Electric power systems for a transition to 100% renewable energy systems in Denmark before 2050

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Electric power systems for a transition to 100% renewable energy systems in Denmark before 2050

Coherent Energy and Environmental System Analysis

Background Report Part 3

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Preface

This report presents a summary of results pertaining to future electric power systems of the strategic research project "Coherent Energy and Environmental System Analysis" which was conducted in 2007-2011 and funded by the Danish Council for Strategic Research together with the participating parties.

The project was interdisciplinary and involved more than 20 researchers from seven different universities or research institutions in Denmark. Moreover, the project was supported by an international advisory panel.

The work was carried out as an interaction between five work packages. In this work package on future electric power systems, researchers from the Department of Energy Technology, the Department of Development and Planning (both Aalborg University) as well as from the Department of Electrical Engineering (The Technical University of Denmark) participated.

A number of reports, papers and tools were reported separately from each part of the project. A list of the main background reports is given at the end of this preface while a complete list of all papers and reports can be found at www.ceesa.dk.

This report details the articles and papers that were written specifically for this work package.

List of background reports:

Part 1: CEESA 100% Renewable Energy Scenarios towards 2050
Part 2: CEESA 100% Renewable Energy Transport Scenarios towards 2050
Part 3: Electric power systems for a transition to 100% renewable energy systems in Denmark before 2050
Part 4: Policies for a Transition to 100% Renewable Energy Systems in Denmark Before 2050
Part 5: Environmental Assessment of Renewable Energy Scenarios towards 2050

November 2011

Poul Alberg Østergaard
Work package coordinator, WP3 – Future Electric Power Systems

1. Introduction

The Danish electricity system has undergone a transition from being primarily based on few and large centrally dispatched power generators based on synchronous generators to being based 40-50% on generators that are either producing according to momentary wind or according to decentralised production strategies as shown in Figure 1.

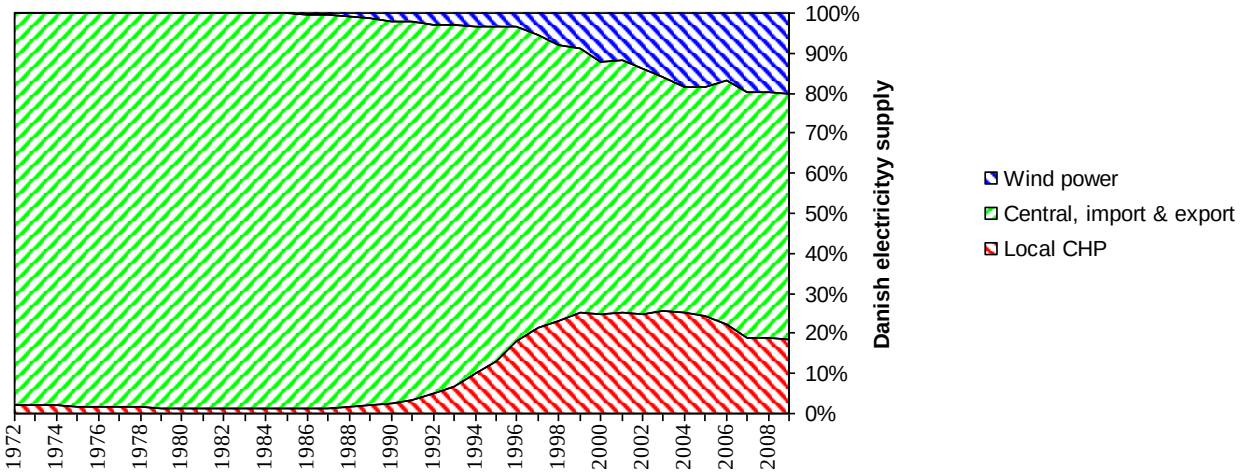

Figure 1: Danish electricity supply. Based on data from Danish Energy Authority.

Concurrent with the increasing wind penetration, development has supported wind turbines with improved electro-technical abilities going from the early fixed blade wind turbines with directly connected asynchronous generators to pitch-controlled wind turbines grid connected through power electronic interfaces. Likewise, local CHP plants have evolved from operating according to a set three-tier tariff system to largely operating on the spot market and thus with incentives to produce when desirable from a system power balancing perspective.

There has also been a transition from a spatially very centralised system with 17 centrally dispatched power plants and 15 local CHPs in 1985 to 17 central and around 300 local CHP plants above 0.5 MW in 2009. Wind turbines have furthered this development with most of the wind turbines being erected in windy but sparsely populated areas.

The transition towards geographically distributed power generation as well as the transition towards production beyond the control of the central dispatch is a challenge from a TSO perspective and, in the light of the CEESA scenarios, a challenge that will grow in the future with a focus on distributed generation and electricity consuming devices like electric vehicles and heat pumps with prospects for integrating fluctuating sources of electricity.

The main purpose of the analyses presented in this report and in the accompanying analyses is to investigate the design space of scenarios for future electricity systems. The three main contributions from this work package are:

- Analyses of and recommendation for electric grids in future power systems with a focus on storage facilities/electric vehicles
- Requirement analysis, method development and recommendations for the control architecture of future power systems
- Improved integration of system stability and short-term balancing considerations into the EnergyPLAN model

In order to study the effects of the envisioned measures in the CEESA project on the electricity system, the measures can be classified into a number of different classes of change. The impact of these changes will then be mapped to different aspects of the electricity grid (impact categories).

A. Central Generation
- In the CEESA 2050 Ideal scenario, solid oxide fuels cells are used throughout the system for power generation
- In the CEESA 2050 Conservative scenario, combined cycle gas turbines are used in combination with gasification
- Expansion from district heating from a level of approximately 50% of the total heating demand to between 63 and 70%

B. Renewable Electricity (uncontrolled, central and distributed)
- Increase offshore wind power to a level of 9710 MW in 2050 compared to 868 MW in 2010
- Increase onshore wind power to 4454 MW in 2050 compared to 2900 MW in 2010
- Increase wave power to 300 MW by 2050
- Increase photovoltaics from 4.6 MW in 2009 to 5000 MW in the ideal scenario or none in the conservative scenario

C. (controllable) Distributed Generation
- In the CEESA 2050 Ideal scenario, solid oxide fuels cells are used throughout the system for power generation
- In the CEESA 2050 Conservative scenario, combined cycle gas turbines are used in combination with gasification

D. Demand Reduction
- Reduce electricity demand by 50 % in private households
- Reduce electricity demand by 45 % in industry

E. Demand flexibility
- Flexible demand in households and in industry
- Heat pumps

F. Electric Transportation – V2G

- In the CEESA Ideal scenario, transportation needs are covered by electricity, V2G, and synthetic fuels

These measures grouped in categories A-F map into the following technical impact categories. The areas identified are:

I. Network

The AC network represents the physical aspects of the transmission system, including different voltage levels, transmission capacities, transformers and the equipment necessary to support the network such as shunt capacitors or voltage regulators.

i. Import/Export (interconnection capacity)
Cross-border exchange within synchronous areas as well as HVDC-based transmission across synchronous areas.

ii. Transmission Networks (transmission capacity)
A change in the location of central generation and load areas changes the loading patterns of the transmission network. Additional overhead transmission lines are not accepted in Denmark, and any further transmission capacity has to be underground, which is significantly more costly and harder to control.

iii. Sub-transmission and Distribution Networks (today passive infrastructure)
At lower voltage levels, resistive losses are larger. Sub-transmission and distribution networks will on the one hand be subjected to higher loads due to EVs and heat pumps but will on the other also be used differently as flows may be bi-directional due to power generation at household level.

II. Intermittency – Balancing (Active Power Balance)

Power system operation is aimed at maintaining the balance between power supply and demand at all times, whilst observing transmission limitations.

i. Inertia
Synchronous machines have rotating inertia and are electrically coupled to rotate at the same speed. The synchronous machines thus commonly provide an energy buffer to the overall system, making it more "patient" with respect to imbalances.

ii. Disturbance and Balancing Resources (Reserves)
Control resources need to be kept available at all times to counter unpredicted disturbances. These reserves correspond to idle generation capacity, but may also be substituted by controllable demand.

iii. Controllability issues
Traditional power system operation is based on long-standing operation principles which may not be prepared for incorporation of new resources or to counter new types of disturbances.

III. Operational stability (e.g. Voltage Control)
   i. Impacts on voltage and load angle stability
   ii. Impact on distribution level
   iii. Reactive flows and congestion management

IV. Protection Systems
   i. Changing flows
   Particularly reverse flows are critical for today's protection systems. Also a higher probability of exceeding operational range (e.g. overloading/voltage dips) is expected with higher penetration of electric vehicles and distributed generation.

Mapping the various measures of the CEESA scenario into technical impact categories gives the following impact matrix:

Measures / Tech. Areas	A. Central Generation	B. Intermittent renewable Electricity	C. Distributed Generation	D. Demand reduction	E. Demand Flexibility	F. Transportation
I. i.	X	x	-	-	-	?
ii.	X	x	x	?	x	x
iii.	-	x	X	x	x	X
II. i.	X	X	?	-	-	-
ii.	x	X	x	x	X	X
iii.	X	X	X	?	X	X
III. i.	X	x	?		?	-
ii.	-	x	X	-	X	x
iii.	x	x	?		x	x
IV. i.	?	x	x	-	x	X
X – major impact, x – minor impact, ? – unclear impact, - – no impact						

Power system simulations are conducted on selected Danish power and distribution networks to verify the technical changes and challenges given in the impact matrix in Work Package 3.1. Some of the worst-case power system operating control scenarios for an increasing amount of renewable energy systems, especially the wind power in Denmark, is used for simulations in the work package. These scenarios provide the basis to validate the ability of electric vehicle based battery storages as alternate and flexible power balancing solutions. The technical challenges and issues as given in categories I and II of the impact matrix, like the limited prospects of network capacity expansion and the decreasing conventional balancing reserves, are accounted by the electric vehicle based future ancillary services study in WP3.1. The studies in WP3.1 were based on system perspective and aggregated levels rather than the secondary local distribution levels which limits a detailed analysis of categories III and IV of the impact

matrix in WP3.1. The scenarios, simulation studies and results of WP3.1 are presented in Section 2 of this document.

In Work Package 3.2, the overall requirements for the control of a power system for the CEESA scenario have been analysed, with a focus on impact category Balancing (II.) and capacity aspects of the Network (I.). It was found that for changes at the scale required in the CEESA scenarios, several aspects of today's grid operation principles will be severely challenged, and that there will be a need for revising control architecture of power systems. Section 3 discusses which aspects have to be considered in the design and summarises two modelling methods for control architecture representation and analysis that have been proposed in the course of this work.

2. Simulation of power systems

In the future Danish power systems, the integration of more wind power is replacing the large conventional generators and the expansion of interconnections with neighbouring countries is limited. These factors demand new power balancing solutions for the reliable and stable operation of power systems. The energy systems have to be made more flexible and intelligent in the power distribution levels to incorporate more variable and uncertain wind power. The intelligent systems can efficiently incorporate more renewable sources with the help of local balancing solutions distributed across heat, transport and electricity sectors. Some of the popular examples include heat pumps in the heat sector and electric vehicles in the transportation sector. To validate these concepts, there is an increased interest among the utilities, industries and the scientific community to test and operate the distribution networks as self-sustainable systems with the support of local balancing solutions. The CEESA project estimates that Denmark can be self-sufficient with a renewable energy system based on domestic resources.

As part of the CEESA project, the simulation studies of power systems in WP3.1 are used to analyse the integration of the transport sector with the electricity sector. This is carried out as a PhD study where the objective is to investigate the use of battery storage of electric vehicles represented as Vehicle-to-Grid (V2G) systems to provide active power balancing to support large-scale wind penetration in Denmark. This research work is divided into five different case studies analysed in selected Danish electricity networks with high penetration of wind power. They are conducted as static or dynamic simulation studies for islanded as well as interconnected power system operation.

Case 1: The role of Vehicle-to-Grid systems as primary regulation reserves is verified for ensuring frequency stability in a Danish distribution system with high wind power penetration [17].
The short-term dynamic simulations were applied to the tested distribution system operated in an islanded mode with 48% and 65% of wind power penetration scenarios. The analyses were conducted based on the different power system events like step load change, loss of combined heat and power (CHP) and loss of wind farm units. Based on the simulation results, the V2G systems provide a fast, robust and stable frequency control better than the conventional generation units in the distribution network. The

rate of change of frequency and the frequency deviations are minimal for simulation results using V2G systems when compared to using only the conventional generation. The V2G systems could operate as either controllable load or generation based on the system's balancing power requirement.

Case 2: The application of Vehicle-to-Grid systems as secondary regulation reserves in an interconnected power system operation of Western Denmark is analysed [16].
The long-term dynamic power system simulations were used to investigate the integration of V2G systems in a Load Frequency Control model. The simulation scenarios were defined based on two typical days with low and high wind power, which are characterised by large power exchange deviations with Germany (UCTE control area) and periods of continuous up-regulation and down-regulation requirements. The simulation results show that the power exchange deviations between West Denmark - UCTE control areas were substantially reduced (within acceptable limits - ±50MW) using V2G as regulation reserves. The regulation power requirements from conventional generators are also significantly reduced with the integration of V2G systems participating in Load Frequency Control. If the electric vehicles have battery storage duration of four hours connected at 10kW each, less than 10% of the total Danish vehicle fleet converted to V2G based vehicles is sufficient to satisfy the regulation needs of the examined scenarios. The operating characteristics like quick start and fast ramp up or down capabilities of battery storages provide superior performance compared to that of the conventional generators delivering power system ancillary services.

Case 3: The Vehicle-to-Grid system is analysed for an islanded power system operation on the Danish island of Bornholm [13].
The long-term dynamic simulations were conducted to provide a qualitative and quantitative analysis of V2G system performance when replacing conventional reserves and when determining the storage capacity required to support large integration of wind. The worst-case scenarios of reduced power balancing reserves, periods of coincident peak demand and wind ramps, and battery storage constraints are considered in this study. The results of the simulations reiterate that the desired frequency quality in an islanded mode of power system operation was ensured using V2G systems responding to power system operation scenarios with high wind and high reserve power requirements. A minimum battery power capacity of 30-40% of the installed wind power capacity is estimated for a stable power system operation for the studied case. More than 80% of conventional generation reserves were replaced by the V2G systems for power system regulation services. These analyses could be representative to other small or large isolated distributed power systems where the wind power outputs are strongly correlated. The overall generation control efficiency could be improved in a wind dominated power system like Bornholm using a quick response V2G frequency regulation which is an attractive alternative to reserves from the conventional power plants.

Case 4: The impacts of increased penetration of electric vehicles as loads on a Danish primary distribution network are investigated [18].
The steady-state power system simulations are conducted on the primary distribution network of Bornholm for an increasing amount of electric vehicles load of different

power ratings in the range of 0-50%. The charging strategies of uncontrolled (dump) and controlled (smart) were examined in the case study. It could be inferred that the electric vehicle penetration levels depend not only on the battery storage capabilities, market mechanisms or policies but also on the various safe operational limits of power system network parameters and the battery charging profile. Controlled charging is found to be more effective than uncontrolled charging when integrating more electric vehicles on a moderate level. The electric vehicle integration of only 10% is possible in the studied distribution network for uncontrolled charging, whereas 40% was possible with controlled charging. The voltage drops in the network are more critical than the line loading for same levels of EV integration as obtained from the simulation results. The impacts of electric vehicle integration at the low voltage secondary distribution and weak networks may yield more conservative results.

Case 5: The results from power system dynamic simulation studies with future power regulation strategies like electric vehicles are used here to compare the results from hourly simulations of energy planning tools to validate the future energy planning scenarios [19]. The key findings of this case study are discussed in detail in the section "Dynamic simulations vs. EnergyPLAN model" of this document.

The results of the case studies have shown that the Vehicle-to-Grid systems provide better performance than the conventional generation sources when balancing the power system with high levels of variable wind power. The Vehicle-to-Grid systems possess fast, quick start and flexible characteristics to provide smooth and robust grid regulation services which could be considered as one of the alternate solutions for replacing the conventional power reserves. The methods, scenarios and control strategies used in the above case studies were applied to selected Danish electricity networks which can be representative in applying the ideas to other similar small and large power systems, where a high level of wind power integration is desired. The Western Denmark and Bornholm power systems used as test cases in the PhD study could be regarded as the ideal electricity systems to validate the interconnected and islanded system operation with high wind penetration, respectively. The various percentages obtained as results of the case studies in this work package are more specific or dependent on the selected Danish electricity networks. It is hard to generalise the results as they may vary or a more conservative outcome may be produced when an analysis is made on other electricity networks. Instead, it could provide fairly reasonable results and trends which can act as "working tools" to simplify the complexity of multivariable and dynamic power system analyses. This could act as a base or reference case for a final synthesis of future power system planning and operation.

3. Future control strategies of power systems

The control architecture of today's power systems is based on a paradigm of controllable central generation and fluctuating demand. The energy mix for Denmark developed in the present scenario studies tends to be strongly based on fluctuating renewable energy, mainly wind power, and includes a variety of flexible demand options due to active integration with the heat and transport sectors. This mix requires

new control strategies, because the formerly clear roles of controllable generation vs. fluctuating demand are no longer given simply by the structure and location of components in the power system. In order to develop such control strategies, we need a different understanding of the operation of electricity systems in which both the identification of system regulation needs and the allocation of appropriate roles to available resources can be handled dynamically. This work focuses on a rigorous top-down approach to both identifying these requirements and providing means to modelling these new control structures.

Behind the idea of studying 'future' control structures is the task to find or design these control structures in the first place. In recent years, a number of proposals for new control and operation schemes aiming at the coordination of more distributed and fluctuating resources with power system control requirements appeared, but their scope tends to be limited to specific use cases and challenges. The challenges considered are typically formulated either in a market perspective, or in a technology perspective focusing on grid issues or information and communication aspects. In their way, all of these schemes may contribute to the control architecture of future power systems. However, even though it seems likely that the final design will be composed partially of a number of these existing proposals, it is quite unclear to which extent and which role these partial solutions will play. What seemed missing was an approach with a broader scope that could provide a meaningful and formally precise representation of power system control architecture, in which roles and interactions of those different concepts with respect to the overall system control could be represented and evaluated.

The approach developed in this work aims to bridge the common chasm between intuitive insights (such as "more wind power leads to a need for more flexibility") drawn from simplistic modelling approaches and (too often misleading) results of detailed simulation studies based on today's operational framework, which require numerous opaque assumptions and typically hardly accessible data. The first step in the design process is to identify overall goals and to relate those to tangible design objectives. As the overall goals and objectives are very abstract, their refinement to more structured requirements depends on an appropriate representation of the system structure. A methodological basis for this representation was found in means-ends functional modelling [8], which provides a framework for modelling power system functions and their relations at different levels of abstraction. The explicit means-ends perspective makes it possible to relate control objectives and control functions to networks of more basic functions at the appropriate level of abstraction. The representation of functions is designed to strictly conform to first principles of physical conservation laws, causality and intention as well as linguistic concepts of action. The method has previously been applied to a range of different processes. In the course of this work, the method has been adapted and extended for application to the control of power systems. Due to the scope of energy scenario studies, the depth of analysis was limited to energy storage and flows, however, there is a potential for adapting the method to voltage control as well as for the representation and integration of other energy systems [8,2,7].

The following insights were generated from the application of means-ends functional models to the study of power system control:

- Aggregation concepts, which are typically at the core of forward-looking control schemes, are inherently based on a functional understanding. Functional modelling provides a logical and consistent framework for modelling these schemes in proper context [9,5].
- The aggregates of functions and their relation present a formal way of modelling different (engineering) perspectives in energy systems [7].
- Means-ends functional modelling can serve as an information modelling method for control service description, fault analysis and situation awareness of control agents in future power system automation [5].
- The consistent means-ends decomposition based on such functional models presents a clear interface to resource allocation problems, analogous to the way in which a cooking recipe can be interpreted as a shopping list. With this property, functional modelling should facilitate market design by providing a transparent representation also for the complex but structured environment of power systems [10,9,1].
- Energy storage is a functional element that is not explicitly recognised in current operation principles of power systems. If energy limited units are to provide regulation capabilities, an explicit consideration of energy limitations in future operation concepts is required [3].

The qualitative framework has been extended to include prediction and scheduling of variable energy resources which are important for the continuous power system operation with uncertain and fluctuating energy resources [6]. Altogether, this framework provides a complete formalism to qualitatively describe and analyse energy control structures for power systems.

An insight of the studies of this project is the effective transition of electric energy systems from the simple supply-follows-demand logic to a power system operation paradigm that includes the management of energy storages at all scales to continuously buffer mismatches between energy supply and demand. Here it is important to realise that operational flexibility may be gained both from reversible (bi-directional) and irreversible (buffering) energy storage. Adaptation of the operation logic in future power systems will lead partially to new control structures, with much finer granulation than today, needed for aggregating and managing the diverse resources and operated more autonomously by means of intelligent agent technology. Along with the adapted operation methods, new operation models, markets, visualisation and operator support tools will also be required.

By harvesting these insights from the qualitative modelling and analysis, a new modelling framework has been developed that combines classic network-oriented power system models with generic scalable energy storage models [3,4]. Based on the qualitative modelling insights, this simulation framework is going to include a structured interface for the modelling of alternative control structures. The generic model structure provides standard evaluation functions enabling the comparison and evaluation of either alternate storage technologies or alternate regulation strategies.
The framework is going to be applied to a comparative study of wind integration with thermal storage buffering and flexible electricity for electric transport, potentially also

comparing a small number of control schemes to evaluate their performance in terms of resource efficiency.

3.1. Engineering requirements for energy scenarios

Questions typically requested of WP3 contributors were those about realizeability, or feasibility: "Is it technically possible to do this?", "What is necessary to make it possible?", and those questions about relations between technologies: "How many electrical vehicles for xx% of wind power?"

The work described in the previous section aimed at interpreting the main directions of the CEESA energy scenarios in terms of their implications for power system operation and control and the development of methods appropriate for this purpose. The following discussion will highlight other aspects of the relation between energy scenarios and power engineering.

Normally, energy planning studies provide design requirements for power system planning, such as the development of the transmission infrastructure. A typical relation between engineering and scenario studies is that the scenarios provide design requirements for the engineering. The questions above point in a different direction: to derive requirements from engineering knowledge to scenario studies. Are the scenario assumptions technically feasible, and can the assumptions be improved? For the sake of the following argument, this question may be divided into two ways of addressing technical feasibility in energy scenarios: 1) For a given scenario, to find out whether or not it would be technically feasible, "can it be done?", and 2) by providing constraints and options to be considered in the generation of "feasible scenarios".

3.1.1. Can it be done?

Simulation studies are a practical approach to evaluating the feasibility of a given scenario. In a simulation study, first a base case that realistically reflects known system behaviour needs to be established. Aspects of the base case are altered incrementally to reflect the effects of changes to the given case. The more complex and 'nonlinear' the base case model, the more difficult it is to reflect changes. Alternatively, model simplifications can be performed by additional modelling assumptions, which enable more flexible modifications of the base case. A typical modelling assumption is for example that a lower-level control objective is always fulfilled (e.g. the voltage is within operation limits) – and sometimes it is questionable if the original assumptions remain valid for the altered system. Further, it is often overlooked that simulation approaches require the definition of control objectives and algorithms. These controls are in part oriented to existing physical needs and, especially in power systems, also to (organisational/legal/market) regulations, both of which could be subject to change. For a simulation study, all these part-assumptions have to be considered to judge the generality and precision of respective conclusions.

In every step of adapting a base case to a new scenario, the engineer implicitly answers the question "How should it be done?". By answering this question, incremental design choices are made, usually on the basis of existing and learned engineering knowledge and procedures. It is thus important to recognise the *design problem* implicit in every

"Can it be done?". In case of major steps in the scenario requirements, an incremental development may not be feasible on the basis of existing domain knowledge. As energy systems are complex, the design space to be explored is vast and the complexity of models may make it hard to evaluate alternatives. Here, model simplifications are used systematically as abstractions in the design process to incrementally structure the design space. In a structured design space, requirements can be mapped to respective model abstractions. Also the methods introduced above are tools to facilitate the structuring of the design space by providing building blocks for a systematic representation of the processes that form energy systems.

3.1.2. Feasible scenarios

Also a scenario tool is aimed at structuring the design space of future energy scenarios. Generally, a scenario tool models the constraints of energy systems at some level of abstraction so that technological alternatives can be evaluated. It simulates the interactions between different technologies based on a number of built-in relations (constraints) and regulation objectives, and calculates figures that serve as decision criteria. The relations and objectives are naturally based on the assumptions built into the scenario model. While the decision process often revolves around the figures, it is the structure of these underlying assumptions which gives rise to the formulation of such figures.

While a scenario model is considered a simplification of the 'real world', its goal is to capture major quantitative interactions in energy systems. In analogy to the model simplifications employed for the technical reasoning, these simplifications are aimed at providing insight for quantitative decision-making. The difference is thus that scenario models are built to approximate the quantitative outcome, not to simulate the actual process. The abstraction level is chosen as high as possible to allow for simple computations whilst providing numerical results as accurate as necessary. The purpose is not the evaluation of alternative system designs but to assess *alternative resource allocations* on a given *approximate system.*

Here, the engineering approach may provide insight by comparing the "approximate design" (scenario model) to potential future engineering realisations, investigating critical points that would render a scenario infeasible and pointing at developing more fundamental decision figures. In this perspective, the following section discusses some potential improvements to the EnergyPLAN model.

4. Grid stability in scenario analyses

The EnergyPLAN model uses a simplification to assess dynamic grid stability; a minimum production during all hours in large CHP or condensing mode power plants as frequency forming units and a minimum share of the total power generation coming from frequency regulating units. This ensures a certain proportionality between non-frequency forming units and frequency forming units as well as a provision regulating power to balance intra-hour imbalances between supply and demand.

EnergyPLAN does not model:

- the uncertainty of prediction of fluctuating resources,
- limitations to the flexibility of generating units,
- power system events, such as sudden outages or the effect of a storm front on the wind power production.

The prediction uncertainty of wind power is rather low if the reaction time of the power system operation and resource allocation can be reduced. It can also be said that both the increase in distributed generation and flexible demand will lead to high availability of highly responsive regulating units and that for a high number of smaller units the ramping limitations and startup times known from today's large scale generators do not apply to the generation mix proposed in the CEESA scenarios.

In future systems without large synchronous generators, the fundamental issue of missing frequency forming units is present. The less synchronous machines, the less inertia of the system, the more sensitive the system will be and the faster it should respond.

Analyses for this work package have primarily focused on the extent to which fewer, smaller plants in combination with electricity storages in electric vehicles connected to the grid through power electronics may ensure dynamic stability.

This has resulted in the EnergyPLAN model having been upgraded with new system parameters qualifying the additional resources required for the technical and minute-to-minute operation of power systems. These are thus issues with an impact on the main scenarios, and restrictions that need to be imposed on the design of the general CEESA project scenarios so adequate allowances are given grid stability issues.

4.1. Grid stabilisation using V2G technology

Extensive work on V2G has demonstrated the technology's ability to add frequency stability to electricity systems due to the energy storage capacity of electric vehicles combined with a quick response time. The analyses have even shown that most conventional generator reserves may be replaced by V2G systems and that the V2G systems have better performance in terms of rapid reaction to imbalances.

Applying the V2G technology reduces the power imbalances that would otherwise be imposed on neighbouring control areas. It is important though, that electric vehicles are charged and discharged intelligently as so-called dumb charge electric vehicles would not add to frequency stability but rather impose a large burden on the electricity system due to coordinated charging.

The technology is modelled in more detail with a focus on impacts on future scenarios as modelled with the EnergyPLAN model. This is presented in the next section.

4.2. Dynamic simulations vs EnergyPLAN scenario modelling

In order to validate EnergyPLAN scenarios designed and analysed using the model's simplified representation of grid stability, an analysis was made where a national Danish scenario was mapped to Bornholm and subsequently analysed using both the EnergyPLAN model and a dynamic simulation model evaluating the frequency response of the system [19]. While the EnergyPLAN ensures power balance at an hourly level, the power balance must be maintained in all time frames in actual systems, and the frequency stability of systems is an indicator of the system's ability to do this.

With a starting point in the mentioned national CEESA scenario, future scenarios for increasing penetration of wind power supported by increasing Vehicle-to-grid regulation capacity were analysed. As cut-off criteria for comparison of the two models, the excess electricity production parameter in the EnergyPLAN model and the standard deviation of the frequency in the dynamic power system model were employed.

The wind power capacity integration ability obtained from the dynamic simulation resulted in about 50% less than what was obtained from the hourly simulation results for the scenarios analysed without V2G regulation. If the V2G regulation is implemented, more wind power production is feasible. A wind power penetration of 82% and 70% is possible from the simulation results of hourly and dynamic models, respectively.

The possible levels of renewable energy integration as well as the required reserve margins differ in these two simulation model types. Since the dynamic model considers the short-term fluctuations from the wind power rather than the hourly aggregated data used in the EnergyPLAN, the results from the former reflect the need for faster and greater balancing capacity (reserves) to ensure a continuous balancing of wind power variations. It should be noted that the difference between the results from the two models was reduced, when the fast and quick start V2G regulation was applied. This also indicates that electric vehicles may have an important role to play in future energy system scenarios due to their fast response in comparison to conventional generators which at present are the main source of balancing power.

It was also noted that the conventional control architecture which was utilised in the dynamic frequency simulation to control the power output of the electric vehicles led to a saturation of the electric vehicle charging capacity. This effect seems to result from an ineffective utilisation of the available energy resources. Including a different control architecture that ensures an improved utilisation of the energy storage capacity of the electric vehicles could be considered for future studies. EnergyPLAN optimises the storage capacity utilisation of electric vehicles directly. To improve the capability of EnergyPLAN to represent the intra-hour regulation capacity offered by energy storage such as electric vehicles, it may be considered to allocate a fraction of the accounted energy storage capacity inside EnergyPLAN for grid regulation instead of optimisation. That fraction would be a function of the power capacity of the respective device, of the system interconnection type and of the energy mix in the system. Estimates for this fraction can be obtained from further comparative studies that isolate the intra-hour operation from optimisation of energy storages in order to avoid the saturation of energy storage capacities.

In the EnergyPLAN model, for the technical optimisation strategy the electricity is exchanged for technical reasons, whereas for the economic optimisation, the aim is to optimise the profit by participating in the external electricity market. However, the transmission capacity and the imports/exports model in EnergyPLAN are aggregated and static which does not account for scheduled power exchange flow in the interconnectors. In order to conduct similar comparative analyses for interconnected systems, the excess electricity production in EnergyPLAN could be compared with power exchange deviations in the dynamic simulation model. For such an investigation, the provision for representing different power scheduled exchanges has to be included as a modification to the EnergyPLAN model, instead of the existing single aggregated interconnector.

4.3. Grid stabilisation in the EnergyPLAN model

As mentioned, EnergyPLAN does not make dynamic simulations of grid stability issues but rather relies on hourly simulations in which certain requirements are being met. The model has three main requirements to ensure that the system works from a grid stability perspective. These are

- Minimum grid stabilisation share,
- Minimum production on central CHPs, and
- Minimum production on central condensing mode power plants.

In the minimum grid stabilisation, users detail the fraction of power production that for each hour of the year as a minimum must come from production units able to ensure grid stability. In addition, users may specify minimum productions on the units that are typically equipped with large synchronous generators – central CHPs and central condensing mode power plants.

These are thus the requirements that must be met during all hours of the year. If the demands are not met based on simple load balancing necessities, central CHPs or central condensing mode power plants will increase production in the given hour until the minimum share is reached.

In addition to the central CHPs and condensing mode power plants – that by default are assumed to be able to provide grid stability – there are three technologies that also provide grid stability if present. These are

- Nuclear power
- Geothermal power
- Hydro power

All plants of these types are also assumed to be able to provide grid stability, however there is no technical minimum they must abide by. Finally there are a number of technologies that may or may not provide grid stability. These are

- Decentral CHP

- Wind, wave, river hydro, tidal and solar power

Each of these technologies may provide a user-defined grid stabilising contribution between 0 and 100% of the hourly production depending on how advanced the user considers the given technology to be.

As a part of the CEESA project and as a consequence of the analyses of electric vehicles, the model has been expanded with the ability to include the following technologies in grid stabilisation:

- Smart charge electric vehicles
- V2G
- Interconnections
- Waste incineration CHP

As opposed to some of the other technologies, electric vehicles, V2G and interconnection do not relate to the actual use of these in the given hour but rather to the connected capacity in the given hour. A given stock of vehicles connected to the grid and an interconnection capacity to surrounding systems can thus be modelled having a grid stabilising ability even if they are not used in the given hour. Waste CHP, on the other hand, is modelled like most technologies meaning that the grid stabilising ability is proportional to the actual production in the given hour.

Electric vehicles account for approximately one quarter of the energy demand for transportation in the CEESA scenarios, and if these are considered grid stabilising, the impact may be significant. In the standard CEESA scenario, however, grid stabilisation is not considered so for these analyses an alternative 30% production share from grid stabilising units is required throughout the year. Half of the installed offshore wind and local CHP capacity is assumed to have a grid stabilising ability as detailed in Table 1.

Stabilisation share of different technologies							
	Min share	CHP2	Onshore wind	Offshore wind	Waste CHP	EV/V2G	Interconnection
Standard	0	0%	0%	0%	0%	0%	0%
Alternative	30%	50%	0%	50%	0%	Varying	0%

Table 1: Grid stabilising ability in the main CEESA scenario and in an alternative with a varying share from electric vehicles.

Under such circumstances, the system may experience hours of the year when the minimum grid stabilising share is not reached, causing power plants to operate extra for the system to remain within the 30% boundary condition. This in turn may give cause to additional export and additional power plant operation in condensing mode.

Figure 1 shows how export and condensing mode operation decrease with more and more electric vehicles modelled as having a grid stabilising ability. Due to the significant installed capacity on electric vehicles, the system experiences saturation even when only 5% of the vehicle stock is considered grid stabilising.

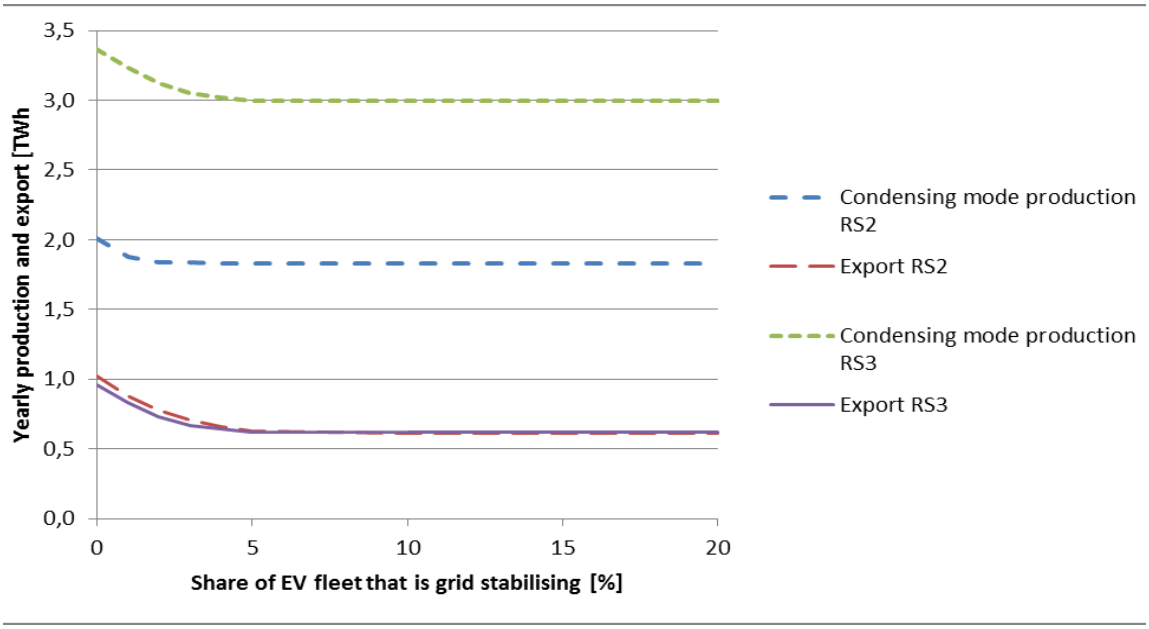

Figure 2: Condensing mode operation and export vs grid stabilising ability of electric vehicles.

The work has also included a more general discussion on grid stabilisation or system stability in EnergyPLAN scenario analyses. The actual modifications to the model have been made within the model's current topology of grid stability as described before with a minimum hourly share from units designated as being grid stabilising as well as a minimum production on certain units.

The EnergyPLAN model does not explicitly incorporate or distinguish between issues such as frequency control, upward regulation, downward regulation, primary reserves, secondary reserves, tertiary reserves, voltage control, short-circuit power and to some extent technical minima of production technologies.

The EnergyPLAN model operates at an aggregate level where technologies are grouped into a number of general categories including e.g. offshore wind turbines, small-scale CHP plants and condensing mode power plants. Minimum production of large CHP units may be specified using the minimum CHP production, however that is more intended from a grid stability perspective than a minimum partial load specification. Partial load is in most cases handled by the circumstance that each group may encompass a number of units each of which may be operated within its technical limits – including being shut down – thereby realising all operating points between zero and full load.

However, the minimum production may be more explicitly separated from technical minima to ensure full distinction between the two non-related issues.

The circumstance that the EnergyPLAN model does not distinguish between upward and downward regulation means that some technologies are likely operated in operating points where they only have the possibility of one of these. Full-load production on a given unit – or maximum generation on a fluctuating energy source – means that the technology cannot provide additional upward regulation though it would be able to

provide downward regulation to the extent that the given technology is used. Conversely, downward regulation may only be provided if the production technology is producing or the consumption technology is not consuming at full load.

If a more rigorous grid stability system was to be implemented in the EnergyPLAN model, such segregation could be implemented, however it would also mean that technologies providing either upward or downward regulation should not be operated to the full extent possible. Wind turbines would e.g. need to be operated sub-optimally to be able to provide upward regulation, thereby reducing the actual production. That would naturally be a more fair representation of how they were to be operated in a system where they were to provide regulating power.

A last consideration is reserve capacity for contingency situations or for n-1 situations, which is not explicitly included in the EnergyPLAN model. If a large unit trips offline, there is little to ensure that its production may be replaced by production from other units. Ensuring sufficient reserve capacity for contingency situations would not affect energy system dynamics in EnergyPLAN unless coupled with the possibility of stochastic events, however this latter would be beyond the scope of EnergyPLAN. Nonetheless, there could be additional capacity costs and/or additional fuel costs for such reserve capacity.

4.4. Grid stabilisation and the CEESA scenario

The CEESA scenarios contain many significant changes compared to the present system, and the dynamic impacts of all of these changes have not been analysed, so while the scenario has been verified in hourly energy terms, it has not been verified in power terms. Analyses focusing on the role of electric vehicles in power systems have demonstrated, however, that these may have a role to play in future power systems.

With a high reliance on wind power in the CEESA scenarios, the behaviour of this resource and technology is particularly important. EnergyPLAN does not capture the intra-hour fluctuations that wind power has, however studies of measured wind power time series have shown that the amplitudes of fluctuations scale with the timescale. That is, fluctuations decrease with decreasing timescale so that fluctuations below the one-hour level will tend to be smaller than the fluctuations already accommodated for in the EnergyPLAN modelling.

5. Articles and papers written as part of the work in WP3

The list below details the articles and papers written as part of the work in this work package on future electric power systems. In general, the articles are also included in the PhD theses that form the main part of the documentation of the work. The articles are listed alongside the abstracts.

[1] Heussen, K.; Saleem, A. & Lind, M., System-awareness for agent-based power system control, *Bulk Power System Dynamics and Control (iREP) - VIII (iREP), 2010 iREP Symposium*, **2010**, 1 -15

Operational intelligence in electric power systems is focused on a small number of control rooms that coordinate their actions. A clear division of responsibility and a command hierarchy organise system operation. With multi-agent based control systems, this control paradigm may be shifted to a more decentralised open access collaboration control paradigm. This shift cannot happen at once, but must also fit with current operation principles. In order to establish scalable and transparent system control architecture, organising principles have to be identified that allow for a smooth transition. This paper presents a concept for the representation and organisation of control and resource allocation, enabling computational reasoning and system awareness. The principles are discussed with respect to a recently proposed Subgrid operation concept.

[2] Heussen, K. & Lind, M. (2010), Representing Causality and Reasoning about Controllability of Multi-level Flow-Systems, *in* 'Proceedings of the 2010 IEEE Conference on Systems, Man and Cybernetics, Istanbul, Turkey'.

Safe operation of complex processes requires operators to maintain situational awareness even in highly automated environments. Automatic reasoning can support operators as well as the automation system itself to react effectively and appropriately to disturbances. However, knowledge-based reasoning about control situations remains a challenge due to the entanglement of process and control systems that co-establish the intended causal structure of a process. Due to this entanglement, reasoning about such systems depends on a coherent representation of control and process. This paper explains modelling of controlled processes with multilevel flow models and proposes a new framework for modelling causal influence in multilevel flow models on the basis of a flow/potential analogy. The results are illustrated by examples from the domain of electric power systems.

[3] Heussen, K.; Koch, S.; Ulbig, A. & Andersson, G. (2010), Energy Storage in Power System Operation: The Power Nodes Modelling Framework, *in* 'IEEE PES Conference on Innovative Smart Grid Technologies Europe, Gothenburg'.

A novel concept for system-level consideration of energy storage in power grids with dispatchable and non-dispatchable generators and loads is presented. Grid-relevant aspects such as power ratings, ramp-rate constraints, efficiencies, and storage capacities of the interconnected units are modelled, while technology-dependent and physical unit properties are abstracted from. This allows for the modelling of a technologically diverse unit portfolio with a unified approach. The concept can be used for designing operation strategies for power systems, especially in the presence of non-dispatchable generation and signicant storage capacities, as well as for the evaluation of operational performance in terms of energy efficiency, reliability, environmental impact, and cost. After introducing the modelling approach and a taxonomy of unit types, a simulation example is presented for illustration.

[4] Stephan Koch, Kai Heussen, Andreas Ulbig and Göran Andersson, "Unified System-Level Modeling of Intermittent Renewables and Energy Storage in Power System Operation". (Accepted for to "IEEE Systems Journal – Special Issue on Renewable Energy Systems")

The system-level consideration of intermittent renewable energy sources and small-scale energy storage in power systems remains a challenge as either type is incompatible with traditional operation concepts. Non-controllability and energy constraints are still considered contingent cases in market-based operation. The design of operation strategies for up to 100 % renewable energy systems requires an explicit consideration of non-dispatchable generation and storage capacities, as well as the evaluation of operational performance in terms of energy efficiency, reliability, environmental impact and cost. By abstracting from technology-dependent and physical unit properties, the modelling framework presented and extended in this paper allows for the modelling of a technologically diverse unit portfolio with a unified approach, whilst establishing the feasibility of energy storage consideration in power system operation. After introducing the modelling approach, a case study is presented for illustration.

[5] Kai Heussen and Daniel Kullmann, On the Potential of Functional Modeling Extensions to the CIM for Means-Ends Representation and Reasoning, Workshop on Energy Informatics, Oldenburg, Nov. 2010

This paper introduces Functional Modeling with Multilevel Flow Models as an information modelling approach that explicitly relates the functions embedded in components of a system to their design objectives. It is suggested that a functional modelling based extension of CIM may form a conceptual basis for the integration of distributed energy resources with system operation and market concepts.

[6] Kai Heussen, Henrik Niemann, On The Formulation of Control and Reserve Requirements for Future Grid Operation Scenarios, submitted to Power System Computation Conference (PSCC2011), *(submitted)*

Contemporary scenarios for the composition and operation of future electric energy systems tend to have several aspects in common. These entail largely increased amounts of fluctuating renewable generation, increased controllability down to the load and small-scale generation as well as suggestions to revise the system's control architecture to accommodate for the new resources. This paper introduces a generic formalisation of active power related control functions, enabling a structured simulation framework for the comparison of alternate control architectures.

[7] Heussen, K. & Lind, M., Functional Modeling of Perspectives on the Example of Electric Energy Systems, in T. Yao, ed., Zero-Carbon Energy Kyoto, Springer 2009

The integration of energy systems is a proven approach to gain higher overall energy efficiency. Invariably, this integration will come with increasing technical complexity through the diversification of energy resources and their functionality. With the integration of more fluctuating renewable energies, higher system flexibility will also be necessary. One of the challenges ahead

is the design of control architecture to enable the flexibility and to handle the diversity. This paper presents an approach to model heterogeneous energy systems and their control on the basis of purpose and functions which enables a reflection on system integration requirements independent of particular technologies. The results are illustrated by examples related to electric energy systems.

[8] Heussen, K.; Saleem, A. & Lind, M., Control Architecture of Power Systems: Modeling of Purpose and Function, in Proceedings of the IEEE PES General Meeting 2009

Many new technologies with novel control capabilities have been developed in the context of "smart grid" research. However, often it is not clear how these capabilities should best be integrated in the overall system operation. New operation paradigms change the traditional control architecture of power systems and it is necessary to identify requirements and functions. How does new control architecture fit with the old architecture? How can power system functions be specified independent of technology? What is the purpose of control in power systems? In this paper, a method suitable for semantically consistent modelling of control architecture is presented. The method, called multilevel flow modelling (MFM), is applied to the case of system balancing. It was found that MFM is capable of capturing implicit control knowledge, which is otherwise difficult to formalise. The method has possible future applications in agent-based intelligent grids.

[9] Heussen, K. & Lind, M., Decomposing Objectives and Functions in Power System Operation and Control, in Proceedings of the IEEE PES/IAS Conference on Sustainable Alternative Energy, Valencia, Spain 2009

The introduction of many new energy solutions requires the adaptation of classical operation paradigms in power systems. In the standard operation paradigms, a power system is seen as some equivalent of a synchronous generator, a power line and an uncontrollable load. This paradigm is being questioned by a diverse mix of challenges posed by renewable energy sources, demand response technologies and smart grid concepts, affecting all areas of power system operation. Both new control modes and changes in market design are required eventually. A proper redesign should start with a coherent approach to modelling. This paper presents a mean-ends perspective on the analysis of the control structures and operation paradigms in present power systems. In a top-down approach, traditional frequency and area control mechanisms are formalised. It is demonstrated that future power system operation paradigms with different generation control modes and controllable demand can be modelled in a coherent way. Finally, the discussion is opened up towards a formalisation of service exchange between market participants.

[10] Heussen, K. & Knebel, P., On Markets and Market Mechanisms for Operational Services in the "Smart" Electrical Power System, in Energizing Markets 2008 *(Proceedings not published)*

We investigate the possible application of markets to support the operation of electrical power systems in the future. A potential purpose of those markets would be the allocation of resources for balancing renewable energy infeed, along with the integration of a high number of smaller distributed resources. In this context we raise two questions: First, how is it possible to establish markets in an environment governed by close technical and dynamical constraints? The design of a market for such ancillary services requires a close consideration of the regulatory framework, and appropriate market mechanisms. Further, how should these distributed resources be integrated in the market – via direct participation or via aggregation through larger market players? This paper highlights technical aspects of a functional integration of system operation and markets.

[11] Heussen, K., Situation-Aware Assessment of Balancing Need and Resource, in Nordic Wind Power Conference, Bornholm, Denmark 2009

Distributed generation and renewable energy sources are both new disturbance and new regulation resource. Most renewable energy sources are quite unlike classical power plants but often have capabilities enabling the provision of ancillary services. For example, modern wind turbines could provide limited fast active power reserves, similar to inertia or primary reserves. If considered disturbance or resource, ultimately depends on the system operator's capability to oversee the need for and availability of such reserves. Wind power may at times provide a certain share of system stabilisation, but it must also be seen that this contribution is limited and that it fluctuates with the available wind. Moving towards the design of tools that may provide such information, this paper proposes a functional modelling approach to identify situational control requirements for a power system with a high share of fluctuating energy resources.

[12] Pillai, J.R. & Bak-Jensen, B., Vehicle-to-grid in Danish Electric Power Systems, in Proceedings of International Conference on Renewable Energies and Power Quality, Valencia, Spain 2009

The integration of renewable energy systems is often constrained by the variable nature of their output. This demands for the services of storing the electricity generated from most of the renewable energy sources. Vehicle-to-grid (V2G) power could use the inherent energy storage of electric vehicles and its quick response time to balance and stabilise a power system with fluctuating power. This paper outlines the use of battery electric vehicles in supporting large-scale integration of renewable energy in the Danish electric power systems. The reserve power requirements for a high renewable energy penetration could be met by an amount of V2G based electric vehicles less than 10% of the total vehicle need in Denmark. The participation of electric vehicles in ancillary services would earn the vehicle owner significant revenues. The power balancing services of electric vehicles in an electricity network with a large variable

[13] Pillai, J.R. & Bak-Jensen, B., Vehicle-to-Grid for islanded power system operation in Bornholm, IEEE PES General Meeting, Minnesota, 25-29 July 2010

Vehicle-to-Grid (V2G) systems are an emerging concept of utilising the battery storage of electric vehicles (EVs) for providing power system regulation services. This technology could be used to balance the variable electricity generated from various renewable energy sources. This article considers a model of an aggregated electric vehicle based battery storage to support an isolated power system operating with a large wind power penetration in the Danish island of Bornholm. The simulation results show that the EV battery storages represented by the V2G systems are able to integrate more fluctuating wind power. The islanded Bornholm power system operates satisfactorily for the case of replacing most of the conventional generator reserves with V2G systems, which may represent a future operation scenario.

[14] Pillai, J.R. & Bak-Jensen, B., Electric Vehicle based Battery storages for future power system regulation services, in Proceedings of Nordic Wind Power Conference, Bornholm, Denmark 2009

The large grid integration of variable wind power adds to the imbalance of a power system. This necessitates the need for additional reserve power for regulation. In Denmark, the growing wind penetration aims for an expedited change of displacing the traditional generators which are currently supplying the reserve power requirements. This limited regulation service from conventional generators in the future power system calls for other new reserve power solutions like Electric Vehicle (EV) based battery storages. A generic aggregated EV based battery storage for long-term dynamic load frequency simulations is modelled. Further, it is analysed for regulation services using the case of a typical windy day in the West Denmark power system. The power deviations with other control areas in an interconnected system are minimised by the characteristics of the EV battery storage of faster up and down regulation.

[15] Pillai, J.R. & Heussen, K., Bornholm as a Model for 100% Renewable Energy Scenarios in Denmark, in Proceedings of Nordic Wind Power Conference, Bornholm, Denmark 2009

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 of Bornholm. First, the model is verified on the basis of the energy mix on Bornholm today, where the Bornholm energy system is studied both as a connected and as an islanded energy system. Future energy scenarios are analysed to develop 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.

[16] Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Integration of Vehicle-to-Grid in Western Danish Power System", *IEEE Transactions on Sustainable Energy*, TSTE-00015-2009, DOI 10.1109/TSTE.2010.2072938 (Status: *Accepted for publication*)

The Danish power system is characterised by a high level of wind power penetration. As the nature of the wind power is unpredictable, more balancing

power is desired for a stable and reliable operation of the power system. The present balancing power in Denmark is provided mostly by the large central power plants followed by a number of decentralised combined heat and power (CHP) units and connections from abroad. The future energy plans in Denmark aim for 50% wind power capacity integration which will replace many conventional large power plant units. The limited control and regulation power capabilities of large power plants in the future demand new balancing solutions like Vehicle-to-Grid systems. In this article, aggregated electric vehicle based battery storage representing a Vehicle-to-Grid system is modelled for the use in long-term dynamic power system simulations. Further, it is analysed for power system regulation services for typical days with high and low wind production in the Western Danish power system. The results show that the regulation needs from conventional generators and the power deviations between West Denmark and UCTE (Union for the Coordination of Electricity Transmission) control areas are significantly minimised by the faster up and down regulation characteristics of the electric vehicle battery storage.

[17] Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Vehicle-to-Grid Systems for Frequency Regulation in an Islanded Danish Distribution Network", *Proc. IEEE Vehicle Power and Propulsion Conference*, Lille, 1-3 Sept. 2010

Electric vehicles (EVs) have gained significant attention in recent years due to their prospects of reducing greenhouse gas emissions benefitting the transportation sector directly and the electricity sector indirectly. Vehicle-to-grid (V2G) systems using the battery storages of electric vehicles could provide power system ancillary services in the form of power balancing reserves to support the large-scale integration of variable renewable energy sources like wind power. This paper investigates the dynamic frequency response of an islanded Danish distribution system operation with a large amount of wind power supported by the Vehicle-to-grid systems. The power system simulations are analysed for scenarios with 48% and 65% wind power penetration. The simulation results show that the V2G systems provide a faster and stable frequency control than the conventional generation units. V2G systems can be considered as a flexible solution for frequency regulation in future electric power systems.

[18] Jayakrishnan R. Pillai and Birgitte Bak-Jensen, "Impacts of Electric Vehicle Loads on Power Distribution Systems, *Proc. IEEE Vehicle Power and Propulsion Conference*, Lille, 1-3 Sept. 2010

Electric vehicles (EVs) are the most promising alternative when replacing a significant amount of gasoline vehicles to provide cleaner, CO_2 free and climate friendly transportation. When integrating more electric vehicles, the electric utilities must analyse the related impacts on the electricity system operation. This paper investigates the effects on the key power distribution system parameters like voltages, line drops, system losses etc. by integrating electric vehicles in the range of 0-50% of the cars with different charging capacities. The dump as well as smart charging modes of electric vehicles are applied in this analysis. A typical Danish primary power distribution system

is used as a test case for the studies. The simulation results show that no more than 10% of electric vehicles could be integrated in the test system for the dump charging mode. About 40% of electric vehicle loads could be accommodated in the network with the smart charging mode. The extent of integrating EVs in an area is constrained by the EV charging behaviour and the safe operational limits of electricity system parameters.

[19] Jayakrishnan R. Pillai, Kai Heussen and Poul Alberg Østergaard, ”Comparative analysis of hourly and dynamic power balancing models to validate future energy scenarios”, *Energy*, EGY-D-10-00628, (Status: *Submitted*)

Energy system analyses on the basis of fast and simple tools have proven particularly useful for the interdisciplinary collaboration work with frequent iterations and re-evaluation of alternative scenarios. As such a tool, "EnergyPLAN" is used for hourly balanced and spatially aggregated annual analyses of energy scenarios. For the relatively fast dynamics of electrical energy systems, additional requirements are formulated to justify the technical feasibility of the respective scenario. In this article, the generation and consumption of energy on the Danish island of Bornholm are studied. First, the model is verified on the basis of the existing energy mix on Bornholm as an islanded energy system. Future energy scenarios for the year 2030 are analysed to study a feasible technology mix for a higher share of wind power. Finally, the results of the hourly simulations are crosschecked with dynamic frequency simulations. The results of this investigation are used to improve the EnergyPLAN model with respect to how it handles stability and ancillary services to study future energy scenarios.

[20] Poul Alberg Østergaard, “Regulation strategies of cogeneration of heat and power (CHP) plants and electricity transit in Denmark”, Energy Volume 35, Issue 5, May 2010

Denmark is in a situation with many scattered sources of electricity that are not controlled by the central load dispatch. At the same time, Denmark is being used as an electricity transit corridor between the hydro based systems of Norway/Sweden and the thermal systems of Germany and continental Europe. Through energy systems analyses and load-flow analyses, it is determined that if geographically scattered load balancing utilising the regulation ability of hitherto locally controlled plants is introduced while also introducing new dispatchable loads in the form of electric vehicles and heat pumps, electricity transit is enabled to a higher degree than if central load balancing is maintained. This is the case of an intact transmission system as well as a system with inoperative transmission lines. With an intact system, the average load of the system is approximately halved when applying scattered load balancing. Utilising the regulating capacity of local plants thus improves the role of the Danish system in the Northern European system.

The CEESA project (Coherent Energy and Environmental System Analysis) presents technical scenarios as well as implementation policies and a road map of Denmark's transition from a fossil fuel-dominated energy system to a supply system based completely on renewable energy with a dominating part of intermittent sources like wind and solar power. Energy conservation and a certain technological development are prerequisites for this transition. The CEESA scenarios show how the transition can be performed before the year 2050 mainly by the use of known technologies combined with significant energy conservation.

The CEESA project has a focus on, among others, transport, electricity power systems and environmental assessment. The need for new systems thinking and new planning principles for energy investments is among the important observations in this scenario project. With dominant contributions from intermittent sources and limited amounts of biomass available, storage problems are solved by integrating the electricity, heat and transport sectors much more than in traditional supply systems based on fossil fuels. The CEESA project shows how this can be done in an efficient and economical way.

CEESA is a multidisciplinary co-operation which combines the forces of leading Danish researchers in the fields of energy and environment. The project is financed by the Danish Council for Strategic Research together with the participating parties and was conducted in the period 2007-2011.

The results of the CEESA project are presented in 5 background reports and a main summary report.

CEESA main report:

- Coherent Energy and Environmental System Analysis

CEESA background reports:

- Part 1: CEESA 100% Renewable Energy Scenarios towards 2050
- Part 2: CEESA 100% Renewable Energy Transport Scenarios towards 2050
- Part 3: Electric power systems for a transition to 100% renewable energy systems in Denmark before 2050
- Part 4: Policies for a Transition to 100% Renewable Energy Systems in Denmark Before 2050
- Part 5: Environmental Assessment of Renewable Energy Scenarios towards 2050

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