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A Virtual Power Plant on the Island of Bornholm

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Electric Vehicle Fleet Integration in the Danish EDISON Project - A Virtual Power Plant on the Island of Bornholm

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Abstract—**The Danish EDISON project has been launched to investigate how a large fleet of electric vehicles (EVs) can be integrated in a way that supports the electric grid while benefitting both the individual car owners and society as a whole through reductions in CO_2 emissions. The consortium partners include energy companies, technology suppliers and research laboratories and institutes. The aim is to perform a thorough investigation of the challenges and opportunities of EVs and then to deliver a technical platform that can be demonstrated on the Danish island of Bornholm. To reach this goal, a vast amount of research is done in various areas of EV technology by the partners. This paper will focus on the ICT-based distributed software integration, which plays a major role for the success of EDISON. Key solution technologies and standards that will accommodate communication and optimize the coordination of EVs will be described as well as the simulation work that will help to reach the goals of the project.**

Index Terms—**Electric Vehicles, Virtual Power Plant, Distributed Energy Resources, Distributed Production, Demand Response, Vehicle to Grid**

I. INTRODUCTION

The depletion of oil reserves and the increase of CO_2 emissions associated with traditional combustion engines have sparked interest in the potential use of electric vehicles (EVs). In parallel, we also observe an increasing number of renewable energy sources, such as photovoltaic panels and wind turbines. These distributed, and intermittent, energy sources pose some challenges to the electricity grid in terms of balancing the power generated and consumed at all times. Sufficient balancing and reserve power has to be made available to offset the natural variations in power generated from these renewable energy sources as well as to accomodate the probabilistic load behaviour of an EV fleet.

If a fleet of EVs can be managed appropriately, a large share of such vehicles can become an asset for the electric grid: electrical load can be shifted in time, and excessive EV battery energy could be fed back into the electrical grid. This concept is known as vehicle-to-grid (V2G) technology. In [1], [2] the authors estimate the value of using the EVs for providing grid support services. The various markets for V2G are presented and it is shown that a significant profit can be made with V2G.

Seen from the ecological point of view, EV fleets can only be sustained if they mainly use energy generated by CO_2-neutral sources. A commonly accepted method is to aggregate the EVs and renewable energy resources into virtual power plants (VPP) [3], [4], [5], [6], [7], [8]. Each of the members in the VPP then represents one of the various distributed energy resource (DER) types, i.e. EVs, photovoltaic panels, wind turbines, and μCHPs[1].

Our focus in the EDISON project is aimed at the challenges of having a sizeable fleet of EVs in an electrical grid. The issues to accommodate this increased load in the electric grid have been studied by various groups, for example, in [9] and [10]. In [9], the authors emphasize the importance of providing a time-of-day pricing of electricity in order to shift charging events to off-peak hours at night and thus balance the grid.

VPP operation and planning involves several non-trivial optimization problems. The first problem is how to schedule the charging of the EVs while respecting grid constraints, production constraints, consumption whilst minimizing costs. In [11], a method of iteratively solving a quadratic program to minimize the losses in the grid is explained. However, the price of energy is not considered, which is likely to substantially affect the time of charging.

To realize the potential of using V2G in a VPP, a distributed platform has to be defined in which each car, i.e., its owner or operator, is encouraged to participate actively in supporting a power system which may include substantial amounts of renewable energies. This platform needs to interface with the power system infrastructure and power market stakeholders when planning the operation of a fleet of EVs. At the same time, the system will have to respect both the charging preferences of the individual car-owners and the electrical constraints of the distribution network to which each car is connected. This can be achieved by exercising soft real-time control of individual EVs connected to the electrical grid.

It is the goal of the EDISON project to create such a platform to support the optimal integration of EVs. The project will investigate V2G technologies and demonstrate the above-mentioned platform on the Danish island of Bornholm. In fact, the platform should be applicable wherever EVs (including total electric vehicles (EV) or plug-in hybrid EVs (PHEV)) are

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The EDISON project is an international research project partly publically funded through the Danish transmission system operator (TSO) Energinet.dk's research programme FORSKEL. The total budget is approximately 49 millions DKK, with 33 millions DKK thereof coming from FORSKEL.

[1] micro Combined Heat and Power plant.

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to be introduced with maximum benefits for all stakeholders.

To estimate the impact of EV fleets on the island of Bornholm, the EVs and the electricity grid have been simulated. The interaction of EV traffic with the power system has been analyzed by Galus *et al.* [12] and Kulshrestha *et al.* [13]. Galus *et al.* study the concept of a multi-energy carrier hub combined with a detailed traffic simulation. Our approach differs in that we consider not only energy hubs with a large number of vehicles but also single-car charging stations. The approach of Kulshresta *et al.* [13] is similar to ours. A hybrid simulation system mixes continuous-state entities with discrete events for traffic simulation (see also [14] for systems to study stability issues in electrical power systems).

The remainder of the paper is organized as follows: Section II describes some standards and components that will be integrated in the proposed VPP. Section III introduces the virtual power plant concept in more detail, and Section IV presents possible architectures for the proposed VPP for EDISON. Section V reports how the island of Bornholm is modelled, both regarding the electricity grid and the EV fleet. Finally, Section VI contains an outlook on future work.

II. Standards and Components

To ensure interoperability, the ICT standards and components used to build the platform should fulfill common ICT requirements for security, robustness, performance, and availability. The following sections describe the components that will be used to meet these requirements.

A. IEC Standard

The IEC 61850 standard [15] [16] has been defined by the IEC Technical Committee 57 - Architecture for Electrical Power Systems (IEC-TC57). The intent of IEC 61850 "Communication networks for power utility automation" is to define an international, flexible, and future-proof standard that supports interoperability in substation automation and communication. Interoperability is achieved by defining a coherent information model for electrical components. The information model of the original standard has been expanded with the IEC 61850-7-420 (DER) set [17] to support Distributed Energy Resources (DER). This expansion is of particular interest to the EDISON project because EVs can now be considered within the standard. The standard is flexible and future-proof by decoupling the domain-specific applications from the communication stack. It has been tested and evaluated in many projects and real-life deployments.

B. Service Oriented Architecture

Service Oriented Architecture (SOA) is a widespread architecture that supports internet communication and collaboration-promoting open web-standards [18], [19]. SOA has inherited many of the attributes of earlier modular architectures in that it helps support loose coupling, separation of concerns and interoperability through functional "building blocks". Highly configurable security technologies have been developed for SOA web services to meet the security requirements of authentication, integrity, and confidentiality in various SOA implementations [20]. The SOA concept can contribute to the reusability of the EDISON distributed solution by making the latter easier to adopt and integrate across organizational and technical barriers.

C. Use of standards in the EDISON project

The above components are expected to be combined to facilitate communication in the platform. It should be possible to support a broad range of EVs through a coherent information model using standardized and service-oriented communication. Although both SOA and IEC 61850 come with a set of recommended protocols (the MMS stack and the WS-Basic profile [21]) neither strictly dictates which protocols or security measures are used in the communication. The individual protocols and security measures to be used shall be evaluated and described in EDISON work package 3.

III. Virtual Power Plant (VPP) Concept

The VPP concept has already been thoroughly researched in numerous publications [3], [4], [5], [6], [7] and tested in large European projects [8]. A VPP describes an aggregated system in which many DERs with small power generation output are partly or fully controlled by a single coordinating entity.

In this way, small DERs can be actively integrated into the power system and market, for which they individually would be too small – in terms of power output and availability – to participate in (see Figure 1). Different kinds of VPP designs have been suggested differing in how the DERs of the VPP are controlled and what purpose the VPP serves in the power system or market.

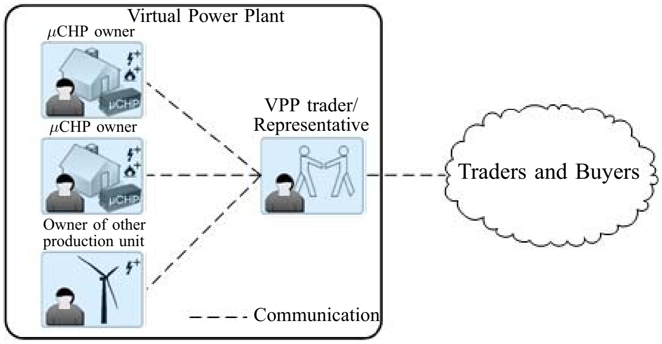

Figure 1. The VPP concept

For example, the challenges in VPPs of balancing the intermittency of renewable energy sources are investigated in [22], [23], [24], [25]. In [26], a VPP is proposed in which multiple μCHPs are used to balance the intermittent energy production of a wind farm. In [25], a small-scale uninterruptible renewable energy system is proposed. The system includes a photovoltaic panel, a wind turbine, an electric vehicle, and a household. The issues of switching between grid-connected and islanding mode are addressed. A study on an isolated island is presented in [27] which deals with the main island of the Azores and calculates the impact of three different projected EV fleets. The authors discuss the possibility of using a "brother model", i.e., charging EVs by intermittent wind energy. A method of reducing communication and computation using a tree-structured market-based approach of balancing wind energy employing distributed energy resources in VPPs is presented in [22], [23]. Results show that the proposed tree-structured market-based method reduces the peaks in consumption and levels out the load.

A. *VPP control*

A VPP can be described as either being *centralized* or *distributed*. A VPP is centralized if the control and decision making is delegated to a common VPP coordinator and each DER is directly controlled by this coordinator (see Figure 2). In contrast, a distributed design means that each DER will act as an independent, intelligent, and autonomous agent that responds based on incentives provided through information sent by the VPP coordinator (see Figure 3). A frequent approach in this design is the use of price signals [28]. A price signal would typically represent modified market prices, and each individual DER would individually decide how to react on these - but may override or ignore such signals.

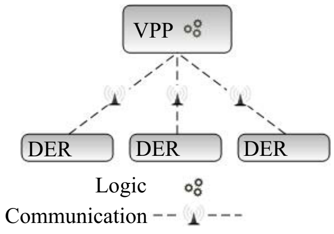

Figure 2. Centralized VPP

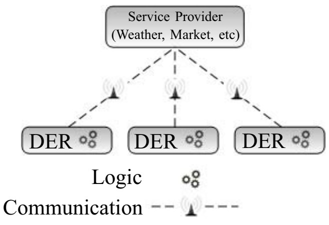

Figure 3. Distributed VPP

B. *VPP purpose*

The DERs of a VPP can be coordinated to meet different objectives. A VPP Coordinator can act on the power market to earn money for its members or it can be used to perform services to the grid such as balancing. Depending on the purpose of the VPP, it can thus be classified as a commercial or technical power plant. These two kinds of VPPs have been described and tested in the European Fenix project [8].

C. *VPP implementation and operation*

The implementation and operation of a VPP Coordinator depends on the control function and purpose as described above. Power market interaction would for instance create certain requirements to the operation logic of the VPP coordinator. In [3], You Shi *et al.* have defined a generic and reusable model that generalizes the objective of the VPPs via a function-based approach. Their Generic Virtual Power Plant (GVPP) architecture assembles a series of services and functional components that a marked-based VPP should implement depending on its operations (see Figure 4).

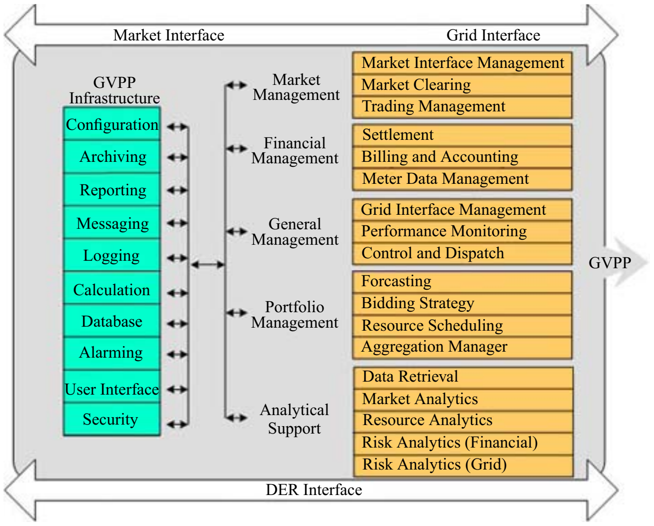

Figure 4. Function-based design for GVPP, source: You *et al.* [3]

D. *Use in the EDISON project*

The DER integration approach offered by the VPP concept matches the aggregation needed when coordinating EVs in the EDISON project. It is therefore useful to leverage VPP research when designing the EDISON distributed platform and to view the solution as a specific implementation of a VPP that focuses on the EV as a DER. The EDISON aggregation platform is therefore referred to as an EDISON *electric vehicle virtual power plant* (EVPP) which can be described as both a market-oriented and thus commercial and a technical VPP using a centralized approach for DER control.

IV. ARCHITECTURE

EDISON currently supports two different architectural options, that reflect the distinct possibilities to integrate an EVPP into the current Danish power system. This section discusses these options.

The EDISON EVPP focuses on EVs as DERs; other DER types are not specifically included. Hence, the EVPP mainly represents a large power consumer, which can, however, also provide some peak-balancing power. This contrasts with other VPP concepts which mainly deal with net energy producers. However, the EVPP will have an open design to allow the integration of other kinds of DERs, such as μCHP and photovoltaics.

An additional EVPP functionality consists of support for *fast* and *controlled* charging stations. For the former, dedicated, high-power, charging stations shall be deployed on the grid. These are capable of delivering large amounts of power within short delays to resplenish an EV's accumulator without overloading the electrical grid infrastructure. When connected to such charging stations, EVs are loads only; they are not considered as potential temporary energy sources able to supply balancing power into the grid. Controlled charging, in contrast, shall occur when EVs are connected over an extended period of time to the electrical grid at lower-capacity charging stations, such as private garages, company parking lots, public parking areas with limited grid capacity, etc. At these locations, and with sufficient connection time, the intelligent grid performs load shifting as well as requesting energy feedback from the EV into the grid by sending appropriate control signals to the EV or its charging station[2].

For both the European and Danish power grids, we observe a two-layered environment. There is the *electrical layer* consisting of power plants, wind farms, high-voltage transmission grids, low-voltage distribution grids, and the metering infrastructure. This domain can be seen as a technical infrastructure with associated physical and engineering constraints, yielding a large and stiffly coupled system. On top of the technical infrastructure layer, mandated by politically and economically motivated deregulation efforts, we see the electricity market layer. There, electrical energy is traded as a commodity on exchanges such as Nordpool or the European Electricity Exchange (EEX), and it allows energy traders to buy and sell energy without owning or operating any of the grid infrastructure.

A. Integrated and standalone architectures

For the EVPP architecture, we have considered two integration variants into the actual Danish power system. One option is to integrate the EVPP into an already existing market player, for example, a power-generation company or any other party that is involved in the electric energy market and can act as a Balancing Responsible Party (BRP). We call this the *integrated architecture*. This architecture provides the integration company with a powerful tool to respect their committed energy schedules and also gives it the ability to act on the ancillary, balancing, services market for spare capacity.

For example, a power-generation company can use the available, stored, energy potential of the managed DERs to smoothen the ramp up/down slopes of its thermal plants. Such reserves can also be used to balance the wind energy production on a company-internal balance area level. The EVPP communicates the expected power excesses or demands in each timeslot to some integration partner SCADA[3] system. Therefore, strategic decisions when to purchase electrical energy and when to bid on the ancillary services market are handed over to the associated SCADA system.

Figure 5 shows an enviroment diagram for such an integration of an EVPP, and Figure 6 is a module diagram of such an EVPP.

An alternative method to integrate an EVPP into the current market structure is to position it as a standalone market player also acting as BRP. We call this approach the *standalone architecture*. There, the EVPP acts on the regular markets to buy electrical energy for EV charging as well as on the ancillary services market to sell ancillary services to support grid stability. By participating in both markets, the EVPP needs more intelligence to decide on buying energy and bidding ancilliary services - it cannot delegate these decisions to other market players. Although the standalone EVPP performs internal power balancing, balancing failures require access to the power markets with the associated costs which cannot be hedged for by offloading these risks to any integration partner. Note, however, that in both integration models, the quality of the balancing forecasts will be crucial to successful VPP operations.

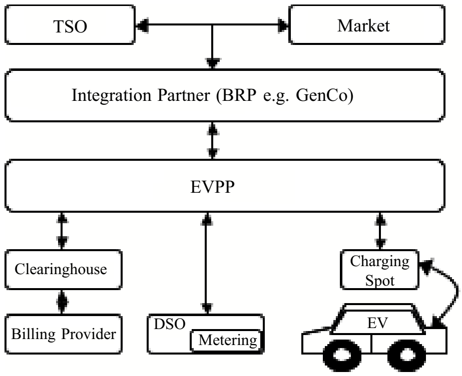

Figure 5. Environment diagram of an integrated EVPP

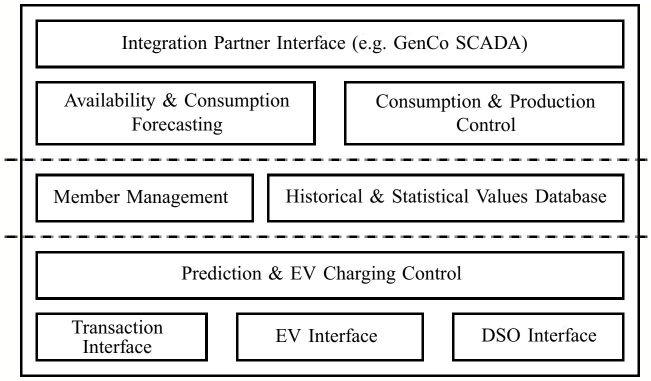

Figure 6. Module diagram of an integrated EVPP

Figure 7 shows an environment diagram of a standalone market player EVPP, and Figure 8 shows a possible module diagram of a standalone market player EVPP.

B. Modular EVPP architecture

Both EVPP concepts contain three different module groups: The *control group for a single EV*, the *data storage and member management* group, and the *aggregation and partner interface* group. The module groups for data storage and member management differ between the approaches in that the standalone variant must handle data for market price prediction whereas in the integrated approach this responsibility and the associated information is delegated to the associated SCADA.

The single-EV control module group, which manages individual EVs, contains four different modules that handle all needs of a single EV in terms of charging, feedback, accounting, and charging prediction.

The *EV Interface* module, which is the communication interface to the EV or other DERs, uses direct control in form of transaction-based session communication. This contrasts with indirect control of EV load by broadcasting price signals

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[2] We assume that the charging station acts as communications proxy to the EV.

[3] Supervisory Control And Data Acquisition

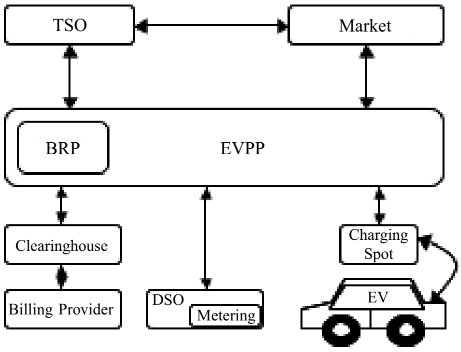

Figure 7. Environment diagram of an standalone market player EVPP

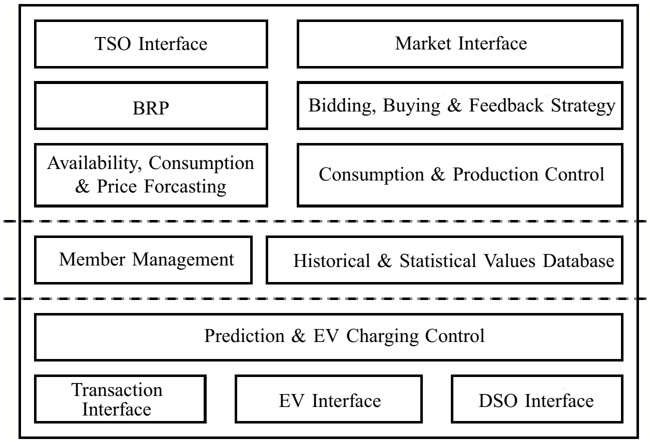

Figure 8. Module diagram of an standalone market player EVPP

to the EV. This session-based control adds communication overhead, but allows better data collection for prediction and planning of charging schedules, as well as guaranteed control messaging.

The *DSO Interface* module is placed in the single-EV group as it should collect the grid state for every EV connected. The crucial point for grid congestions are the feeder level transformers, that are the closest to the charging EVs, therefore the DSO interface is on this level. In addition, the metering information for accounting is also collected at the DSO via this interface. The latter may change because regulation may split this functionality off the DSO into a distinct *Meter Reading Service Provider* (see Figures 5 and 7).

The *Transaction Interface* interfaces with the *Clearinghouse and Billing Provider* to allow the billing of energy costs to the EV user.

The main module in the single-EV control goup of the EVPP is the *Prediction & EV Charging Control* module. This module predicts, based on historical and statistical values, when a specific EV will connect to a charging spot and what the required amount of energy to be charged will be. The prediction also includes the assumed connection and thus the charging time and the current state of charge. Based on these forecasts, the module calculates an optimal charging plan, which takes into account the charging price and the grid constraints regarding power transmission capacities. If an EV connectes to the EVPP, the module first checks whether the EV state and grid state matche the prediction and if this is the case, the module sends the precalculated, optimized charging plan to the EV. If the connection time, state of charge, grid state or EV operator requirement (e.g. fast charge request vs. predicted smart charge request) do not comply with the prediction, the module will calculate a new charging plan and send it to the EV. The variances will be stored in the database as input for training the prediction module.

The *data storage module group* contains two modules, the *Historical & Statistical Values Database*, which is used by the *Prediction & EV Charging Control*, the *Consumption & Production Control*, the *Availability & Consumption Forecasting*, the *Bidding, Buying and Feedback* and the *BRP* modules. In addition, the module group contains the *Member Management* module, which enables an EV operator to modify his or her default settings and requirements.

The main differences between the two integration approaches are in the aggregation and partner interface modules groups. The integrated EVPP contains three modules in that group. The *Availability & Consumption Forecasting* module aggregates the single-EV predictions from the database module and creates an overall EVPP energy consuption and availabilty (for ancillary services) schedule for a future time period. This schedule is sent from the *Integration Partner Interface* module to the upperlevel SCADA system. The time interval and validity time can be chosen between the EVPP and the *Integration Partner* (see Figure 5).

The *Production & Consumption Control* module controls the daily operation of the EVPP. On an aggregated level, it enforces compliance with the charging schedule agreed and will override possible variations in cooperation with the *Prediction & EV Charging Control* module. It also gets commands from the upperlevel SCADA system to provide ancillary service via the *Integration Partner Interface*, which connects the EVPP with the SCADA system.

In difference to the above integrated approach, the standalone market player approach can not offload all the grid and EV control complexity to an already existing system. Hence, the software complexity is much higher and the interfaces and time constants are determined by external parties.

The aggregation and partner interface module group includes six modules. The *Consumption & Production Control* is similar to that of the integrated EVPP approach, with differences in the control of non-compliance with the charging schedules agreed. The *Availability, Consumption & Price Forecasting* module performs a similar job as the *Availabilty & Consumption Forcasting* module in the integrated EVPP approach. However, it also has to do price forcasting, based on historical values, for ancillary services and for buying electrical energy. The module makes this forecast data available to the *Bidding, Buying & Feedback Strategy* module, which decides upon market participation. The module aims to maximize overall trading profit, for example by minimizing the need for purchasing regulating power in case of a power trough. The bidding and buying are done via the *Market Interface* module connecting the EVPP to the electricity market.

The *Balance Responsible Party* module supports the BRP in creating and submitting mandatory schedules to the TSO[4] via the *TSO Interface*. This interface is also used by the TSO when sending activation commands for accepted ancillary service bids. These TSO commands are processed by the *Consumption & Production Control* module.

V. ISLAND OF BORNHOLM - SIMULATION WORK

The Danish island of Bornholm has been selected as simulation scenario for EDISON WP3 because it represents a small grid with the option of operating in island mode[5] and with a high wind power penetration. The ØSTKRAFT company is the distribution system operator (DSO) as well as the generating company on the island, supplying more than 27,000 customers.

The production capacity is as follows [29], [30]:

- 14 diesel generators (oil): 39 MW
- 1 steam turbine (oil): 27 MW
- 1 steam turbine (oil/coal): 37 MW
- 35 wind turbines: 30 MW
- 1 gas turbine (biogas): 2 MW

The 14 diesel units and the 2 steam units are able to control both voltage (10.5 kV) and frequency. The six newest wind turbines, owned by ØSTKFRAFT, are able to control voltage, production, ramp rates, etc. The wind turbines generated 53 GWh in 2007. This corresponds to 22% of the load. The peak power load at Bornholm is 55 MW.

The aim of EDISON's WP3 is to optimize the utilization of variable windenergy supply within the grid by coordinating the charging and discharging of EVs and, at the same time, satisfy the car-operators' energy needs.

The distribution infrastructure of Bornholm can be split into three distinct voltage levels:

1) 60 kV network: the 60 kV network at Bornholm is meshed and consists of the following elements:
   - 18 substations,
   - 23 60 kV/10 kV OLTC transformers of a total of 219 MVA, and
   - 22 cables and overhead lines, 73 km and 58 km of length, respectively.
2) 10 kV distribution grid consisting of
   - overhead lines with a length of 247 km,
   - 634 km in length of cables, and
   - 91 feeders, with an average of 6 feeders per substation.
3) 400 V distribution grid composed of
   - overhead lines with a length of 518 km,
   - 1,341 km of cables, and
   - 998 10 kV/400 V transformers, with a total of 265 MVA and an average of 273 kVA and 29 customer connections per transformer.

Our simulation is based on modelling this layered electrical grid and has been motivated by the lack of an analytical system description as well as the impossibility to build a physical, experimental, model of the system [31]. A vast number of general-purpose simulation environments exists [32], [33]; for power distribution scenarios Matlab/Simulink/Powersim [34] and DigSilent's PowerFactory [35] are two of the well-known industrial tools to analyze transport and distribution grids, as well as power generation and loads.

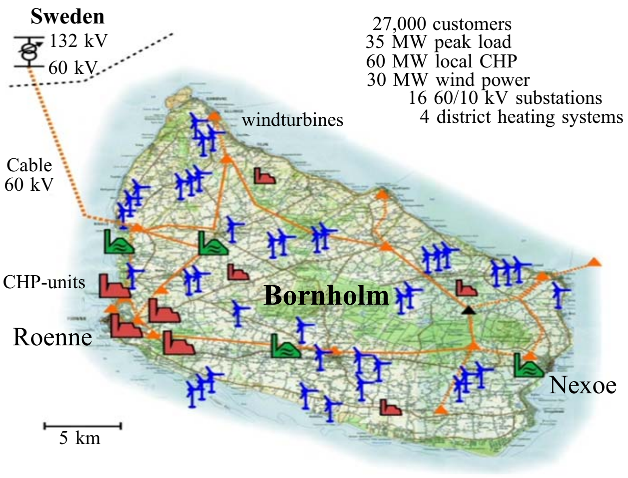

Figure 9. The Bornholm 60 kV distribution grid

To support the EDISON project - in particular to provide a simulated system environment for VPP development - we have implemented the above grid model combining some real-world data with purely synthesized grid characteristics.

The 10 kV distribution layer has been layered onto the Bornholm geography and the known 60 kV grid, starting with the (known) 60 kV/10 kV substations. Using GoogleMaps, we have arbitrarily placed radial 10 kV end-points around the substations, so that we can cover the entire island. The average number of feeder transformers (10 kV/400 V) is known, and thus we have placed such transformers on the radial 10 kV distribution lines ensuring constant surface coverage[6].

The 400 V distribution grid represents the lowest layer of our model. We have divided the island in different region types, for each of which we assume a statistical load type distribution. (We use the publically available VDEW[7] load characteristics [36].) The loads are placed randomly around the feeder transformers – knowing the average number of end-points per feeder transformer – and we compute a minimum spanning tree to lay out the distribution lines by minimizing the overall length [37].

The ratings of transformers and transmission lines, as well as their admittances, are currently based either on known information about the 60 kV grid or on educated guesses using typical parameter values.

The generating entities in our grid model are a set of wind turbines for which we were able to get location and technical information about their power characteristics. In addition, we have the power-plant located in Rønne, modelled as a single entity.

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[4] Transmission Services Organization

[5] When not connected to Sweden via the HVDC connection.

[6] This coverage depends on the square of the radial distance to the substation.

[7] Verein Deutscher Elektrizitätswerke.

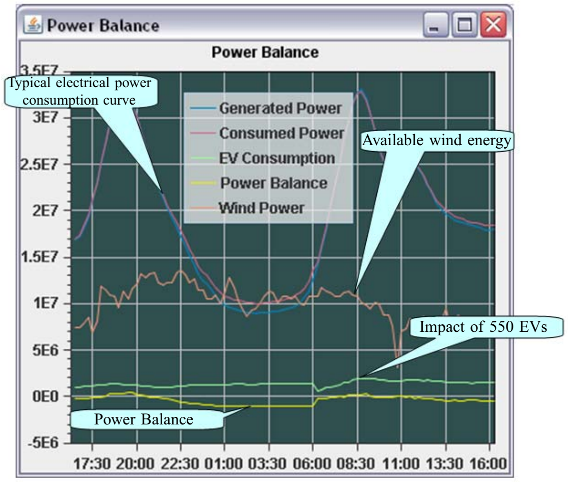

Figure 10. Generation and load visualization

Figure 11. Traffic and grid visualization

For the wind turbines, we simulate wind conditions based on some historical average windspeed data for Rønne or other publically available winddata time-series.

The net result of our grid model is the corresponding node admittance matrix, which we use to compute the power flows over the network [38].

For the traffic simulation, we have currently defined three types of electric vehicles:

- *commuter cars*: these have strongly pendular driving characteristics. A well defined location is considered the home location and the cars travel to one of a limited set of destinations in the morning and return in the evening.
- *taxis*: taxis have a more randomized traffic pattern, both in time (inter-trip delays) and space (set of locations visited). They also have a higher battery capacity. Note that we do not yet distinguish between different battery capacities within the vehicle categories.
- *family cars*: these travel along one set of locations on weekdays and a different set of places on weekends. The inter-trip delays take into account typical behavior such as breakfast, lunch, and dinner times.

These vehicles represent typical agents in an agent-based simulation environment. The agent logic in our case is kept simple and implemented using our programming language of choice; we have not designed a special-purpose agent simulation environment.

An important issue in our effort has been the notion of *location*. From the very beginning it was clear, that this was key to both, the traffic and the electrical aspects of the simulation. We use WGS84 geographic coordinates and define locations across the island. Electrical grid abstractions, such as transformers, transmission lines, generators, and loads, are bound to their respective locations. The EVs travel between such locations consuming some electrical power average. Note that our traffic simulation is admittedly simplistic: our aim has been to obtain a rough model that allows us to develop the data collection, forecasting and optimization of operational aspects of the overall system.

Regarding the charging behavior of the EVs, we assume a given accumulator charging characteristic, in which we have the charging power as a function of the state-of-charge. This then yields a typical ordinary differential equation (ODE) of the form

$$s\dot{o}c = f(soc, t).$$

The rate of change of the state-of-charge ($s\dot{o}c$) is nothing else but the charging power of the accumulator.

Our work has now reached the stage where we can simulate the grid's load-flow with associated vehicle traffic. We compute the load-flow in 15-minutes[8] intervals to assess the load on transmission lines and transformers. The generated and the consumed power is balanced by regulating the windturbines and the (single) power plant in the system.

The simulation output is captured in two visual frames: One represents the temporal evolution of the power generation and demand with special attention to EV charging (Figure 10). The second frame shows the grid's geography and the EV traffic on the island (Figure 11).

VI. FUTURE WORK

The EDISON project, work package 3 and others, shall continue to focus on the above topics for future work.

For ICT issues, application-level protocols need to be designed, implemented, and deployed across physically available infrastructure reaching from the VPP to the EV. Operational data and control signals need to be exchanged between the various entities in the system, such as marketplaces, SCADA systems, VPPs, and EVs. Non-fuctional issues include reliability, performance, security, and cost of operations. Independent of the VPP architecture chosen, well functioning communication channels between VPP and EVs are a necessity.

Prototypical VPP functionality shall be implemented and tested against our simulation model. In particular, we plan to address issues such as

1) *forecasting*: the energy demands of EVs have to be estimated for the planning of power generation and

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[8] Simulation time.

balancing. In addition, the time windows during which EV charging can take place have to be predicted.

We shall assume that windforecasts will be provided by some external source, e.g., weather forecasts or historical winddata for simulation purposes and thus do not intend to perform work on windforecasting models.

2) *optimization*: optimization can be applied at various places in the VPP functionality envisioned. The size and the complexity, for example nonlinearities, of interdependent grid entities pose some true challenges in building a coherent whole.

Optimizations may include, but are not restricted to, cost optimizations, power balancing in the presence of intermittent generation, grid constraints, as well as EV operator requirements in terms of delivered charging power.

As we proceed, we intend to include more real-world data for wind time-series, EV travel patterns, and grid layout and parameters as these become available. In parallel, the EVPP architecture will be refined to reflect the various use-cases defined within the EDISON project.

REFERENCES

[1] W. Kempton and J. Tomic, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *Journal of Power Sources*, vol. 144, no. 1, pp. 268–279, June 2005.

[2] ——, "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy," *Journal of Power Sources*, vol. 144, no. 1, pp. 280–294, June 2005.

[3] S. You, C. Træholt, and B. Poulsen, "Generic virtual power plants: Management of distributed energy resources under liberalized electricity market," in *Proceedings of the 8th IET International Conference on Advances in Power System Control, Operation and Management*. Hong Kong, China: Institution of Engineering and Technology, 8–11 November 2009.

[4] P. Lombardi, M. Powalko, and K. Rudion, "Optimal operation of a virtual power plant," in *Proceedings of the IEEE Power & Energy Society General Meeting*, Calgary, Canada, 26–30 July 2009, pp. 1–6.

[5] S. You, C. Træhold, and B. Poulsen, "A market-based virtual power plant," in *Proceedings of the International Conference on Clean Electrical Power (ICCEP)*. IEEE, June 2009.

[6] R. Caldon, A. Rossi, and R. Turri, "Optimal control of a distribution system with a virtual power plant," in *Proceedings of Bulk Power System Dynamics and Control Conference - VI*, August 2004.

[7] P. B. Andersen, C. Træhold, and B. Poulsen, "Evaluation of a generic virtual power plant framework using service oriented architecture," in *Proceedings of the IEEE International Conference on Power and Energy (PECon 2008)*. IEEE, April 2008.

[8] "Flexible electricity network to integrate the expected energy evolution," http://www.fenix-project.org/.

[9] M. M. Collins and G. H. Mader, "The timing of EV recharging and its effect on utilities," *IEEE Transactions on Vehicular Technology*, vol. 32, no. 1, pp. 90–97, 1983.

[10] F. Koyanagi and Y. Uriu, "A strategy of load leveling by charging and discharging time control of electric vehicles," *IEEE Transactions on Power Systems*, vol. 13, no. 3, pp. 1179–1184, 1998.

[11] K. Clement, E. Haesen, and J. Driesen, "Coordinated charging of multiple plug-in hybrid electric vehicles in residential distribution grids," in *Proceedings of the Power Systems Conference and Exposition*, Seattle, WA, 15–18 March 2009, pp. 1–7.

[12] M. Galus, R. A. Waraich, M. Balmer, G. Andersson, and K. W. Axhausen, "A framework for investigating the impact of PHEVs," in *Proceedings of International Advanced Mobility Forum (IAMF)*, Geneva, Switzerland, March 2009.

[13] P. Kulshrestha, L. Wang, M.-Y. Chow, and S. Lukic, "Intelligent energy management system simulator for PHEVs at municipal parking deck in a smart grid environment," in *Proceedings of IEEE PES General Meeting 2009*. IEEE Power Engineering Society, August 2009.

[14] V. Crastan, *Elektrische Energieversorgung II*. Springer Verlag, 2004.

[15] *Communication networks and systems in substations*, 1st ed., Commission Electrotechnique Internationale (IEC), July 2003.

[16] R. Mackiewicz, "Technical overview and benefits of the IEC 61850 standard for substation automation," http://www.sisconet.com/.

[17] *Communication networks and systems for power utility automation - Part 7-420: Basic communication structure - Distributed energy resources logical nodes*, 1st ed., Commission Electrotechnique Internationale (IEC), November 2009.

[18] *Web Services Architecture*, W3C, February 2004, http://www.w3.org/TR/ws-arch/.

[19] *Reference Model for Service Oriented Architecture 1.0*, OASIS, October 2006, http://docs.oasis-open.org/soa-rm/v1.0/soa-rm.pdf.

[20] *Web Services Security: SOAP Message Security 1.0*, OASIS, March 2004, http://docs.oasis-open.org/wss/2004/01/oasis-200401-wss-soap-message-security-1.0.

[21] *Basic Profile Version 1.0*, Web Services Interoperability Organization, April 2004, http://www.ws-i.org/Profiles/BasicProfile-1.0.html.

[22] J. K. Kok, C. J. Warmer, and I. G. Kamphuis, "Powermatcher: Multiagent control in the electricity infrastructure," in *Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems*, The Netherlands, 25–29 July 2005, pp. 75–82.

[23] G. J. Schaeffer and H. Akkermand, "CRISP, distributed intelligence in critical infrastructure for sustainable power - D5.3 final summary report," EC-funded Thematic Network - 5th Framework Programme - Energy, Environment and Sustainable Development - Key Action: "City of Tomorrow and Cultural Heritage", Tech. Rep. ENK5-CT-2002-00673, 10 July 2006.

[24] Y. Gurkaynak and A. Khaligh, "Control and power management of a grid connected residential photovoltaic system with plug-in hybrid electric vehicle (PHEV) load," in *Proceedings of the Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition*, Washington, DC, 15–19 February 2009, pp. 2086–2091.

[25] I. Cvetkovic, T. Thacker, D. Dong, G. Francis, V. Podosinov, D. Boroyevich, F. Wang, R. Burgos, G. Skutt, and J. Lesko, "Future home uninterruptible renewable energy system with vehicle-to-grid technology," in *Proceedings of the IEEE Energy Conversion Congress and Exposition*, 20–24 September 2009, pp. 2675–2681.

[26] M. Houwing, G. Papaefthymiou, P. W. Heijnen, and M. D. Ilic, "Balancing wind power with virtual power plants of micro-chps," in *Proceedings of the IEEE Bucharest PowerTech*, Bucharest, Romania, 28 June - 2 July 2009, pp. 1–7.

[27] P. Kadurek, C. Ioakimidis, and P. Ferrao, "Electric vehicles and their impact to the electric grid in isolated systems," in *Proceedings of the International Conference on Power Engineering, Energy and Electrical Drives*, Lisbon, Portugal, 18–20 March 2009, pp. 49–54.

[28] F. L. Alvarado, "Controlling power systems with price signals," *Decision Support Systems*, vol. 40, no. 3-4, pp. 495–504, 2005.

[29] J. E. Nielsen, "Co-generation and operating network cells," in *Proceedings of the International Conference & Workshop on Micro-Cogeneration & Applications*. Ottawa, Canada: Natural Resources Canada, April 2008, pp. 1–8.

[30] *Årskraft 2007*, ØSTKRAFT Net A/S, Ronne, Denmark, 2007.

[31] A. M. Law, *Simulation Modelling and Analysis*. McGraw-Hill, 2007.

[32] M. J. North, N. T. Collier, and J. R. Vos, "Experiences creating three implementations of the repast agent modeling toolkit," *ACM Transactions on Modeling and Computer Simulation*, vol. 16, no. 1, pp. 1–25, January 2006.

[33] M. Balmer, K. W. Axhausen, and K. Nagel, "An agent based demand modeling framework for large scale micro-simulations," Institute for Transport Planning and Systems (IVT), ETH Zurich, Zurich, Switzerland, Working paper 329, 2005.

[34] Hydro-Québec, *SimPower Systems 5: User's Guide*, The MathWorks, Inc, Natick, MA, USA, 2009.

[35] *Digsilent PowerFactory*, Digsilent GmbH, 2009, http://www.digsilent.de/Software/DIgSILENT_PowerFactory/.

[36] R. Tiedemann and C. Fünfgeld, *Die Repräsentativen VDEW-Lastprofile - Der Fahrplan, Version 3.7*, VWEW Energieverlag, Frankfurt/Main, Germany, 2006.

[37] E. Horowitz and S. Sahni, *Fundamentals of Computer Algorithms*. Computer Science Press, Inc., 1978.

[38] P. Kundur, *Power System Stability and Control*. McGraw-Hill, 1994.