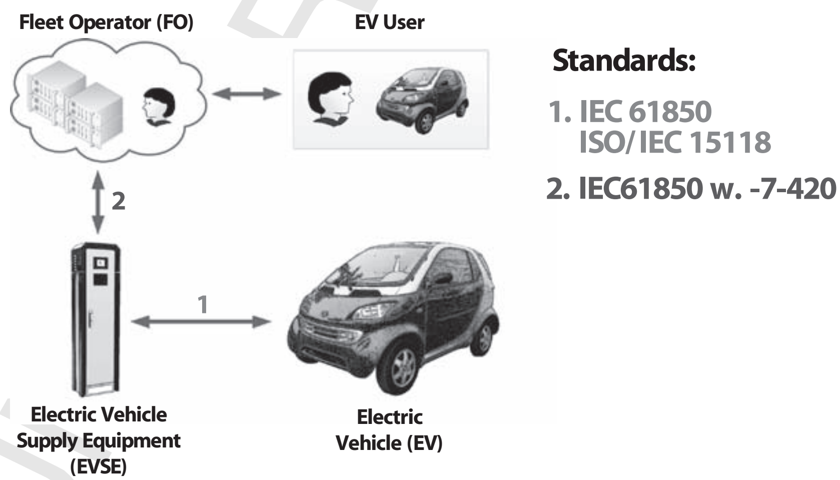

Figure 15.4. Standards used in EDISON.

physical connection and charging of an EV. The future ISO/IEC 15118 deals both with the physical interconnection and a high level communication protocol that, as opposed to IEC 61850, will be oriented toward data and services specific to EVs. Although the ISO/IEC 15118 standard will not be ready for implementation by EDISON, its relevance to EV integration justifies a brief mentioning in this section.

15.3.1 Standards Between Electric Vehicle and Electric Vehicle Supply Equipment: IEC 61851 And ISO/IEC 15118

Between the EV and the EVSE, the following two standards with special relevance to EDISON have been identified.

15.3.1.1 IEC 61851. The "IEC 61851—Electric Vehicle Conductive Charging System" standard was first published in 2001 and has been released in a 2nd edition in 2010. It describes the charging of EVs using different AC or DC voltages over a conductor using on- or off-board equipment.

The main topics of the standard are:

- General system requirements and interfaces
- Protection against electric shock
- Connection between the power supply and the EV
- Specific requirements for vehicle inlet, connector plug, and socket outlet
- Charging cable assembly requirements
- EVSE requirements

"General System Requirements and Interfaces" covers the definition of four different charging modes that an EVSE can support. These modes vary in the currents they support, safety requirements, and location of the charger (in the EV or in the EVSE). EDISON must, for instance, support mode 2 to allow for up to 32 amperes with three phases charging using an onboard charger.

IEC 61851-1 supports the plugs defined by IEC 62196-2. IEC 62196-2 specifies the requirements for plugs, socket outlets, connectors, inlets, and cable assemblies. Among the plugs to adhere to IEC 62196-2 is the Mennekes EV plug, which was developed and tested during the German e-mobility projects and is close to becoming a common European standard.

Another important component of the standard is the definition of simple EV–EVSE communication via a control pilot wire using a *pulse width modulated* (PWM) signal with a variable voltage level. This allows for the definition of different "states," which are listed in Section 15.5 within the description of the EV–EVSE interface.

The use of IEC 61851 is relevant to EDISON for several reasons. First, the safety recommendations described by the standard could be essential in having the developed components approved for live demonstrations. Second, adherence to standards

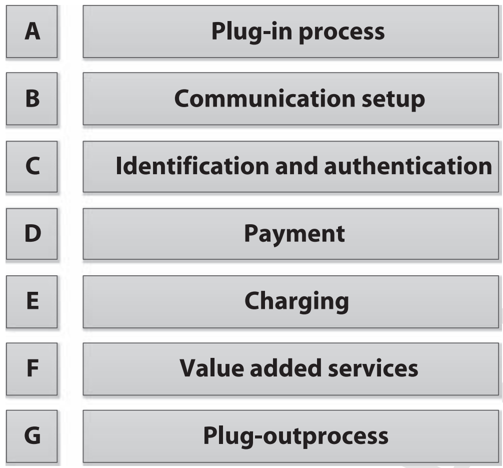

Figure 15.5. The IEC/ISO 15118-1 use case elements.

such as IEC 61851 is one of the prerequisites for roaming, allowing EVs of various brands to use EVSE from different manufacturers.

15.3.1.2 IEC/ISO 15118. The standardization process involving “IEC/ISO 15118—Vehicle to Grid Communication Interface” is still ongoing. The purpose is to make a standard for scenarios that require advanced communication between EV and EVSE.

The standard is divided into the following three parts:

1. IEC/ISO 15118-1 (General Information and Use Case Definition)
2. IEC/ISO 15118-2 (Message and Protocol)
3. IEC/ISO 15118-3 (Physical Layer)

The first part (15118-1), which describes the use cases and terms and definitions, is currently in a Committee Draft (CD) stage and the following use case elements have been identified (Figure 15.5).

In the EDISON project IP-based communication will be implemented, including the use case elements above. The “Value added services” element could include smart charging as defined by EDISON. Adherence to IEC/ISO 15118 would further benefit roaming.

15.3.2 Standard Between Electric Vehicle Supply Equipment and Fleet Operator: IEC 61850

For a couple of decades, the IEC 61850 standard has been one of the preferred ways to relay information and control within the domain of substation automation. Lately though, with the added support for distributed energy resources in the form of the

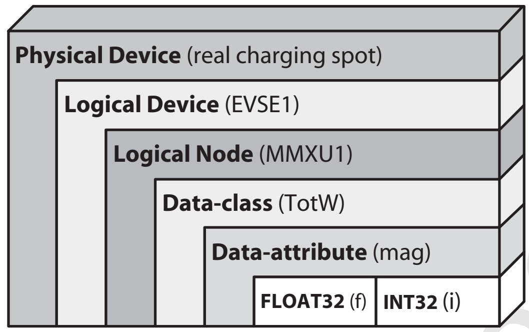

Figure 15.6. The hierarchical structure of an IEC61850 model.

IEC 61850-7-420 substandard, it has moved out of the substation domain to see much wider use.

As illustrated in Figure 15.6 the IEC 61850 standard is highly modular and consists of a large collection of hierarchical building blocks, with which almost every feasible piece of electrical equipment can be modeled. Starting from the top, the device is represented by a logical device. This in turn consists of a series of logical nodes representing various components within this device, and for every layer the granularity becomes even finer. This continues toward the bottom of the structure, where basic data types like strings, Booleans, and integers or floating point numbers make up the final link.

The structure illustrated in Figure 15.6 shows a part of a charging spot model, specifically the *total consumption* (TotW). TotW, which is a data class of type *Measured Value* (MV), is contained in an MMXU logical node. The latter is defined in the basic IEC61850 standard and is used to represent power system measurements. Because TotW is an MV class it contains the data attribute for magnitude (mag), which in turn contains the floating point value in question.

15.3.2.1 IEC 61850 with -7-420 Extension. To move the use of the IEC 61850 standard beyond that of the substation environment for which it was designed, an extension called IEC 61850-7-420 was developed to add the necessary logical nodes needed for communicating with *distributed energy resources* (DERs). Wherever possible, the extension makes use of the existing logical nodes; the standard defines nodes for generation and storage devices, including reciprocating engines, fuel cells, microturbines, photovoltaic arrays, combined heat and power units, and batteries. While IEC 61850-7-420 has been released as an international standard, development of the extension is an ongoing process and logical nodes are being redefined as well as added. During the course of the EDISON project, a proposal was made to extend the standard with logical nodes for both a charging spot (DCHS) and an electric vehicle (DBEV).

15.3.2.2 IEC 61850 Energy and Power Schedules. Sometimes trying to enforce instant control over distributed energy resources (DERs) is not desired and

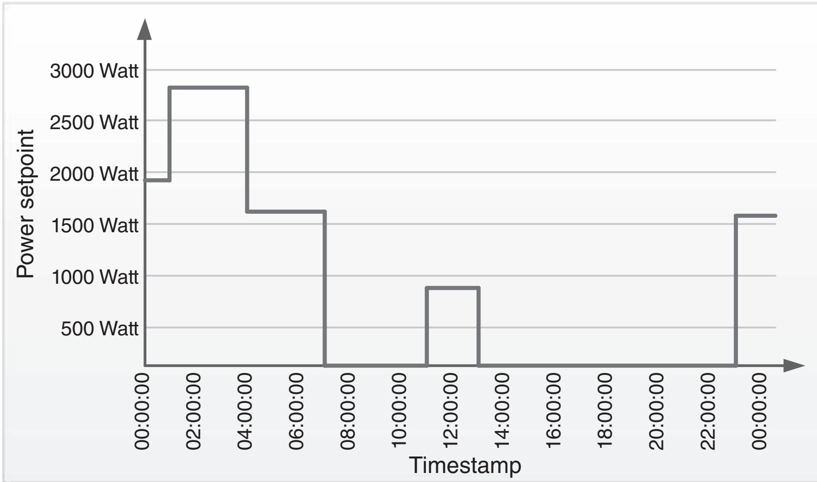

Figure 15.7. Illustration of an EDISON charging schedule.

for this reason the IEC 61850-7-420 extends the standard with the logical nodes for handling absolute and relative timed energy schedules. Consisting primarily of a group of arrays, one of the logical nodes allows for the definition of a series of power setpoints and ramp types together with individual timestamps or time offsets. The usage can vary greatly, allowing the scheduled production of generators, the load of pumps, or, in the case of the EDISON project, the charging schedules for the electric vehicles. Figure 15.7 illustrates how such a charging schedule might look, defining the load the vehicle charger should draw from the grid at the various times specified in the schedule. Though not implemented as yet, support for vehicle-to-grid is easily done with the power schedules by simply stating negative power setpoints.

15.4 SMART CHARGING COMMUNICATION COMPONENTS

This section describes the software and hardware components that have been developed in EDISON to implement the communication interfaces and facilitate smart charging.

As illustrated in Figure 15.8, the components covered in this section will be the I/O board located in the EV and the EVSE, the IEC 61850 compatible server, and the EVPP software used by the fleet operator. The following sections will cover these components in turn.

15.4.1 The IEC 61850 Server

Early on, in the course of the work done in EDISON's work package 3, the IEC 61850 standard was chosen as the main communication protocol between the EVPP and the EVSE.

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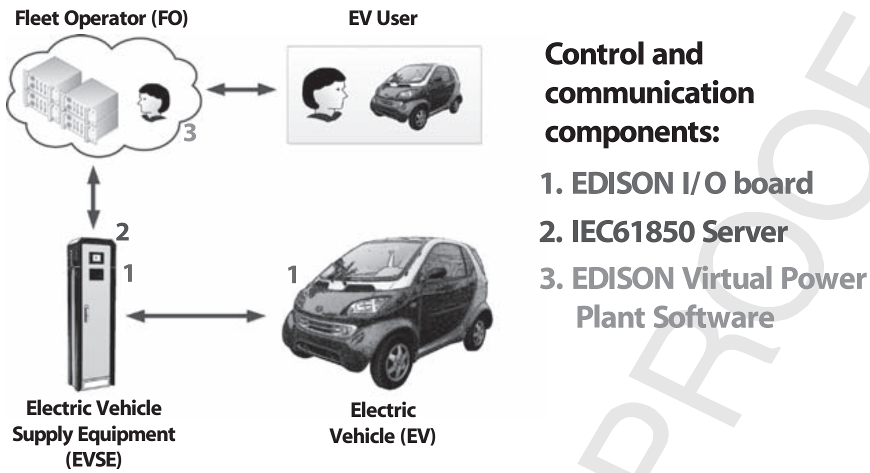

Figure 15.8. EDISON main components.

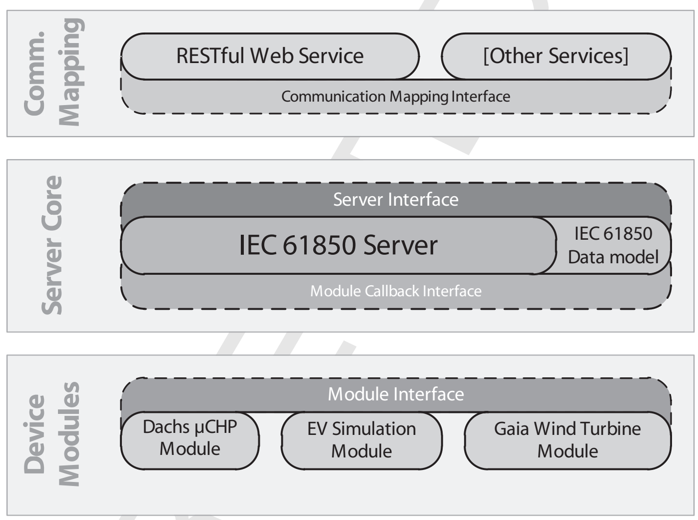

Figure 15.9. System overview of the REST enabled IEC 61850 server.

In order to aid developing and testing, and to get rid of proprietary dependencies, an IEC 61850 enabled server was developed. To further facilitate the interoperability between parties within EDISON, the server was designed with a mapping of the standard to so-called *representational state transfer* (REST) web services. The use of REST services is described in greater detail in Section 15.5.2. Due to its modular construction of the IEC server, it can, however, be extended to support other protocols should the need arise. As seen in Figure 15.9, which gives an overview of the primary server components, the setup comprises three layers. In the middle is the server core, sandwiched between the communication layer and the device modules. The same modularity that enables additions of communication protocols also allows

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the server to support any number of devices through the use of device-specific plug-in modules. In the course of the EDISON project, modules have been written for anything from photovoltaics, wind turbines, micro combined heat and power units, and of course charging sports and electric vehicles.

Successful tests have been carried out with all of the above running off the same server instance. Because electric vehicles have not always been available when needed, and in the quantities needed, a simulation was developed as a specific plug-in device module, enabling any client to access the simulated vehicles and charging spots through the IEC 61850 protocol—as if they were real.

15.4.2 The EDISON VPP

The EDISON VPP is a piece of server-side software that coordinates the behavior of a fleet of EVs while communicating with external power system stakeholders. To illustrate the internal workings of the EVPP, it can be useful to group its functions into three groups: data, analytics, and logic. This is done in Figure 15.10, which also differentiates between the aggregated and the individual level of EV management.

Basically, the EVPP handles the EV fleet as an aggregated group when acting and optimizing toward market players (upper interfaces), but will have to take individual considerations into account when handling the behavior of a single car (lower interfaces). The three main functional groups perform the following:

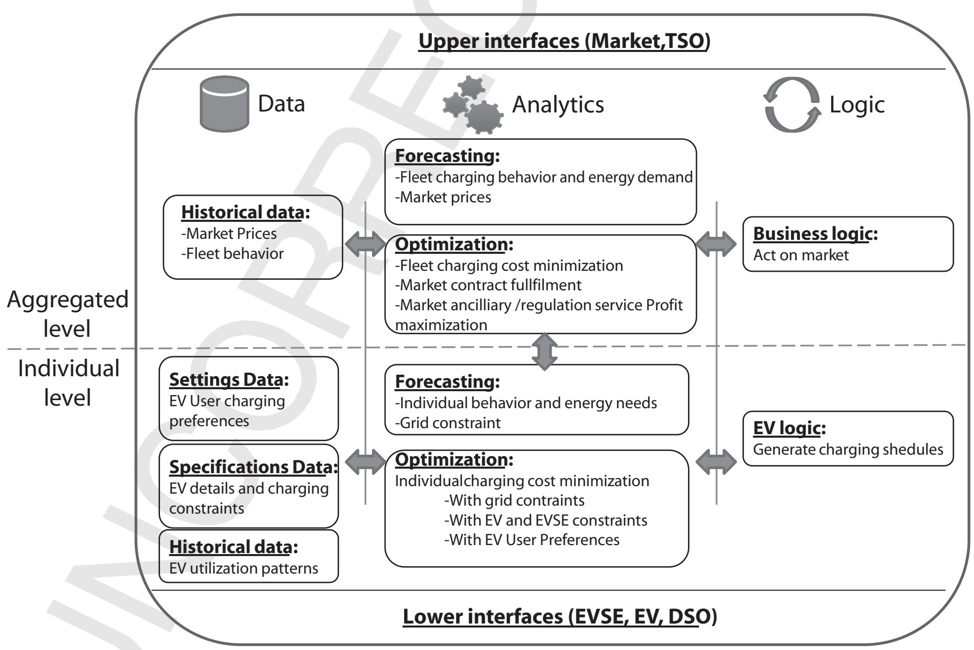

Figure 15.10. EVPP functionality.

- *Data.* This group stores previous market prices and fleet behavior on an aggregated level, enabling better forecasting and optimization for acting on the power market. On an individual level, data are stored that describe the service level agreement between the EVPP and an EV owner, for example, to which degree the EVPP should control the charging process. EV hardware specifications, like battery size and supported charging powers, are also stored. Finally, the EVPP stores the EV users plug-in habits, that is, where, when, and for how long the EV is typically connected to the grid for charging. These parameters are all vital for individually optimizing the charging of an electric vehicle.
- *Analytics.* Analytics means the mathematical computations necessary to support the logic of the EVPP. Forecasting relies on historical data to predict market prices on an aggregated level, which supports better bids and strategies. Forecasting also determines future individual EV usage patterns. The latter helps the EVPP predict when the EV user will need the EV for the next trip and can thus better estimate the time period available for smart charging. Such a prediction can be based on the statistical methods of exponential smoothing or using the Markov chain approach.

  Optimization is used to minimize charging costs of the EVs on both the aggregated and individual level. The individual optimization is limited by the constraints introduced by the distribution grid, EV specifications, and EV user energy requirements. On the aggregated level, profit maximization can be done when acting on the regulating and reserve markets. Such optimization can be achieved through stochastic or linear programming.
- *Logic.* The logic defines the main operational goals of the EVPP, namely, to act on the power market to generate savings or revenue for itself and its clients, and to intelligently manage the charging behavior of EVs through individually tailored charging schedules.

The operation of the EVPP is illustrated through the EVPP panel interface, which is described in Section 15.6.

15.4.3 The EDISON I/O Board

The EDISON I/O board was developed to allow testing of the interface described in the IEC 61851-1 standard, by handling the initial signaling between EV and EVSE. Furthermore, it facilitates the communication with the internals of both the EV and the EVSE and the exchange of information between EV and EVSE.

Figure 15.11 shows the conceptual overview of the features of the I/O board. The board itself has virtually no processing power and in common terms only provides a means of transportation (the envelope) without knowing what is being transported (the content). Hence, an external controller is needed to utilize the features of the board and handle the business logic in the application. As the features needed by an EV and an EVSE are slightly different, the board shall be configured to be used

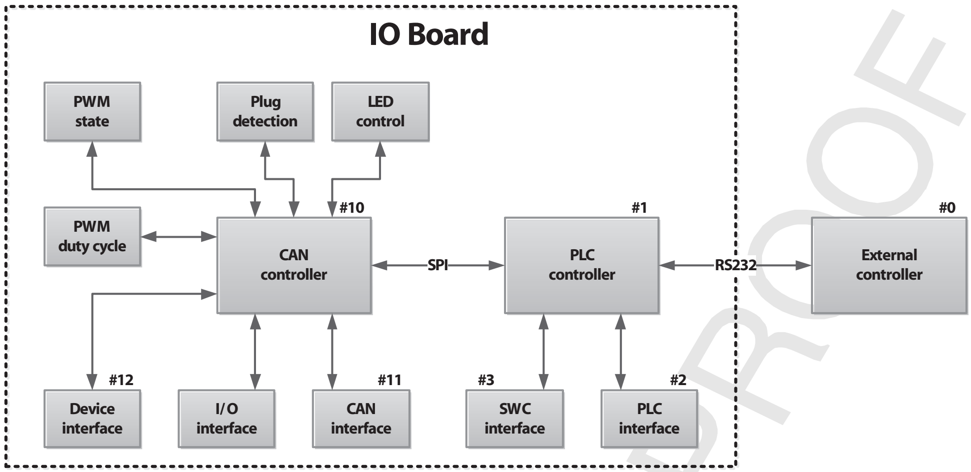

Figure 15.11. Functional modules of the EDISON I/O board.

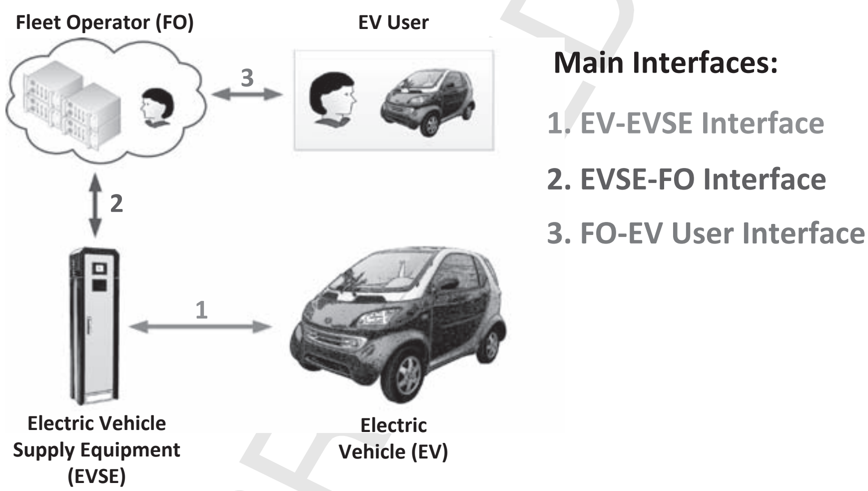

Figure 15.12. Charging infrastructure communication.

specifically for one or the other. As an example, the PWM duty cycle module provides duty cycle selection in EVSE mode and duty cycle detection in EV mode.

15.5 CHARGING INFRASTRUCTURE COMMUNICATION

The main interfaces investigated are those between the EV, the EVSE, the fleet operator, and the EV User, all of which can be seen in Figure 15.12.

The following will describe the main protocols and technologies used in the interfaces that connect the stakeholders.

15.5.1 Interface Connecting EV to EVSE

The question of how to connect the EV with the EVSE is both a question of which physical medium to choose and which standards and protocols to follow. The two main communication technologies that could be considered are wireless and wireline, as discussed in Chapters 6 and 7, respectively.

The use of wireless technologies is researched in several Smart Grid applications to allow for network communication. Wireless technologies such as GSM, GPRS, and 3G are well tested and are valid options for transferring data to and from EVs. The upcoming 4G technology will increase support for applications where high data rates are required. If, or when, all EVs require connectivity for features beyond managing the charging, a constant Internet connection supplied by, for example, 4G could become a necessity.

If, however, the EVs only need Internet connectivity for the purpose of smart charging, such a connection only needs to be maintained for the duration of the electrical connection. In other words, the fleet operator primarily needs to communicate with the vehicle when it is plugged in and it could be practical to use the physical medium already linking vehicle and EVSE, namely, the power cable. *Power line carrier* (PLC), where data is carried on a conductor, is the technology primarily explored by EDISON and the standards. It has been chosen in EDISON for a scenario where EVs would implement an I/O board, as described in Section 15.4, and would not have any permanent wireless network connection. A RENESAS chip is installed using a proprietary PLC technology.

The two standards investigated by EDISON, IEC 61851 and IEC/ISO 15118, both concentrate on using a wired medium but have different focuses on the EV-to-EVSE communication. The communication can, for AC charging using an on-board charger, be divided into initial signaling as described in IEC61851-1 and a high-level protocol-based communication, which is going to be standardized in ISO/IEC 15118.

The initial signaling in IEC 61851 has the purpose of indicating the state of operation between the EV and the EVSE.

State A—No vehicle connected

State B—Vehicle connected, not ready for energy flow

State C—Vehicle connected, ready for energy flow, ventilation not required

State D—Vehicle connected, ready for energy flow, ventilation required

State E—Vehicle connected, charge spot fault

State F—Charge spot not available for action

The EVSE will also be able to signal the maximum charging current back to the EV, in order to protect the EVSE's circuit breaker, allowing for simple load control by an external energy controller or operator.

A high-level IP-based communication protocol, as part of ISO/IEC 15118, would be required for more sophisticated services, including exchange of contract-ID, charging schedules, charging status, and value added services.

15.5.2 Interface Connecting EVSE to Fleet Operator

With the predicted increase in electric vehicle penetration in the coming years and the ever increasing number of players in this field, the use of standards, especially for communication, is one of the primary resolutions of the EDISON project.

For the connection between EVSEs and the fleet operator, the well-tested IEC 61850 standard was chosen. In a bold move, mainly to ease interoperability between parties and facilitate quick prototyping, the traditional MMS standard (ISO 9605) was abandoned in favor of RESTful web service.

15.5.2.1 IEC 61850 Using REST Services. As illustrated in the IEC 61850 section the data model is a hierarchical tree structure and in order to be able to navigate this model, every element has a path that uniquely identifies its position within the structure. All paths are absolute, meaning that they list every element from the root of the structure to the element in question—exactly as seen in a file system and as illustrated in Figure 15.13.

Traditionally, the IEC 61850 standard is paired with a communication standard called the *manufacturing message specification* (MMS), which is extensively used in some industries where it is also known as ISO 9605. Being a binary protocol, MMS requires a detailed understanding just to get started, unless of course one uses a prebuilt API. Unfortunately, only proprietary solutions seem to exist, which further hinders interoperability. In order to better facilitate the communication among components in EDISON, an implementation was developed which enabled the use of IEC 61850 through so called RESTful web services. Apart from the academic exercise, it had the added benefit of allowing IEC 61850 enabled communication across virtually every known computer platform with little effort, improving the interoperability between parties in the project.

The cornerstone in this mapping from IEC 61850 to REST lies in the resemblance between the reference path and the URL scheme used by the HTTP protocol on which REST is based. REST, which is short for representational state transfer, was first introduced in the doctoral dissertation by Roy Fielding in 2000 [8]. Fielding is a coauthor of the HTTP protocol on which the World Wide Web is built and is a cofounder of the Apache Web Server project, the most widely used web server in the world.

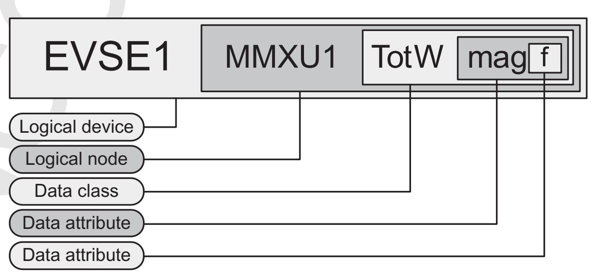

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Figure 15.13. Illustration of the reference path structure for an IEC 61850 element.

Unlike the well-known SOAP services, the RESTful web services do not follow a specific standard, but rather a set of guiding principles central to which is the fact that data should be exposed as a resource. This principle closely adheres to the HTTP protocol; in fact, URL is short for *uniform resource locator*. In its simplest form, data is retrieved from a REST service by issuing an HTTP GET request for the URL representing the data one wishes to retrieve. Using this approach, access to the measurement of Figure 15.13 is a simple matter of retrieving a piece of XML from the URL http://hostname/EVSE1/MMXU1/Tot/*mag/f*, resulting in the following:

```
<DA Name="f" Type="FLOAT32" Ref="EVSE1/MMXU1.TotW.mag.f">0.5</DA>
```

Since REST services put no restrictions on the format used for transporting the data, it is completely at the developer's discretion to use whatever he/she deems suitable. If a file transfer is needed, which the IEC 61850 standard allows (e.g., for transferring configuration files or perhaps performing firmware upgrades), binary data could be the preferred option. In the case of the EDISON REST implementation, the basic format chosen is XML because it allows the relaying of hierarchical data, which means that any portion of the data model could be transferred in a single request. This has some added benefits when clients are discovering devices on the server because it allows them to retrieve the complete setup in a single request, without prior knowledge of the system. The use of IEC 61850 and REST is described by Anders Bro Pedersen et al. [9].

15.5.2.2 The Session Initialization Protocol. REST has inherited many of the benefits from the HTTP protocol, but unfortunately also suffers from one of its main drawbacks when used in a decentralized domain, which is the case with EVSEs: it is client/server based. Because many EVSEs will be attached to either private Internet connections, mobile uplinks, or the like, one cannot expect them to be reachable at a fixed network address as illustrated in Figure 15.14. One solution,

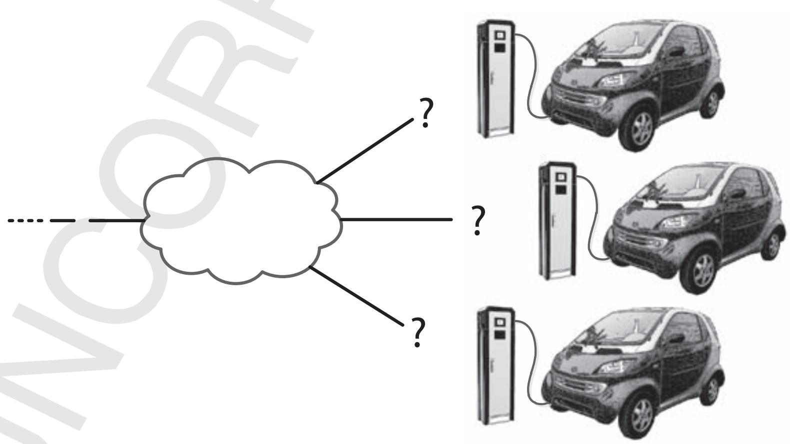

Figure 15.14. Session initiation issues in distributed systems.

the one we propose in the EDISON project, is to use the *session initiation protocol* (SIP), which was designed for use in IP-based cellular systems to solve such issues. The use of SIP has been explored by Bernhard Jansen et al. [10].

SIP, which dates as far back as 1996, is an open and incredibly flexible protocol whose primary purpose is to allow clients to locate and reach each other over the Internet. When an SIP-enabled user agent starts, it contacts an SIP registrar to register its location. When another user agent on the network needs to reach a particular user agent, it does not need to know the location of the other party in advance. Instead, it simply sends an INVITE message to the SIP proxy of its SIP domain. If the inviting user agent and the invitee are in the same SIP domain, the SIP proxy contacts the location service connected to the SIP registrar with the name in the INVITE message to look up the contact's details and then contacts the invited user agent by forwarding the INVITE message. Using the SIP proxies, the session is negotiated and set up between the user agents who, as a result, are provided with the information needed to create a point-to-point connection. Figure 15.15 illustrates the message sequencing for initializing, reinitializing, and closing an SIP session.

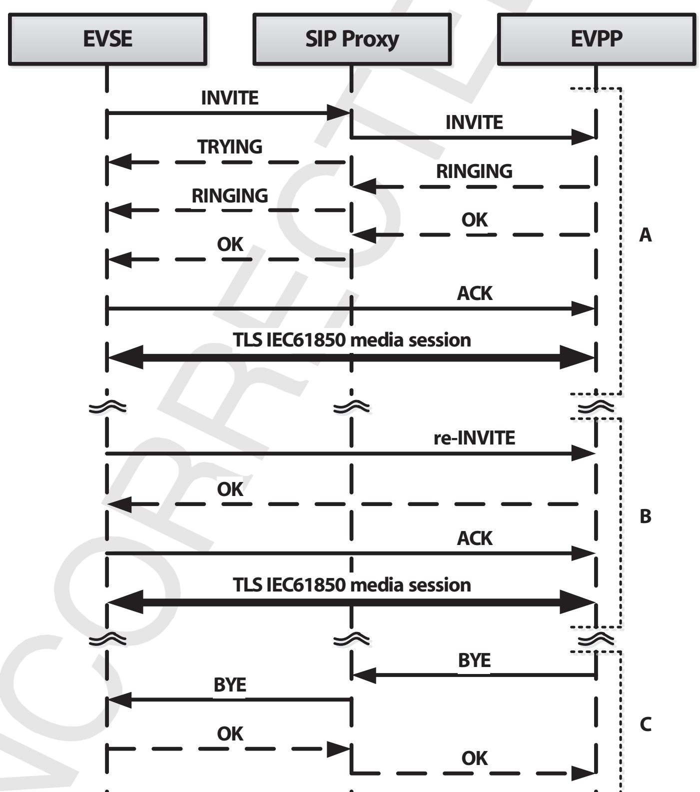

Figure 15.15. (a) SIP INVITE sequence diagram to establish an SIP dialog and a TLS/IEC 61850 session; (b) SIP reINVITE to reestablish a TLS/IEC 61850 session and (c) closing the SIP dialog.

Once the session has been initiated and the direct connection established, any type of traffic can be tunneled through. Because SIP builds on many of the same technologies as the HTTP protocol, it is also capable of using an identical security mechanism such as *transport layer security* (TLS) for encrypting the traffic.

Because SIP separates signaling and media transport, the media sessions are created and closed between requests. Most of the resources otherwise associated with keeping multiple connections open can therefore be freed. The SIP dialog, however, is kept open throughout the entire charging session and allows a quick reestablishment of a media session. As SIP dialog is connectionless, this is very resource effective. This helps to greatly improve the scalability, and effectiveness, allowing the EVPP to aggregate even more vehicles and keep communication costs low.

SIP allows the user agents in the network to be directly connected, but it does not handle barriers such as firewalls and the *network address translation* (NAT) often found in routers. To overcome these issues, the SIP protocol can be extended with additional technologies, such as the *session traversal utilities for NAT* (STUN) and the *traversal using relay NAT* (TURN).

Throughout the EDISON project great effort has been put on using standards for communication, such as SIP, TCP/IP, TLS, and IEC 61850. In this regard the SIP is considered as highly suitable to provide control and data communication between EVSE and the EVPP. As mentioned, the use of the RESTful approach helps to facilitate a much more versatile interface to the IEC 61850 server, but like all client–server communication, has some drawbacks, one of which is the ever present issue with firewalls. By combining IEC 61850 and REST with the use of the SIP protocol and NAT traversing techniques such as STUN or TURN, these issues can, to a large extent, be overcome. This allows SIP/IEC 61850 enabled EVSEs a seamless and scalable integration into an EVPP system, regardless of their location or network connection.

15.5.3 Interface Connecting EV User to Fleet Operator

For intelligent EV charging to be successful, the adherence to the EV user's driving requirements is key. User requirements can range from a general target state-of-charge for the EV to specific requirements such as having the EV at a certain state-of-charge at a certain time. The latter can be important for the user if, for example, he/she wants to leave exceptionally early the next day or go on a long trip.

To explore ways of communicating with the user, a couple of user interface prototypes, both for desktops and mobile phones, are under development within the EDISON project. The desktop interface has the form of a web site and allows the user to sign his/her vehicles up for fleet operator controlled charging, monitor the charging history, and set user specific preferences. The mobile phone interfaces can be divided into two categories: SMS and Internet based.

The SMS-based user interface enables the widest coverage, as most users have at least an SMS capable mobile device. The user then always has the ability to send a status request SMS, for example, the text "?" to a certain number, to which the fleet operator will reply via an SMS gateway, providing the latest information about the state-of-charge. Additionally, the user might receive an SMS when plugging in the EV, containing an offer for doing smart charging.

The Internet-based interaction is either in the form of a device specific application or a web site. While device specific applications probably offer the richest user experience and allow for push notifications to the device, a mobile-specific web site can reach a broader spectrum of devices. In the prototypes of these interfaces currently under development, the user can monitor the charging process, see the fleet operator's current availability prediction for the EV, and update the estimated plug-out time to meet his/her requirements, while still allowing for smart charging. It is important that the user always understands what the server-side system is allowed to do, and what state-of-charge he/she can expect when the vehicle is needed.

Apart from desktop and mobile phone based user interfaces, the EVSE and the EV could also have a user interface, which could offer similar functionality as the mobile phone interface (due to the similar screen size). A solution for these could be to simply host a browser component which displays web pages served by the fleet operator, thus allowing for communication with any fleet operator. Alternatively, device-specific applications could be used to communicate with the fleet operator via web services; this would, however, require standardization of the fleet operator APIs and would make support for different fleet operators difficult.

All of the above-mentioned user interfaces rely on the fleet operator to provide the data and do not therefore require the EV to have a wireless Internet connection.

15.6 DEMONSTRATION

This section shows some of the interfaces developed in EDISON to test and illustrate smart charging.

15.6.1 End-to-End Demonstration: From EV to Operator Panel

The EDISON VPP operator panel has been developed to demonstrate the operation of an EVPP and is implemented as a Microsoft Silverlight application hosted by a web browser. A screenshot of the panel is shown in Figure 15.16.

The interface features the following areas: "1" is a full list of EVs managed by the EVPP followed by a fleet summery in "2." When an EV is selected in "1," its status and data are displayed in the right portion of the interface. While "3" displays the selected EV's last known status, "4" displays a subset of the static information on the specific EV. The EV's location is available to the EVPP when the EV is plugged in and can be seen in "5." The graphs labeled "6" through "8" display information for a selected 24-hour period. Here "6" displays the availability periods

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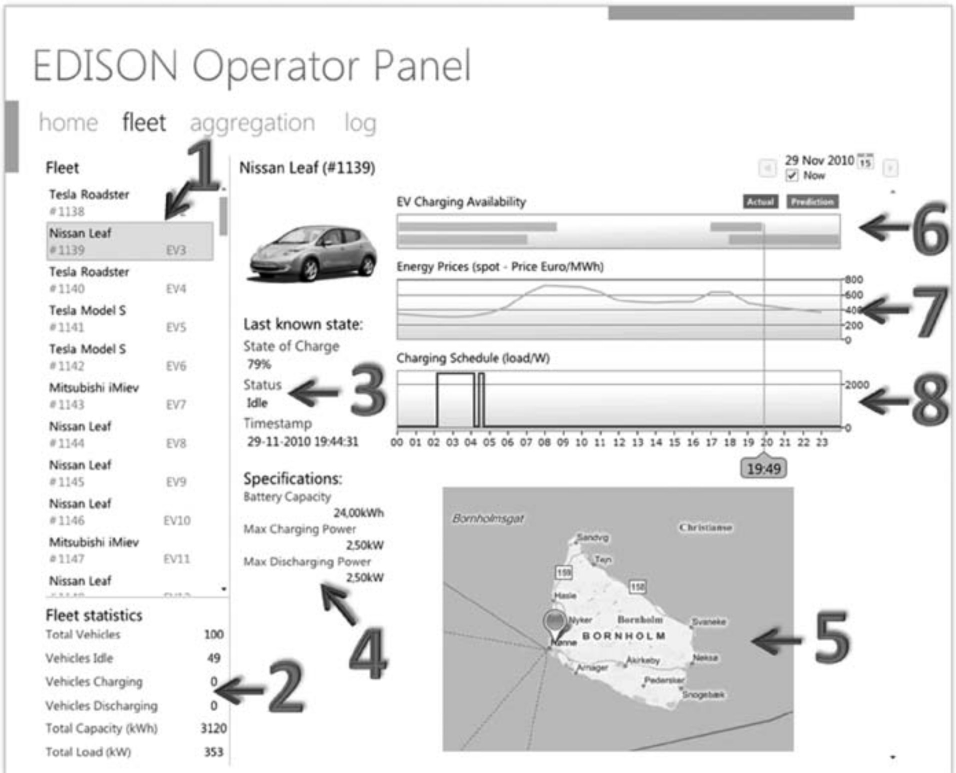

Figure 15.16. EDISON operator panel screenshot.

of the EV, that is, the periods where the car is parked and plugged in. Graph "6" shows both the recorded and predicted availability of the vehicle, illustrated by the upper and lower horizontal bars. Graph "7" displays the energy prices for the time period and "8" shows the charging schedules, which have been generated by the EVPP and are sent out to be executed by the EVSE.

The interface screenshot demonstrates that the EVPP can be connected to a set of real or virtual cars each with their own unique patterns and characteristics, and generate charging schedules that avoid charging at expensive hours. The latter can be seen by comparing prices "7" and charging periods "8" on the screenshot. The EVSE panel is also useful in retrieving and visualizing historical data.

15.6.2 Physical Demonstration Assets

The island of Bornholm has been chosen as a test site for demonstrating the technical solutions developed by EDISON. As an island, it is an isolated environment capable of running independently from the surrounding power system and it has a suitable composition of renewable energy sources, which are representative for the whole of Denmark. It is on Bornholm that the ICT architecture and its components will be

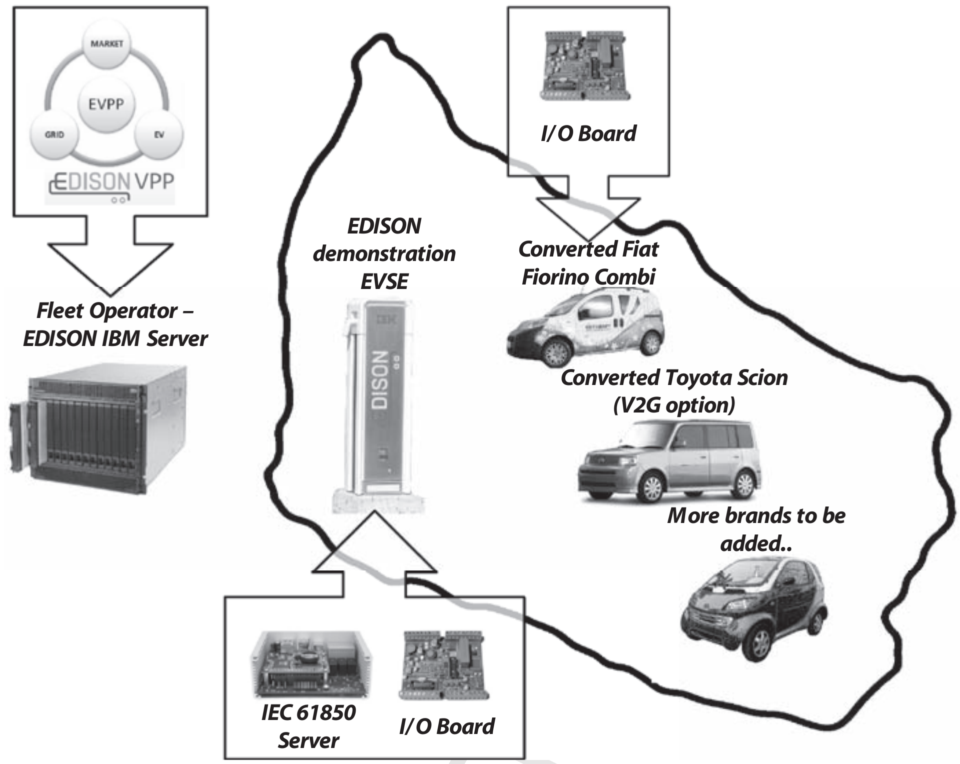

Figure 15.17. Physical demonstration assets of EDISON.

put to the test in managing smart charging for EVs of various brands and types. Figure 15.17 shows the main physical assets that will be used to validate smart charging on the island of Bornholm.

Since at least one brand of EVs (converted Toyota Scion) will support vehicle-to-grid (V2G) technology, the EDISON island demonstration can also cover advanced EV services, in which power is delivered back to the grid. Finally, roaming scenarios can be tested on the island using different EV and EVSE combinations.

Although lessons learned from the physical demonstrations will be an important part of EDISON, the project should also analyze integration scenarios where very high numbers of EVs are introduced on Bornholm. For practical reasons this requires simulations, which are the topic of the next section.

15.6.3 A Large-Scale Virtual Fleet

Potentially massive roll-outs of electric vehicles have been predicted within the next few years and already several major automotive manufacturers are trying to get a head start: most with their individual visions for the future, what it may bring and what may be chosen as the de facto standards. Some are sticking with one type of charging socket, others another. Some are leaning toward battery swapping while others are set on fast charging and so on and so forth. On top of all the above-mentioned uncertainties, there are also questions that need to be answered regarding the impact of all these EVs on the power grid. How will the grid handle the extra load? Where and when will this dynamic load be connecting geographically? Where are the potential bottlenecks in the distribution system? How do we prevent them from occurring? The list goes on.

Common for all these questions is that they represent potential problems, for which we need a solution before the problems actually occur and the only way to test this “in practice” without causing a disaster is through the use of simulations.

For the EDISON project a very flexible EV simulation system was developed as an extension to the IEC 61850 server described earlier.

By using geographic data, demographic statistics, and recorded vehicle data from real-world experiments, large groups of virtual EVs can be created with behaviors closely resembling people’s current driving habits. Because the grid impacts resulting from increased EV penetration is an important topic, it was not enough to simply simulate the consumption of a fleet of vehicles. Instead, using route data obtained from online services, the vehicles were simulated in real time as they would be driving around on the island—see Figure 15.18. In practical terms, it would have been enough to simply calculate the consumption from a given trip and then move the vehicles around, but the added effect of having moving vehicles makes for a very audience friendly demonstration.

Because the simulation runs as an extension of the IEC 61850 server, all devices are automatically made available through the IEC 61850 RESTful interface, allowing the VPP to actively aggregate the whole fleet as if they were real EVs—see Figure 15.19.

15.7 CONCLUSION AND FUTURE WORK

This chapter has explored the technologies used by the EDISON project in terms of communication standards, components, and stakeholder interfaces.

Initial testing indicates that the IEC 61850 and IEC 61851 standards are valid candidates for EV integration. Also, the upcoming ISO/IEC 15118 standard could prove very beneficial for promoting advanced EV services as well as roaming and should be followed carefully. The chapter also puts emphasis on a few selected components that were developed by EDISON partners to demonstrate smart charging. The software and hardware developed for the vehicle, charging spot, and fleet operator will serve as input to standardization work.

Another topic covered by the chapter is the specific protocols that will enable communication in EDISON. In this context we looked at how HTTP based web services and the SIP protocol fulfill certain requirements of interoperability, security, and scalability. Transport layer security (TLS), a technology used in such areas as Internet banking, has been suggested for improving security. Ap

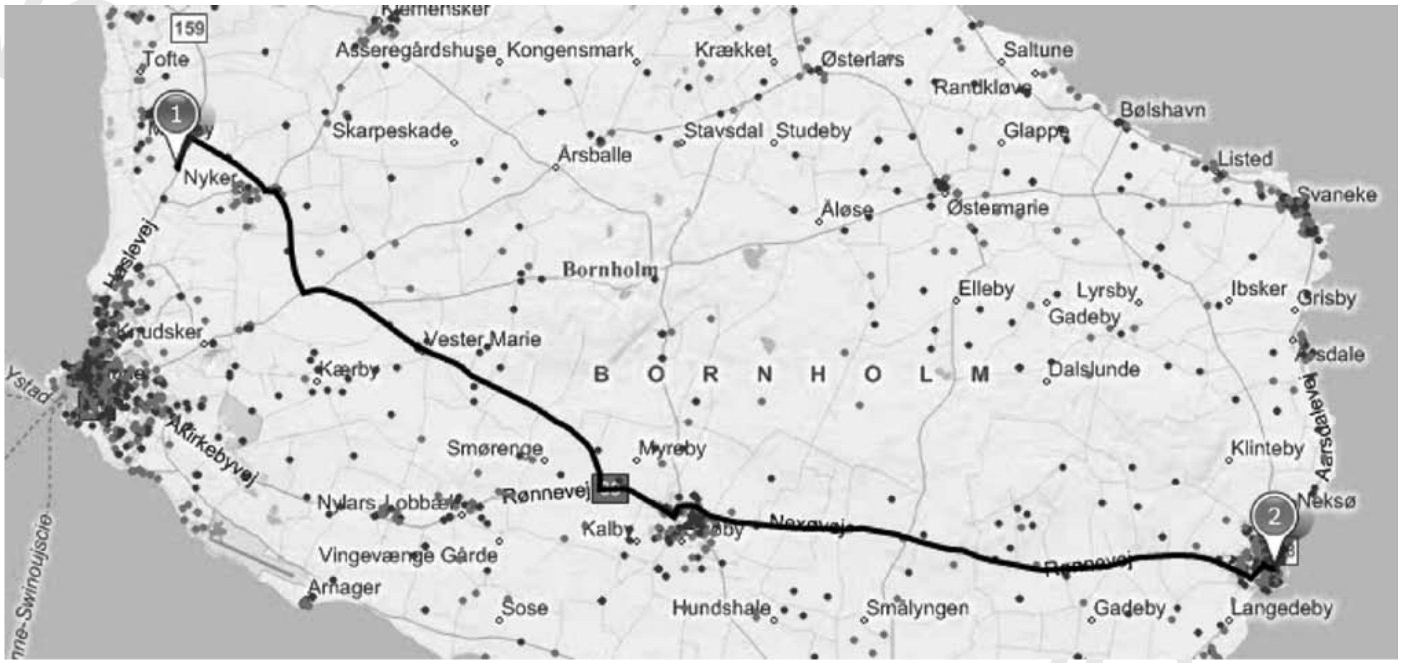

Figure 15.18. Simulated commuter route across the island of Bornholm.

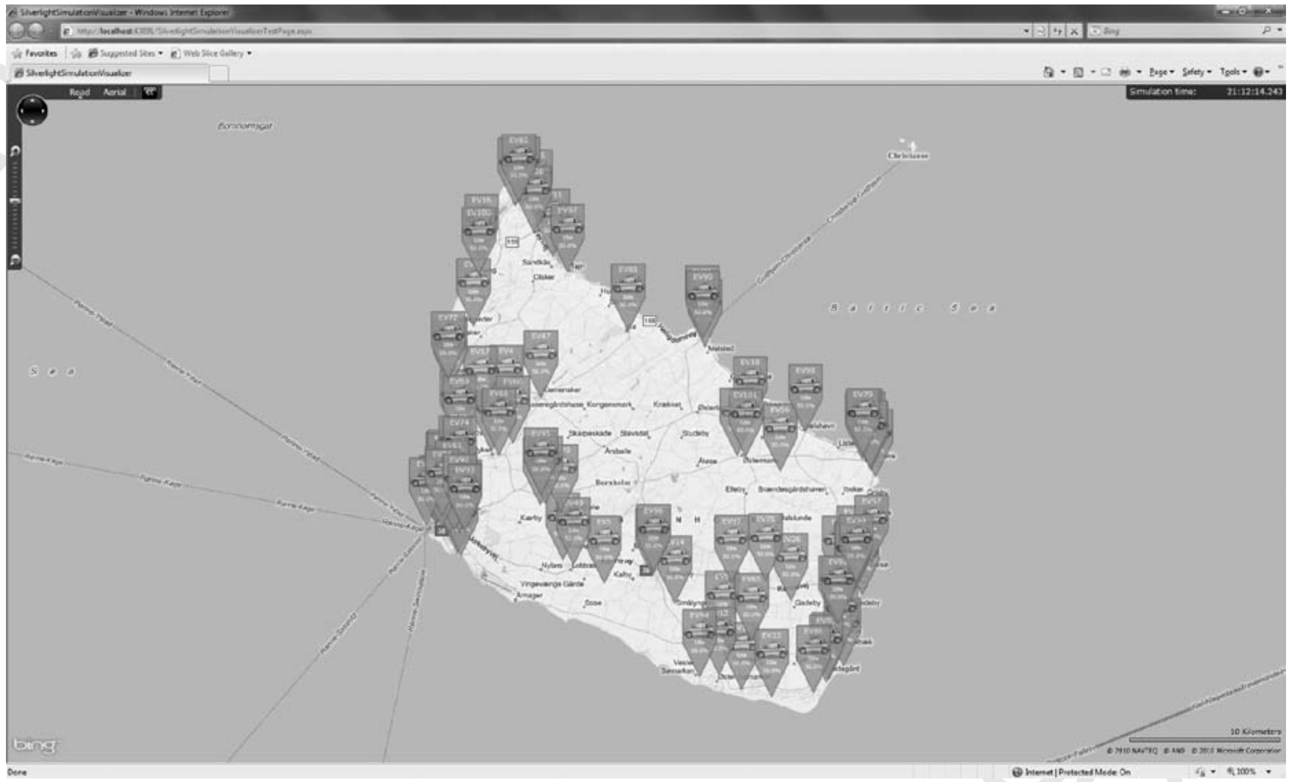

Figure 15.19. Birds-eye-view of medium-sized virtual EV fleet.

The chapter concluded with a few examples of how EDISON aims to prove and validate its work through a set of demonstrations. This includes a field test of an EV fleet on the island of Bornholm and the use of large virtual fleets simulated in software.

A suitable and standardized ICT architecture, which has been the focus of this chapter, is a vital piece in EV integration and a key part of EDISON. Other research areas such as battery technologies, fast charging, and distribution grid impacts are, however, equally important and are covered by partners in the project. Only by covering all topics relevant to society's transition to electric transportation can EDISON achieve its goal of aiding and promoting the cause of the electric vehicle.

The EDISON project will continue with its V2G research and evaluate which standards best support this type of service. While the IEC 61850 schedules presently used support V2G, the OpenV2G project [11], associated with ISO/IEC 15118, and the V2G project [12], led by Professor Willett Kempton from the University of Delaware, both represent possible alternatives and should be studied thoroughly.

The progress of EDISON is continuously updated on the project web page.

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A.6 Implementation of an Electric Vehicle Test Bed Controlled by a Virtual Power Plant for Contributing to Regulating Power Reserves

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Implementation of an Electric Vehicle Test Bed Controlled by a Virtual Power Plant for Contributing to Regulating Power Reserves

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***Abstract*-- With the increased focus on Electric Vehicles (EV) research and the potential benefits they bring for smart grid applications, there is a growing need for an evaluation platform connected to the electricity grid. This paper addresses the design of an EV test bed, which using real EV components and communication interfaces, is able to respond in real-time to smart grid control signals. The EV test bed is equipped with a Lithium-ion battery pack, a Battery Management System (BMS), a charger and a Vehicle-to-Grid (V2G) unit for feeding power back to the grid. The designed solution serves as a multifunctional grid-interactive EV, which a Virtual Power Plant (VPP) or a generic EV coordinator could use for testing different control strategies, such as EV contribution to regulating power reserves. The EV coordination is realized using the IEC 61850 modeling standard in the communication. Regulating power requests from the Danish TSO are used as a proof-of-concept, to demonstrate the EV test bed power response. Test results have proven the capability to respond to frequent power control requests and they reveal the potential EV ability for contributing to regulating power reserves.**

***Index Terms*— Electric vehicles, Test Bed, Regulating power, Virtual Power Plant**

I. INTRODUCTION

THE Electric Vehicles and Plug-in Hybrid EV (PHEV) are expected to play an important role in the future power system. Within smart grids research, electrical transportation has a complementary role in the overall system management of energy and power [1]; moreover the European target on reducing CO_2 emissions and increasing penetration of renewable energy are among the major drivers for the research [2].

The energy storage capability is the key factor for smart grid applications of EV in power system. When parked and plugged into the grid, EV are expected to either charge intelligently, or discharge feeding power back to the grid [3]. In the latter case, EV would enter a mode known as Vehicle-to-Grid (V2G), permitting the provision of several grid services [4]. In general, if the individual EV can be intelligently managed, a large number of such vehicles can become an asset in the future power system. The charging process could be controlled by modulating the charging power, as well as the discharging process, by enabling the V2G mode when there is a need from the grid [5]. Many projects are addressing the aforementioned EV operation, as coordinated charging using different simulation tools. In [6], the authors analyze, through dynamic simulations, the potential daily profits for EV users, with the provision of regulating power. In [7], the authors studied the benefits offered by EV for facilitating the integration of large scale wind power in Denmark; EV fleets are modeled in a simulation platform as storage units when charging or as small generators during V2G operation. Galus et al. in [8] presented a method for tracking secondary frequency control using groups of PHEV and a simulation platform to simulate an EV aggregator.

The participation of EV in regulating power schemes is possible using an aggregation entity for EV coordination. This is done in the Danish EDISON project [9]-[10], where the contributors proposed a centralized coordination solution for an efficient integration of EV in the power system. The aggregation technology is based on the Virtual Power Plant (VPP) concept [11], where the Edison VPP is the EV coordinator.

Evaluating the contribution of an EV for regulating power reserves in a VPP framework, where a huge amount of communication and hardware interfaces are involved, gives raise to the need of new grid-interactive evaluation platform.

This paper describes the implementation phases of an EV test bed, working under the coordination of a VPP and contributing in regulating power reserves, as secondary frequency control [12]. A real regulating power request from the Danish Transmission System Operator (TSO) is processed by the VPP and sent in form of a charging/discharging power schedule to the EV test bed.

Test results performed using the EV test bed show that an EV is in fact capable of real-time communication with a VPP and can quickly react to contribute to grid power reserves.

II. ELECTRIC VEHICLES FOR SMART GRIDS

The interaction between EV and the electric power system is only possible if the vehicles can connect to the electrical

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grid for charging.

An effective interaction between EV and grid requires the combinations of different factors such as:

- Grid interactive vehicle architectures;
- Controllable charging/discharging operation;

A. Electric vehicle architectures

Among different types of hybrid electric vehicles and pure electric vehicles, a general distinction is based on their ability to plug-in. In this work, non plug-in hybrid vehicles will be disregarded, as an interconnection with the grid is not possible.

This section lists the system architectures capable of charging using the grid [13]. There are mainly two classes of plug-in EV: plug-in hybrid EV (PHEV) and battery-powered EV. An overview on the different architectures is depicted in Fig. 1.

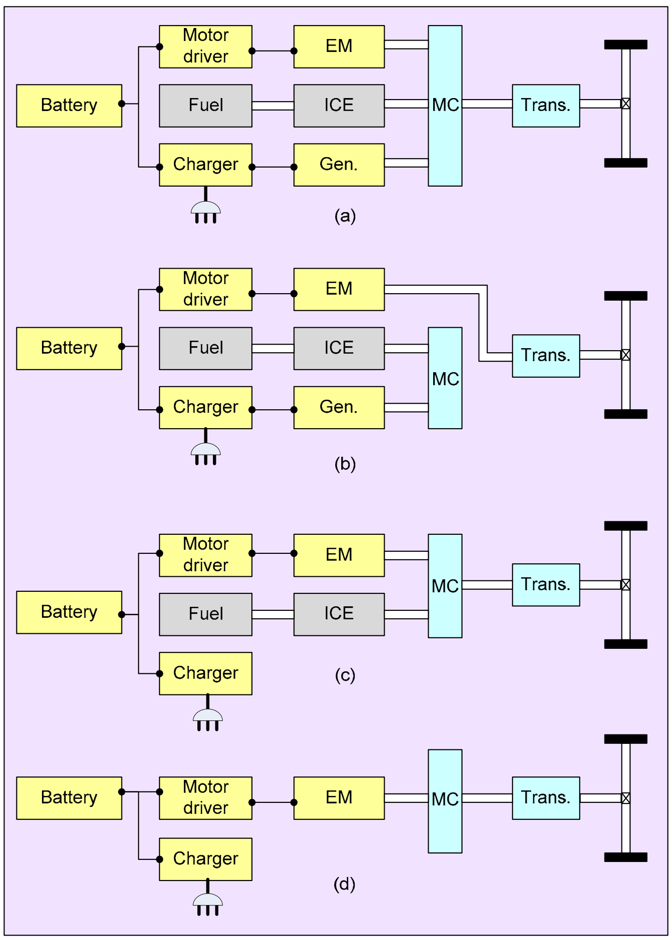

Fig. 1. Plug-in Electric Vehicles system architectures. (a) Series-parallel hybrid EV. (b) Series hybrid EV. (c) Parallel hybrid EV. (d) Battery-powered EV

In the PHEV class, three variants have been developed so far:

- Series-parallel hybrid
- Series hybrid
- Parallel hybrid

The main difference among the topologies is the drive system used and the interconnection of its components, before the power is transferred to the wheels.

In the series-parallel hybrid vehicle, Fig. 1 (a), the system is designed to operate both in a series or parallel configuration. The reconfigurable system is made possible by the use of a planetary gear, which is the mechanical coupling (MC) for the three machines. In the series hybrid vehicle, Fig. 1 (b), the electric traction system and Internal Combustion Engine (ICE) system operate in a series connection. In sequence, the ICE is coupled with a generator (Gen.) which generates the electric power for recharging the battery, the battery then supplies an electric motor driver to transfer power to wheels. In the parallel hybrid vehicle, Fig. 1 (c), the ICE and electric motor (EM) operate in parallel mode, where the ICE supports the electric traction at certain points of the driving pattern, e.g. when higher power is needed to the wheels.

In the battery-powered EV class, Fig. 1 (d), the drive system is realized using only an electric motor and a motor driver. Therefore the only energy source is the battery pack.

In this work a battery-powered EV is the architecture chosen for the EV test bed implementation.

B. Controllable charging/discharging operation

All plug-in EV are able to absorb power from the grid while charging their battery packs. The controlled charging or discharging (V2G) process can be achieved using different infrastructure concepts, such as home charging or public charging stations [14]. According to the IEC 61851 standard [15], the most common power rates for domestic and public charging are depicted in Table I.

TABLE I
CHARGING POWER RATES

AC current	AC voltage	Grid connection	Power
10 A	230 V	single phase	2.3 kW
16 A	230 V	single phase	3.7 kW
32 A	230 V	single phase	7.4 kW
16 A	400 V	three-phase	11 kW
32 A	400 V	three-phase	22 kW

All power rates, regardless of charging or discharging, are characterized by an AC current, usually 16A or 32A, and based on the grid connection type, single-phase or three-phase.

In this work a charging/discharging power rate of ± 2.3 kW is used for the experimental validation.

C. Planned EV test bed operation with Virtual Power Plant

The EV system architecture is planned to respond to different control signals from a centralized EV coordinator.

The control signals for the vehicles can be generated by a VPP and based on different variables such as the power system frequency, the market spot price and others.

In this paper, the centralized control concept for EV fleet management as described by Binding et al. in [10] is used as a study framework. The EV test bed operation is planned within the VPP framework depicted in Fig. 2. Different interfaces have been defined to establish communication between the Edison VPP and other entities in the architecture. While a generic VPP can aggregate and control various distributed energy resources (DERs), e.g. combined heat and power units (CHPs), PV plants, wind turbines, medium/large consumers, other power units and smart houses, in this paper, only EV are considered.

An interface with the TSO is defined to receive the activation commands for accepted regulating power reserves contracts.

An interface with the Distribution System Operator (DSO) is also defined to collect the grid status for the location of every connected EV. Grid constraints are considered at this interface, to ensure that the charging/discharging operation complies with power quality issues. In addition, the metering information for accounting is also collected via the DSO interface.

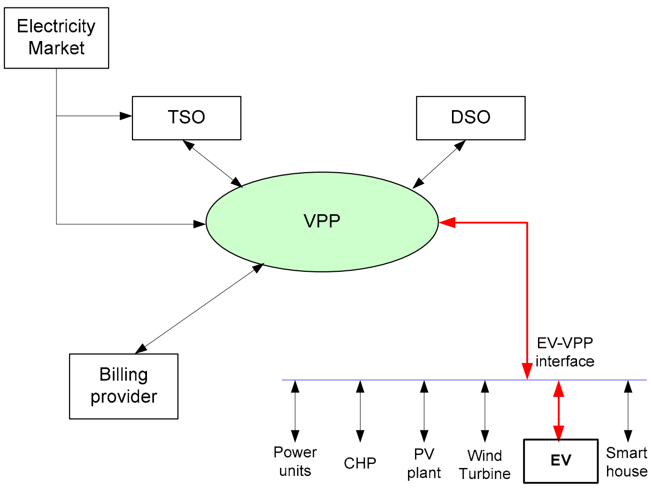

Fig. 2. EV test bed operation in a Virtual Power Plant framework

The transaction interface with a billing provider is used to perform billing to the resources providing regulating services.

In this paper, the EV-VPP interface is implemented to establish communication between the VPP and the EV test bed. The control requests for the EV test bed are generated from the VPP, based on the grid needs of regulating power reserves of the TSO.

III. Test Bed Implementation

Designing an EV test bed for testing the potential EV operation with a VPP was performed in two phases:

- Planning the EV test bed architecture
- Dimensioning the EV components

A. *Planning the EV test bed architecture*

With reference to the EV architectures described in Section II, a battery-powered EV architecture was the choice for the EV test bed implementation. The main reasons for choosing this architecture is that with a pure battery EV, zero emissions can be achieved during driving [16], while grid interaction is more meaningful, due to a larger storage capacity.

In a battery-EV the following components can be considered:

- a battery pack
- a battery charger
- a BMS
- a three-phase motor driver
- an electric motor

For the scope of the study, the three-phase motor driver and the electric motor are not needed, therefore these two components were not considered in the development.

Since with the architecture of Fig. 1 (d), the V2G operation is not possible, this was enhanced by adding a V2G unit which could operate in a complementary way to the charger. The implemented EV test bed architecture is shown Fig. 3.

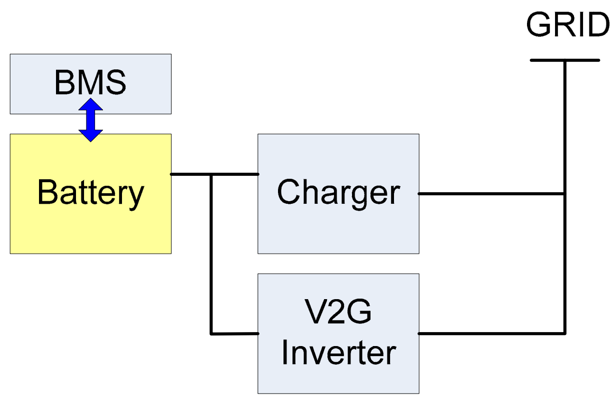

Fig. 3. EV test bed architecture

The battery pack is interfaced to a battery management system (BMS), which monitors its status.

The charger is designed as an AC/DC converter, directly connected to the main grid, by means of a three phase cable connection; while the V2G unit is made of a single phase DC/AC inverter.

It is worth noticing that, since the aim of the EV test bed is to emulate a real EV connected to the grid, all EV components were dimensioned according to realistic EV energy and power levels.

B. *EV test bed components*

The design of the battery pack took into account the following requirements:

- Common designs of battery-EV [17][18]
- V2G operation requirement

The choice of a battery technology to use for the test bed was based on the analysis of current market trends for EV. Some consulting companies, e.g. Frost & Sullivan [19], foresee more than 70% of EV in 2015 to be powered by lithium-ion (Li-ion) batteries. Compared to other battery technologies, Li-ion batteries offer a greater energy-to-weight ratio, greater power levels and low self-discharge when not in use [16]. For the reasons mentioned, a Li-ion battery was the choice for the EV test bed.

The electrical features of the battery pack were chosen considering common designs of EV battery packs. Generally battery-EV have battery pack voltages in the range of 300-400V and a battery capacity of at least 10-15 kWh. A battery pack was designed integrating 110 Li-ion series connected battery cells, which leads to a total nominal pack voltage, V_{pack}, of 363 V. Each cell has nominal voltage V_n, of 3.3 V and nominal capacity C_n, of 40 Ah.

Based on the nominal parameters, the following expression is valid for calculating the nominal battery energy:

$$E_n = V_{pack} \cdot C_n = N \cdot V_n \cdot C_n \quad (1)$$

where N is the number of cells.

The requirement of V2G operation, a DC/AC power converter with input DC voltage in the range of 250 – 500 V was used. The rated output power of the V2G inverter is about 4 kW, which leads to a maximum generated AC current of around 16 A. The V2G inverter is also equipped with an internal transformer, which serves as galvanic isolation.

A battery management system (BMS) is linked to the battery pack. The main function of the BMS is to ensure a safe operation of the battery pack during charging or V2G operation. It estimates the SOC information which is used by VPP and monitors the battery voltage, current and temperature.

The charger was designed as a single-phase AC/DC. The output voltage V_{dc} was dimensioned using the empirical formula shown below, according to [20]:

$$V_{dc} = 1.25 \cdot V_{pack} = 453\ V \quad (2)$$

The current I_{dc} on the battery side is dimensioned of 10 A at full load, which leads a charging power of about 4.5 kW.

The implemented test bed with integrated EV components is depicted in Fig. 4.

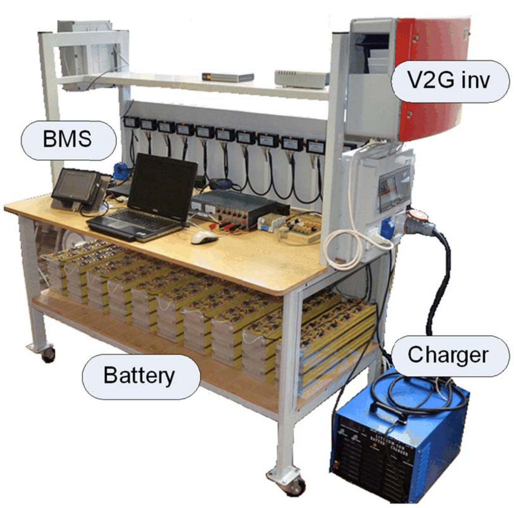

Fig. 4. EV test bed

IV. Communication and Control with VPP

As previously mentioned, the EV test bed was designed to operate as part of a centralized aggregation framework, under the direct control of a VPP, as described in [21]. For the purpose of future research, it will be possible, in any case, to adapt the software system in order to e.g. test decentralized control schemes.

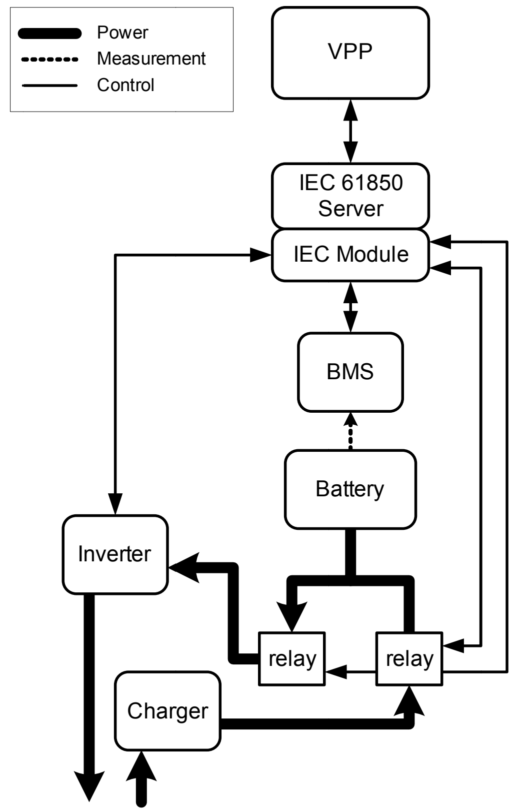

Fig. 5. EV test bed communication and control architecture

To facilitate centralized coordination, the VPP-to-EV interface was implemented in accordance with the communication and control architecture depicted in Fig. 5.

The communication is based on the well-established IEC 61850 standard [22]. As an academic exercise and in the attempt to promote the use of existing web standards in power system communication, the IEC 61850 standard was mapped to HTTP/REST. This work was presented in details in [23].

The VPP used for this paper was designed by Pedersen et al. [23] and has been used for generating and sending power schedules, in response to the requirements for regulating power reserves specified by the TSO.

Though used for an EV test bed in this case, these schedules are simply based on positive/negative power requests with an associated time stamp. For this reason, they are potentially applicable to any type of Distributed Energy Resource (DER) [24].

A. IEC 61850 Server and Module

The server, which was developed in compliance with the IEC 61850 standard, is designed based on a modular plug-in architecture, in order to facilitate an easier adaptation and installation of new devices of virtually any type [23].

A device specific plug-in, or IEC Module, was implemented, in order to enable direct control of the test bed from the VPP, as well as to facilitate the collection of battery status information along with any other measurements.

Because the charger and inverter are two separate pieces of hardware connected to the same battery, an algorithm was written into the plug-in module to guarantee the mutually-exclusive operation of the connecting relays. This prevents the simultaneous operation of both devices.

Another communication link is established between software plug-in and the BMS to extract the state-of-charge (SOC) information from the battery.

B. Charging

As indicated by Fig. 6, there is no direct control link between the IEC Module and the charger; this is because the charger has not communication interface for remote control. For the purpose of this paper, the charger is fixed to a fixed power rate and is coupled or decoupled from the battery by means of a DC relay, which is controlled via RS232, as illustrated in Fig..

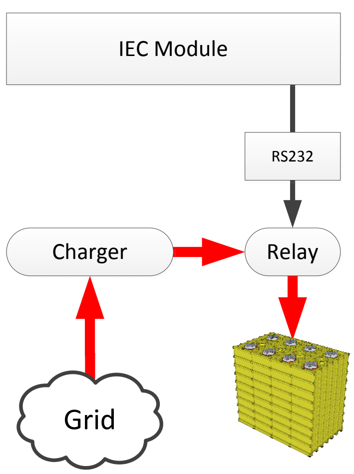

Fig. 6. Charging communication in detail

As previously mentioned, the charger and inverter are both connected to the battery pack using two mutually exclusive relays. In order to ensure that the devices have exclusive "access" to the battery, a simple timing scheme was used in the IEC Module. As depicted in Fig., a time gap was added between two switching events to ensure a safe transition.

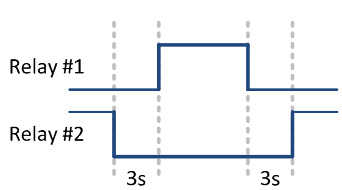

Fig. 7. Relay timing scheme

C. V2G

The coupling of the V2G inverter is achieved by means of an identical DC relay as for the charger. Under V2G operation, the generated power level is controllable and this is managed through an attached communication hub. The same hub implements an HTTP/JSON web interface. A more detailed illustration of the V2G architecture used for the EV test bed is depicted in Fig. 8.

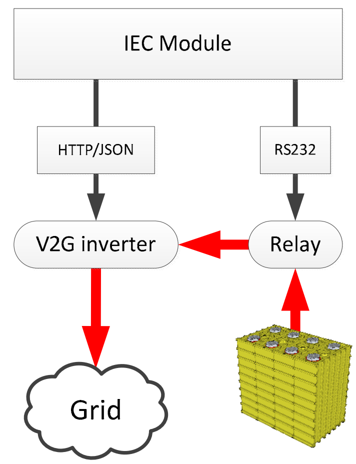

Fig. 8. V2G communication in detail

D. Battery Status Information

The real-time status of the battery is monitored by the BMS. The BMS information is acquired by the IEC Module using RS485 based serial communication link. By means of this link, all battery data can be extracted as a set of values and made available to the VPP via IEC 61850 for detailed monitoring. The set of values includes:

- Battery pack voltage
- Current
- State of charge
- Temperature in different areas of the battery pack
- Remaining energy and single cell voltages

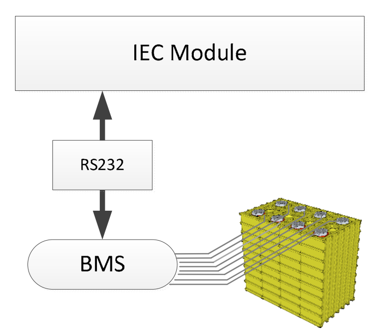

Fig. 9. BMS communication in detail

The BMS comes equipped with an RS232 port for remote monitoring of the battery pack, as well as controlling various limits/alarms. Connected to the BMS are a series of sensors, which connection are depicted as a series of smaller wires in Fig..

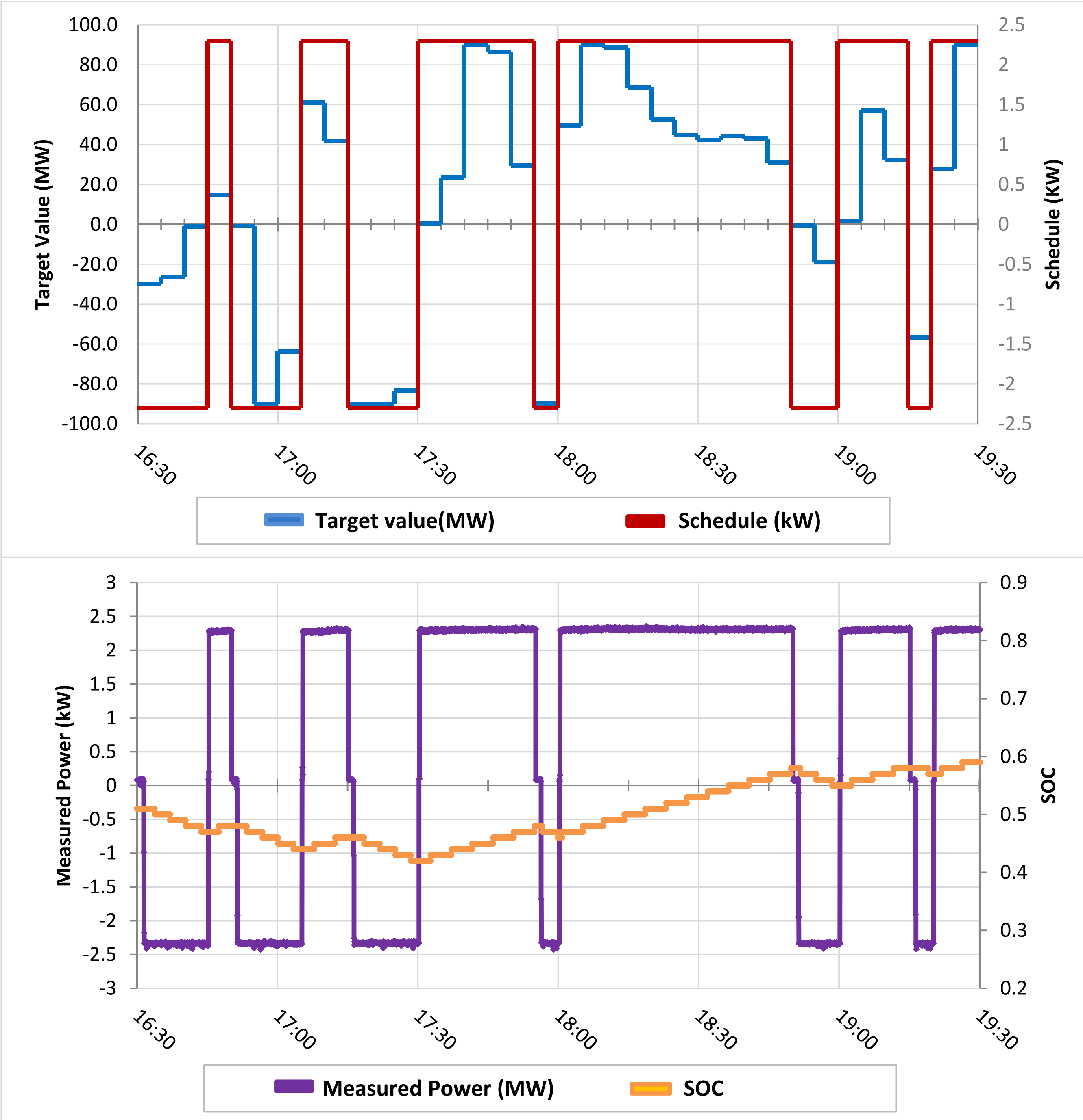

Fig. 10. Test results of EV test bed contribution in regulating power service – Secondary control. (a) Target regulating power of the Danish TSO and VPP generated schedule for the EV test bed and the other EV. (b) Measured power response and battery SOC of EV test bed.

V. Experimental Results

The EV test bed participation in regulating power reserves was tested considering the regulating power required for secondary control, by the Danish TSO, on the 1st of January 2009 [25]. The regulating power profile sent from the TSO to the VPP is given in 5-minutes average MW values as shown in Fig. 10(a). The target regulating power is derived by the sum of all up and down regulation requests sent out by the TSO to an array of providers in the same 5-minutes. The target anyway does not reflect the exact need of the system but rather the value is used to drag the providers in the right direction. Nevertheless, the target value is a very good approximation to the real-time need of regulation reserves.

A new schedule, related to the TSO power target, was generated by the VPP every 5-minutes, and sent to the EV test bed. The regulation was tested in the time interval 16h30 to 19h30. The schedule is shaped as ±2.3 kW power requests with time stamps, indicating the activation/deactivation time of charging and V2G mode, Fig. 10(a). Since each EV has a very small capacity compared to the grid needs, it was assumed that the VPP meets the TSO target by aggregating a number of simulated EV. The EV system response, Fig. 10(b), is taken measuring the electric power flow at the point of common coupling (PCC) of the EV test bed with the grid. The power was recorded with 1 minute sampling time. Test results are depicted in Fig. 10(b). It is possible to observe that the EV test bed is able to react in real-time to the power schedule sent by the VPP. The measured power profile in Fig. 10(b) validates the effectiveness of the EV architecture proposed in this work. Furthermore, the SOC profile shows the energy variation in the EV test bed battery, during the regulation service. The EV test bed started to contribute to regulating power service with an initial SOC of about 0.5 or 50%.

VI. Conclusions

Testing the capabilities of EV for smart grid applications requires the development of adequate evaluation platforms. In literature it was demonstrated that EV can potentially operate under a number of coordination schemes, including the participation in regulating power reserves. While this was extensively presented by simulation scenarios, in this paper, a real implementation of regulating power reserve performed by a full-scale EV test bed was presented. The test bed was designed to flexibly interact in real-time with an EV coordinator and the electricity grid, under different coordination concepts. To do so, real EV components and communication interfaces were used, that make possible an end-to-end interaction with a VPP. The implementation of an EV test bed from scratch enabled the management of the single components involved in the EV system: charging/discharging units and BMS. With the implemented communication and control architecture it was possible to establish a stable communication between the EV the test bed and the Virtual Power Plant.

The potential offered by EV for regulating power was demonstrated testing the EV test bed hardware and software interfaces. An array of regulating power requests (load frequency control) within a 3-hours time interval, sent by the Danish TSO on the 1st of January 2009, was used as study case. The TSO target values were converted to an EV compatible schedule by the Edison VPP and sent down to the EV test bed among the other simulated EV. Test results revealed the potential capability of EV to respond in real-time to different charging/discharging requests based on different coordination plans. Further investigations will be performed for evaluating the reliability of the communication involved, when several fleets of EV are simultaneously coordinated.

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