Bornholm as a Model for 100% Renewable Energy Scenarios in Denmark

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***Abstract*— An energy system planning tool, "EnergyPLAN" is used for the analysis of energy scenarios to study the generation and consumption of energy on the island, Bornholm. First the model is verified on the basis of the energy mix on Bornholm today, then the Bornholm energy system is studied as an islanded energy system. Future energy scenarios are analysed to study a feasible technology mix for a very high share of wind power. Finally, the results of the hourly simulations are crosschecked with dynamic frequency simulations. The goal of this project is to improve the energy system tool to study future energy scenarios.**

I. Introduction

Denmark is eager to be amongst the "greenest" nations in the world. Its successful development of wind energy has made Denmark the country with the highest penetration of wind power in at this time. In a major interdisciplinary effort, the CEESA[1] project seeks ways to extend this successful development until a 100 per cent renewable energy supply in 2050. The approach is centred on the development of feasible energy scenarios for the years 2030 and 2050 [1]. As part of this project, the authors study the technical feasibility of these scenarios with respect to the power system. Given the uncertainties about available technology with such a time frame, the study needs to focus on fundamental feasibility aspects.

For simplicity and fast computation, the scenarios developed in the CEESA project are typically in lumped parameters. Further, the scenarios are evaluated on basis of hourly energy balances for the model years. Scenarios based on such coarse specifications are insufficient to address detailed aspects of technical feasibility in the scenarios directly. The design space of possible scenario realizations is vast, but the question is simple: Would it be possible to realize such a scenario? And further, are there simple criteria that should be satisfied by a scenario to be qualified as "technically feasible"?

The problem is firstly, to identify critical parameters that need to be evaluated to make a statement about feasibility, and secondly, to find a representation of the scenario in which it is tractable to perform this evaluation. The parameter studied in this paper is frequency control. The approach taken for evaluation of frequency stability, seeks to reduce the complexity of the problem by mapping the scenarios in two steps. First, the scenarios given for the whole of Denmark are interpreted and scaled to the island of Bornholm. In a second step, the coarse, lumped parameter and hourly, scenario is specified with technical details from the island of Bornholm. This second mapping leads to detailed simulation models that are more easily modified and require much less data then an attempt the same for the whole of Denmark. In order to draw valid conclusions from these reduced model simulations, a careful mapping is essential.

The island Bornholm was chosen as a model region for a number of practical reasons: It is a typical energy system as the mainland Denmark with combined heat and power (CHP) and it is a model region for electric cars and future power regulation services. Further, it has sufficient generation to be operated as an electrical island and it is in the focus of a number of research efforts and studies

The remainder of this paper is organized as follows. In Section II, we introduce the background data of Bornholm and Denmark for the reference year 2007 and discuss the scaling between two regions. The dynamic simulation model and the mapping from scenario data to technical parameters are introduced in Section III. Thereafter, in Section IV, the scenarios are introduced and the simulation results are presented. Finally the results and their implications are discussed and concluded in Section V

II. Bornholm and Denmark

In Section II-A, we introduce the energy balances and resources of Denmark and Bornholm for the reference year. In Section II-B the scaling between the two is discussed.

A. Energy Balance and resources in the reference year

The year 2007 is chosen as reference to compare the energy systems of the whole of Denmark and Bornholm. The comparison presented in Table I is made on the basis of annual energy consumption in form of heat and electricity, installed plant capacities and total exchange. Differentiations are made with respect to characteristics of generation technologies: central vs. distributed generation, combined heat and power (CHP) vs. electricity-only power plants. For

[1] Coherent Environmental and Energy Systems Analysis

comparison of power system dimensions, installed generation and exchange capacities are listed as well as peak and minimum demand.

TABLE I BORNHOLM ELECTRICITY AND HEATING DATA – 2007 ([2], [3])

Electricity		%peak (%total)
Customers	27,895	
Annual electricity consumption	240 GWh	(100%)
Peak load	55 MW	100%
Min. Load	13 MW	24%
External connection	Sweden, 60 MW	110%
Exchange (pos.=Export)	139,1 GWh	(-56%)
Power Plants		
CHP plant, operating modes:	Backpressure: 16MW el/ 35MW heat	29%
	Extraction: 33MW el/35MW heat	60%
	Condensation: 37MW el/-	67%
14 Diesel generators	39MW	71%
1 Steam Turbine (oil/coal)	37MW	67%
1 Steam Turbine(oil)-CPP	27 MW	49%
Gas turbine (Biogas)-CHP	2 MW	4%
Wind turbines(35Onshore)	30 MW	54%
- Total production 2007	53 GWh	22%
Heating [4]		
CHP plant	105GWh	
Electric heating	32.5GWh	
Biogas - CHP	8GWh	
District heating plants	100GWh	
Total annual heat demand - 560GWh		

TABLE II: DENMARK ELECTRICITY DATA – 2007 [5]

Electricity		%peak (%total)
Annual electricity consumption incl. losses	36.443 GWh	(100%)
Peak load	6.436 MW	100%
Min. Load	2.300 MW	36%
External connection	DE, NO, SE	
	5290 MW (import)	82%
	5840 MW (export)	91%
Exchange (Export - Import)	11.377 -10.426 = 951 GWh	(32%-29% =3%)
Power Plants		
CHP plants (central)	7.200 MW	112%
-Total production 2007	22.731 GWh	(62%)
Decentralized, incl. industry	2.322 MW	36%
-Total production 2007	7.179 GWh	(20%)
Wind turbines - onshore	3.125 MW	49%
- offshore	418,6 MW	7%
-Total production 2007	7.173 GWh	(20%)

Table II presents the electricity data for whole of Denmark for the same reference year 2007. By first inspection, it appears that the power systems are similar with respect to their power-capacities. The electricity consumption and generation capacity is less than 1% of the whole of Denmark. One uncertainty was the operation the Power plants. The resources showed several possible modes for the coal/oil fired CHP plant and large additional capacities for electricity generation in diesel and oil-fired thermal generation. It was not evident how much the other generators are in operation.

Using the data given in Table I, the Bornholm energy system has been simulated in EnergyPLAN as an open system. Hourly distributions for heat and electricity consumption where used as typical for Denmark. It was possible to reproduce the level of electricity imports only if the CHP plant was set up to be following heat demands. Further it was operated in backpressure mode for most of the year, producing about 47 GWh of electricity (~20% of annual energy demand).

. From the available data, it was evident that in Bornholm the CHP plant is operated in Backpressure mode to satisfying local heat demand. It should be noted that Bornholm is importing the larger part of its electrical energy, being a net-exporter only in the winter months when the CHP plants need to be running according to the heat demands. This can be explained by the Bornholm (Østkraft) participates in the Nordpool market, and its most competitive unit is largest power plant on Bornholm is a CHP plant (backpressure and extraction modes), which is operated most economical on the basis of combined heat and power production.

Wind energy is generated amounting to about 22% of the electricity consumption in the reference year. The penetration increased, when about 11 MW of wind power where installed in late 2007. Data for the Danish system has been collected mainly from Energistyrelsen and the Danish Energy Association. One should note that Denmark consists of two independent electricity systems (DK west and DK east), however this is ignored for the rest of this paper, as overall scenarios are studied.

B. Mapping between Bornholm and Denmark

With a similar proportion of energy generated by wind, both systems utilize electricity exchange with their neighbours. Also the proportion of installed generation and exchange capacities to peak demand are comparable.

In fact, the main difference between Denmark and Bornholm is that local generation capacities are rarely utilized on Bornholm. Backup generation is brought online mostly for islanding situations, when the connection to Sweden is down for maintenance. Denmark has a much larger fraction of co-generation, whereas Bornholm uses two heat-only boilers for district heating and more electric heating than all-Denmark.

As the energy scenarios generated in the CEESA project aim at a self-sufficient energy mix for Denmark, the scenarios adapted for Bornholm must assume sufficient local generation to achieve a net-zero energy balance for Bornholm. However, there are several levels of “zero exchange”, which need to be distinguished, particularly with respect to the power system.

First, as practiced for example for the “renewable energy island” of Samsø, is the annual energy balance, referring to zero net annual energy exchange. Particularly with respect to electricity, such a system heavily relies on the systems it is electrically connected to.

Second, similar to the annual energy balance it is possible to use any other discrete time-window to zero-out the energy exchange. This comes near to system independence, and it is applied for the hourly-simulation in EnergyPLAN (“Hourly

Island”). With an electrical perspective, this corresponds to the exchange between control areas which is continuously controlled to follow discrete exchange schedules. This concept allows the sharing of contingency reserves and market-based interaction, while system operation is local responsibility.

Third, zero power exchange means that there is no electrical connection to another system, the “electrical island”. Bornholm is in principle able to operate as an electrical island, but this mode is not employed in normal operation, as it is more costly to run both fully local production as well as standby capacity as contingency reserve. The authors assume that the ability to operate Denmark as an electrical island in the future, as a security requirement, is critical.

These different modes of understanding the zero-exchange requirement lead to different ways of mapping. The CEESA scenarios have been developed as a closed system from the hourly EnergyPLAN simulations (the second method). For the dynamical simulations, instead, we consider islanded operation critical criterion.

III. Dynamic Simulation Model

The grid frequency is the basic indicator of the power balance in a power system. The grid frequency deviations are caused by the power imbalance between the planned generation and unpredictable demand fluctuations which in turn disrupts the power quality of the grid. To normalise such power imbalance, the regulation power reserves are activated. In a wind power integrated power system, unpredictable wind variations may also introduce power imbalance. The wind power is not often used as regulation reserves due to their variable power output. Thus, the regulating power requirement is relied mostly on the reserve power capabilities of the conventional generators. The situation is of concern for a reliable power system operation and control in the future, when the conventional generators are replaced by more wind power. New regulation solutions have to be implemented in such a future scenario.

Any substantial grid frequency deviations call for an instantaneous primary regulation where the droop characteristics of the generators are adjusted to a new operating point by which the frequency deviations are minimised. This is followed by a secondary control which is a slow process that enables the power system to retain the nominal operating frequency range and to maintain the scheduled power interchange with other control areas. This enables the system to restore the primary frequency reserves. The automatic mode of such secondary control operation is realised by a load frequency control (LFC) or an automatic generation control (AGC) control. The LFC retains the power balance of a system by allocating the imbalance between selected generator units through economic dispatch.

The island of Bornholm is part of the synchronous Nordic power system where the secondary control operation is manually operated. As long as the grid frequency remains within 49.9-50.1Hz, the Nordic system depends on the instantaneous automatic primary reserves for frequency-load control. Each member nation of the Nordic power system is obliged to provide a minimum primary reserve proportional to the energy consumption in the country [6]. However, when the frequency deviations are larger, the transmission operator will seek the use of the additional generation capacity from the regulating power market which will be manually activated. These frequency reserves are activated when the grid frequency drops below 49.9Hz and fully activated at a grid frequency of 49.5Hz.

A. V2G based regulation in Bornholm

The island of Bornholm is considered as a prototype for testing future electric power regulation systems. Instants of planned islanded operation has been reported in ([7], [8]).Under the present manual operation mode, only 20% of the installed wind power could be brought online along with the CHP and condensing power plant as reported from the results of the intentional islanding operation in Bornholm [7]. Such less wind penetration during islanding are due to the insufficient regulation reserves and less inertia. The ability to undergo a planned island operation in Bornholm enables an ideal platform for research and testing of new regulation techniques to support large scale grid integration of wind power. For flexible islanding operation in Bornholm with large variable renewable generation, techniques like heat and electricity demand as frequency controlled reserves, wind frequency regulation and storages are under investigation ([2], [7], [8]). The dynamic simulations in this paper focus on electric vehicles (EV) based aggregated storage for the regulation services under an islanding operation in Bornholm. The faster charging and discharging characteristics of EV based battery storage could provide up and down regulation services when connected to the grid, which is generally termed as the Vehicle-to-grid (V2G) concept [9].

The aggregated battery storage representing Vehicle-to-grid system reduces the reserve requirement of the selected generators participating in the regulation services. Apart from the activation and communication delay which amounts to few seconds, the V2G regulation is instantaneous compared to the conventional generators that are constrained by ramp rates. The net contribution of V2G regulating power will be dependent on the battery state of charge limits, future vehicle driving requirements and available EV battery capacity. In this paper, the battery capacity of new commercially available EV, “Tesla Roadster” is considered which has storage capability of 53kWh and vehicle efficiency of 5.65 miles/kWh [10]. Based on the calculation using equation from the reference article [9], the net available battery storage capacity after a daily driving requirement is approximately 40kWh. The power line capacity to connect the electric vehicle integrated to the grid is considered as 10kW. About two-third of the 42,000 Bornholm population owns a car [11]. An approximate 10% of total fleet (2000 vehicles) when converted to electric vehicles with V2G contract could provide 80MWh of aggregated battery storage. If 50% of vehicles are always available for V2G regulation services, it accounts to 10MW, 40MWh of aggregated EV based battery. The aggregated battery model and parameters used in this paper are detailed in the reference article ([12], [13]).

B. *Load frequency control model for Bornholm*

Instead of an existing manual secondary control mode in Bornholm, an automatic load frequency control model with V2G regulation under islanded mode is analysed in this paper. Two different scenarios are identified and simulated using the LFC dynamic simulation model. First, the reference scenario 2007 for Bornholm is analysed, where the existing generator configurations and capacities as shown in the Table 1 are used. Second, a future scenario where more offshore wind is integrated into the power system is simulated. The generators capacities are scaled down to the Bornholm case from the CEESA 2030 future energy scenarios as given in the Table 3. The total wind installed capacity in the future scenario amounts to 54%, an increase of 24% from the reference scenario. The conventional generation is reduced by an equal amount, thus reducing the total regulation reserves available.

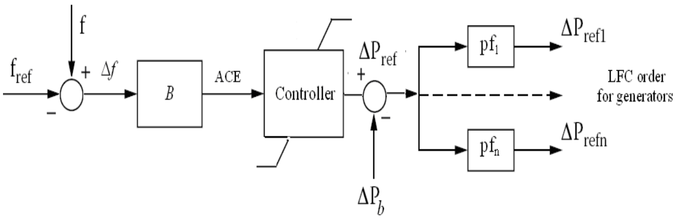

Fig. 1 Load frequency control model with aggregated battery storage

Figure 1 shows a load frequency control model incorporating an aggregated EV battery storage. For an isolated power system, the area requirement or area control error due to power imbalance is $ACE = -B.\Delta f$, where B the frequency bias factor and Δf is the frequency deviation. A LFC feedback loop delay time is considered for the signals to be fully activated. The error signal is filtered to remove any short period fluctuations and when large enough to overcome the load frequency control dead band, it will be passed through a PI controller. The controller calculates the average power that has to be distributed among the generators connected to the load frequency controller. The resultant control signal specifies the active power set points to the selected generators for power production adjustment based on participation factors , pf_1…..pf_n, where the sum of the participating factors are equal to unity. For the LFC model incorporating the regulation services of V2G storage, the resultant LFC order for generators are calculated by subtracting the integrated ACE signal from the aggregated EV storage power. The V2G regulation power minimises the regulation reserves from the conventional generators and reduces the frequency fluctuations by the fast charge/discharge capabilities of the battery storage.

IV. FUTURE ENERGY SCENARIOS SIMULATED FOR BORNHOLM

The CEESA scenarios are based on the detailed system designs and energy balances for the two energy target years: year 2050 with 100 per cent renewable energy (wind, solar, wave energy); and year 2030 with 50 per cent renewable energy as the first step. The results of the studies conclude that 2030 scenarios are feasible followed by the 100 per cent renewable energy systems from the domestic resources available within Denmark. The scenarios and energy system analysis are explained in detail in the reference article ([1], [14]). The feasibility studies and energy system analysis of these scenarios were carried out using the EnergyPLAN software model.

The EnergyPLAN software tool is a deterministic model which uses hour by hour simulations of energy systems for a period of one year, enabling the design and evaluation of a flexible energy system that can balance energy supply and demand in electricity, heat and transport sectors [15]. The EnergyPLAN model can analyse different energy systems, regulation strategies and integrates different mix of energy technologies. The energy balance for 2030 and 2050 flexible energy systems designed for closed Danish system were realised from EnergyPLAN model simulations based on the various regulation technologies like the electrolysers, energy storages, CHP regulation using heat pumps, electric vehicles (V2G), flexible electricity demand etc [16].

A. *Energy System Scenarios in EnergyPLAN*

As evident from the Section II, the island of Bornholm has similar energy system features as the Danish mainland. To identify and analyse the future energy scenarios for Bornholm, the CEESA scenarios analysed for Denmark is used. To simplify the analysis, the CEESA 2030 is considered by scaling the generation capacity to Bornholm as given in Table III. The scaling factor is based on an approximate equivalent generation capacity of Bornholm compared to Denmark which is 0.75%.

TABLE III: CEESA 2030 SCENARIO SCALED TO BORNHOLM

Power Plants	**CEESA 2030 [1]**	**Bornholm – CEESA 2030**	**Total %**
Centralised Power Plants (CHP)	4500MW	34MW	34%
Renewable Power Generation	7200MW	54MW (Total) Onshore Wind -30MW Offshore Wind - 24MW	54%
Decentralised Power Plants (DCHP)	1726MW	12MW	12%

The Bornholm 2007 energy system as shown in table I is used as a reference case for the EnergyPLAN model simulations. The reference energy system provides the existing system characteristics which serves as a benchmark to develop appropriate future energy systems. The reference energy system for Bornholm is used here to analyse large scale integration of wind power in a closed system. Such a scenario can be used to evaluate the ability of different future technologies and regulation strategies to accommodate high wind penetration in excess electricity diagram [17]. In this paper, only the V2G regulation (10MW, 40MWh) is used for the energy system analysis for both the Bornholm reference and Bornholm CEESA 2030. This is to simplify the comparative analysis between the hourly EnergyPLAN and dynamic LFC model simulations for both scenarios.

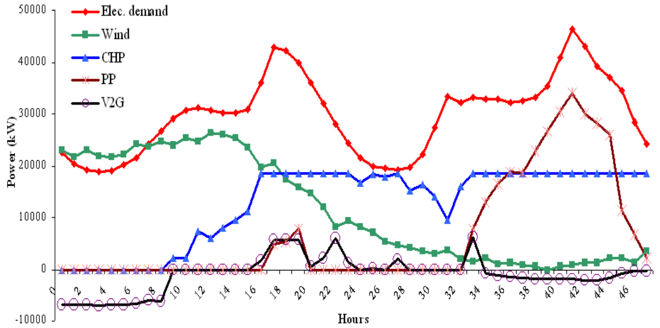

Fig. 2 Electricity production and consumption profile for two typical days from EnergyPLAN hourly simulations - Bornholm 2007 reference

The EnergyPLAN hourly simulation gives priority to electricity production from renewable energy sources and from the CHP plants. Any further deficit of electricity and heat demand is met by the condensing power plant (PP) and boilers respectively. The objective of the energy analysis will be to minimise the condensation power plant production by replacing them with CHP supported by heat storages. When the demand is lower than the electricity production from wind and CHP, the excess production is minimized by the use of regulating CHP plants with heat pumps or with flexible technologies like electrolysers, energy storages, electric vehicles etc. Figure 2 shows the typical hourly electricity production and consumption profile supported by the V2G regulation for two typical days from EnergyPLAN simulation for the Bornholm 2007 reference.

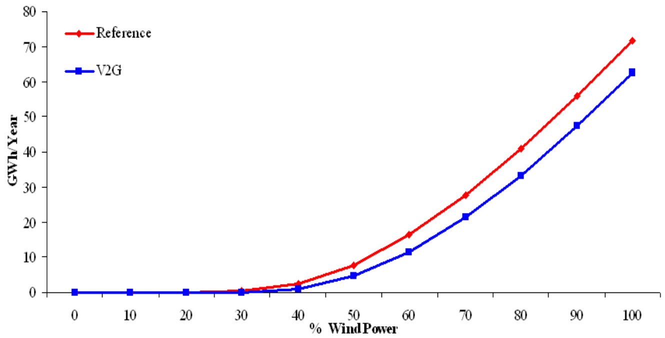

Fig. 3 Excess electricity diagram from EnergyPLAN - Bornholm 2007 reference simulations

For the Bornholm 2007 and CEESA 2030 scenarios, the impact of V2G for a range of 0 to 100 per cent of wind power supplying the load demand is simulated in EnergyPLAN. The excess electricity diagram for V2G in figure 3 shows that the annual excess electricity production increases when the wind power supplying the load is beyond 35%. A high excess production is an indication of large wind power being not able to integrate to an energy system without the help of an inter-country power transmission. For the 2030 case, 45% of the wind can be accommodated with V2G system as shown in Figure 4. More wind could be integrated for the future scenario than the reference case as due to the less power production capacity from the condensation power plants in the 2030 scenario.

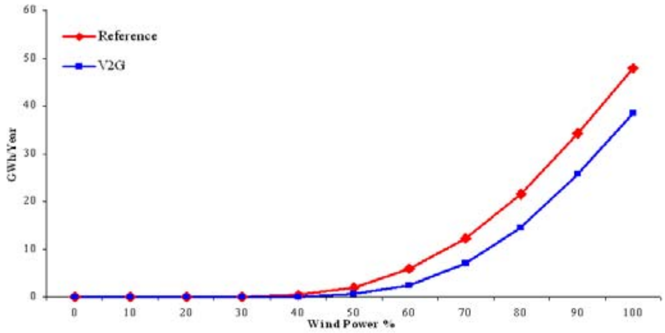

Fig. 4 Excess electricity diagram from EnergyPLAN - Bornholm CEESA 2030 simulations

B. *Studying the Scenario Feasibility*

Creating energy scenarios for the future energy systems is a complex problem, connected with many uncertainties. The EnergyPLAN model aims at simplifying this complex task to a large extend. The goal is to ensure the technical feasibility of scenarios generated by the EnergyPLAN model. In order to be able to study the effect of parameters in the EnergyPLAN model on the crucial parameters of a power system, we developed a mapping between, power system parameters and those of the EnergyPLAN model. We intend to improve the model simplifications by studying the similar energy scenarios generated in the previous section using dynamical simulations.

The LFC model dynamic simulations investigated in this paper are performed using DIgSILENT Powerfactory software. The centralised thermal power plants (Blok5 and Blok6) in Bornholm are modelled based on steam turbine units and the decentralised power plants are based on gas turbine units. The ramp rates of the units are considered as 4% and 10% per minute respectively [18]. The IEEE recommended models [19] [20] are used in long term dynamic LFC simulations which are available in the Powerfactory global library. An aggregated generic wind power model for dynamic power system simulations from [21] is adopted in this work. The power system model is based on single bus bar system connected with aggregated generator models. The transmission line capacities and constraints are neglected in this study as it primarily focuses on the collective performance and regulation capabilities of the generators in the system. For simulations, real time series data for short time frame were not available from Bornholm power system. So, the load consumption and wind power profile of five minutes time frame for a typical day in January which was available from the Danish mainland was scaled to the Bornholm power system are used for simulations.

TABLE IV GENERATOR CAPACITY UTILISATION AND WIND POWER SUPPLIED - BORNHOLM 2007

	Ref. and V2G	**V2G worst case**
CHP	100% (37 MW)	100% (37 MW)
Wind	50% (15 MW)	60% (18MW)
CPP	100% (27 MW)	100% (27 MW)
Wind Power - % of load demand	18%	22%

For LFC simulations on Bornholm reference scenario in an islanded mode, the generators and capacity utilised as given in the Table IV is used. The results of a simulation case for a typical day in winter, where an aggregated wind power of 15MW, which is 50% of the installed capacity, is shown in figure 5. The total wind power supplies 18% of the total load. The grid frequency is deviated beyond the Nordic levels of 50.1Hz as shown in Figure 6 during the morning hours (4:00 – 5:00hrs) even under the automatic secondary control operation. During these hours, the power imbalance is caused by the planned generation exceeding the demand. Thus, the use of higher wind power capacities than 15MW for simulations will further increase the frequency. It is also observed that the frequency drops during the peak hours (17:00 -19:00 hrs) but not large enough to violate the Nordic acceptable frequency limits of 49.9Hz.

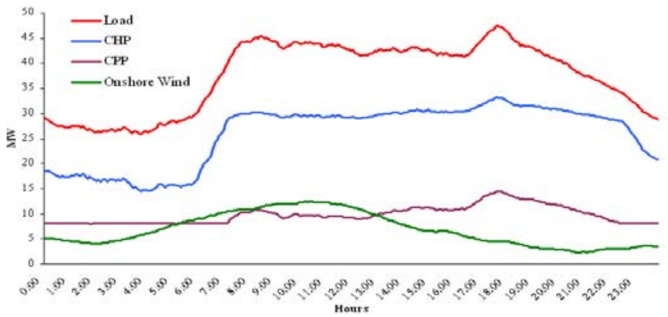

Fig. 5 Electricity production and consumption profile of Bornholm reference without V2G regulation

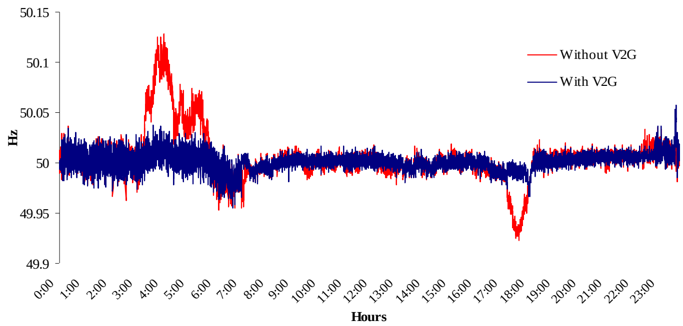

Fig. 6 Frequency profile from LFC simulations for Bornholm Ref and (Ref + V2G) cases

Figure 7 shows the daily electricity profile when a 10MW, 40MWh V2G based aggregated storage is applied to the Bornholm reference. It is assumed that the initial charge of aggregated EV battery storage is 50%. The V2G battery provides the regulation up by discharging stored power and regulation down by charging the storage, thus helping to maintain the grid power balance. The regulation capabilities of the conventional generators are minimised by an amount equal to the battery power cycled over the time period. Typically, the regulation signal fluctuates between positive and negative cycles very frequently. Over a time period, the net total energy balances to approximately zero for the battery storage regulation. However, LFC may require extended periods of regulation up or regulation down where the storage could reach its lower or upper limits. So, to maintain the regulation capabilities of V2G storage for a longer period, the power output is limited to avoid excessive charging or discharging. The battery power output is limited to 20% of the capacity in the simulations. In figure 6, the frequency deviations during the morning and peak hours present for the base case without V2G has greatly reduced for the case with V2G. To verify the more severe electricity imbalance, a worst case scenario with V2G regulation is simulated, where the frequency exceeds a range of 49.5-50.5Hz. The second column of the table 4 gives the generator capacities used and the percentage wind power supplying the load. Figure 8 depicts the deviation of power system frequency beyond the upper acceptable levels resulting from excess electricity production. The maximum wind power that can be regulated with V2G was found to be 22 per cent of the total demand.

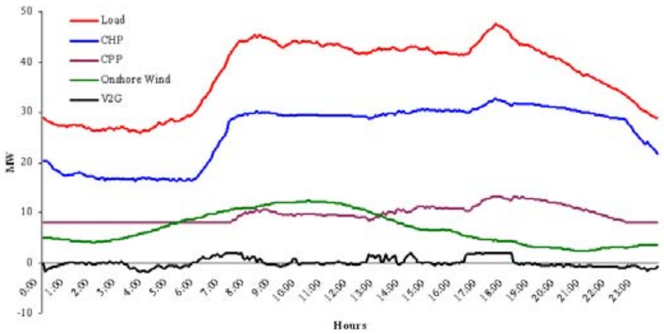

Fig. 7 Electricity production and consumption profile from Bornholm reference simulations with V2G regulation

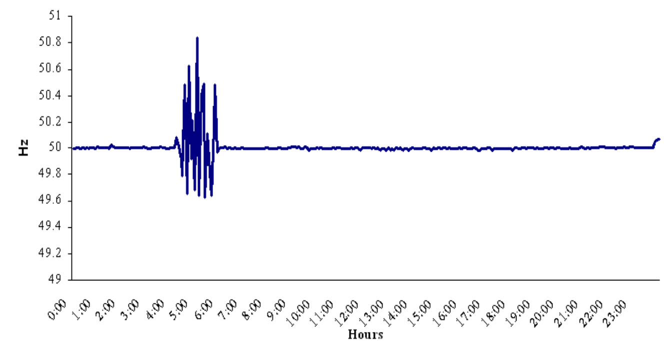

Fig. 8 Frequency profile from LFC simulations for Bornholm (Ref + V2G) worst case

TABLE V GENERATION CAPACITY UTILISATION AND WIND POWER SUPPLIED - CEESA 2030

	Ref. and V2G	V2G worst case
CHP	100% (34 MW)	100% (34 MW)
Onshore Wind	47% (14MW)	50% (14 MW)
Offshore Wind	33% (8MW)	42% (10MW)
DCHP	100% (12 MW)	100% (12 MW)
Wind power - % of load demand	32%	37%

For the CEESA 2030 Bornholm scenario, the installed capacities of the generators are adopted from the Table V. Keeping in view, the frequency deviation to be within the Nordic power system acceptable levels (49.9-50.1Hz), a simulation case with an offshore wind capacity of 8MW and onshore wind power of 14 MW was considered. The daily electricity profile of the base case without V2G regulation is shown in figure 9. The wind power fluctuations are more and the generators have to undergo more regulation. The power generated is more than the demand during the morning hour (4:00 hrs) as visible from the frequency deviation in Figure 10 which is above the upper threshold of 50.1Hz. Adding an aggregated battery to the LFC model of similar configuration as given in scenario 1, the above frequency deviation is minimised and brought to the nominal operating levels as evident from the result in Figure 10.

V2G regulation. To analyse the stage where the V2G regulation could not support the islanded mode, a worst case scenario is analysed. Table 5 gives the generation capacities used for the worst case simulation. The frequency profile results of LFC simulations for the worst case is shown in figure 12. The excess generation produces the power imbalance in the power system which is reflected as the frequency exceeding the higher threshold limits. The maximum wind power that is possible with V2G regulation is 36 percent of the total load demand for the typical day considered.

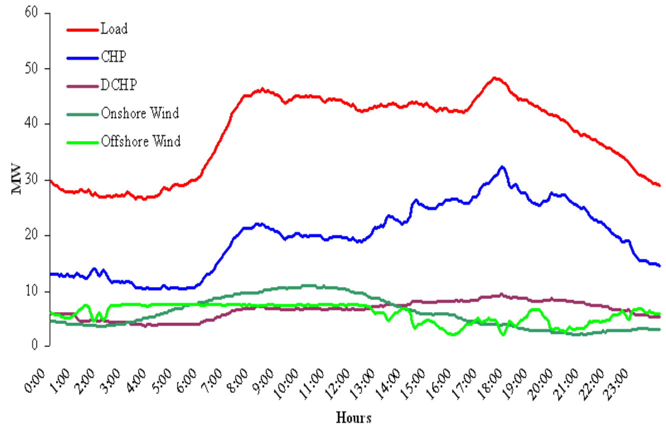

Fig. 9 Electricity production and consumption profile for a typical day of Bornholm CEESA 2030 without V2G regulation

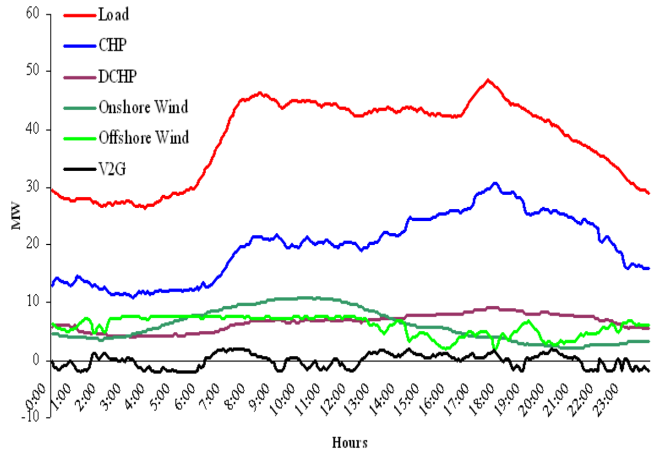

Fig. 11 Electricity production and consumption profile from Bornholm CEESA 2030 simulations with V2G regulation

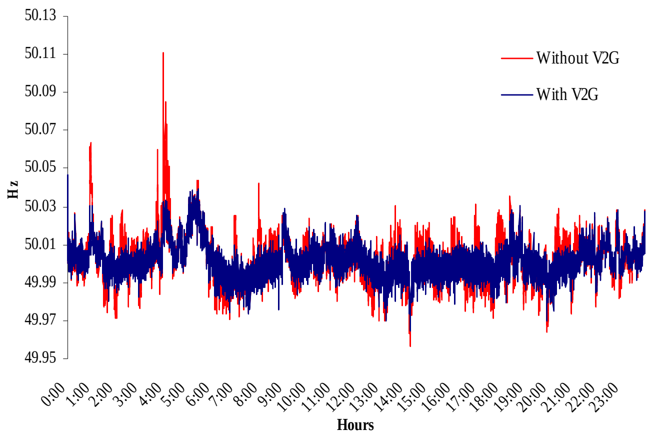

Fig. 10 Frequency profile from LFC simulations for Bornholm CEESA 2030 with and without V2G cases

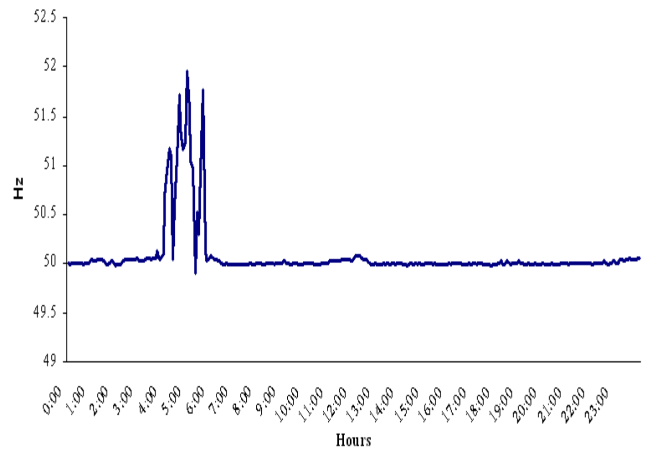

Fig. 12 Frequency profile from LFC simulations for Bornholm CEESA 2030 V2G worst case

The V2G regulation ensures that the frequency remains within threshold limits of the power system as evident from the frequency profile in Figure 10. From the electricity profile in figure 11 depicting the case with V2G power, the aggregated battery up and regulation are more frequent than the results of scenario 1, due to the high volumes of wind power and fluctuations. The frequency profile is well within the acceptable Nordic power system levels for the case with

V. CONLUSIONS AND DISCUSSION

To compare the results from the hourly simulation in EnergyPLAN and the dynamic long-term simulations of LFC model for the two scenarios analysed, the per cent wind power supplying the total electricity demand is considered. There is a significant difference if we compare the "hourly" island vs. "electrical island".

TABLE VI
ENERGYPLAN VS. DYNAMIC SIMULATION RESULTS – BORNHOLM SCENARIOS

Wind power (% of total energy demand)	Bornholm Reference	Bornholm Reference with V2G	CEESA 2030	CEESA 2030 with V2G
EnergyPLAN (hourly simulations)	25%	30%	35%	45%
LFC model (short time dynamic simulations)	18%	22%	32%	37%

The "hourly" island from EnergyPLAN simulations is based on the criteria of excess electricity production and that of "electrical island" from dynamic simulations is based on a larger system frequency deviation ($49.5<f<50.5Hz$). Table VI shows the comparative results from the hourly simulations and shorter time frame LFC simulations for the scenarios analysed for Bornholm. The percentage wind power that could be integrated in the Bornholm scenarios is much lower for the dynamic simulations than for the hourly simulations. Hourly simulations thus provide insufficient criteria to ensure the feasibility of an energy scenario. The dynamic simulations even in seconds are crucial to ensure stable power system operation and control. The simulations in this paper used only five minute average values for the wind data. Thus, shorter-term power system dynamic characteristics have not been accounted for. The use of time series data with higher time-resolution would provide more accurate simulations results, and we can expect that the wind-integration percentage will be even more conservative. The time series data used in this paper are typical for the whole of Denmark and do not directly compare with the actual Bornholm grid operation. This inaccuracy, however, is rather intended as we are studying the feasibility of the Danish scenario.

The results show that scenario evaluation tools like EnergyPLAN need to be taken conservatively if used for islands and islandable systems. Further, V2G is a good tool especially to improve the short-term balancing. Additional reserves need to allocated, depending on the short-term variability of wind and uncertainty of prediction. It has been shown how this mapping can in principle be done. In principle, conclusions for the whole of Denmark are possible, but should be taken carefully on the basis of the weak data-sets available so far.

It is important to be able to interpret the meaning of results obtained on Bornholm for the whole of Denmark. Future work needs to consider the appropriate scaling of reserves and more careful consideration of wind power smoothing effects. The ongoing work will use Bornholm for future network studies than can utilize a smaller-scale system.

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