EcoGrid.dk Phase I
Summary Report

Steps towards a Danish Power System
with 50 % Wind Energy

PSO ForskEL R&D-contract for project no. 2007-1-7816
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The wind power challenge

Invitation to the reader: The government has decided to double the share of wind energy in the Danish Power system by 2025. This is not a trivial task; more wind power in Denmark will increase imbalances in the power system. For example will wind power production exceed electricity demand more frequently than today. Hence, more measures are needed to absorb the surplus of electricity and secure supply of electricity when the wind is not blowing.

Today the international electricity market acts as a significant provider of power system stability. This will also be the case in the future, but energy experts and scientists warn us: Denmark cannot expect to have the same access to foreign power markets in the future. Higher wind power penetration will happen outside Denmark as well. This means higher competition for balancing power capacity or system support services. Future balance cannot be established through trade alone! Hence, Denmark must develop other alternatives or domestic solutions to cope with the new dimensions and aspects of the wind power challenges.

In the Danish EcoGrid R&D project the conclusion is clear: The nature of the wind power challenges will require rethinking the design of the Danish power system within the next 10-15 years. Further, the experts present the reader with a complex set of solutions to a complex set of challenges. The reader should not expect to find one single solution to accommodate 50 % wind energy (or more), nor two solutions, but rather a variety of coherent solutions.

The key challenge for the transmission system operator (i.e. Energinet.dk) is not only to identify and develop technical solutions, but also to create an economical optimal balance between the various solutions besides consideration to security of supply and environmentally friendly issues.

According to the EcoGrid experts one starting point would be to develop a coherent, national “SmartGrids” strategy. In parallel, they recommend new tools for managing the energy system while in transition. Future R&D must focus much more on projects that look at the energy system as a whole. Currently national research projects cover environmentally friendly generation, energy savings and demand response solutions separately. Much more attention must be given to how these solutions should work together.

We invite you to read this report and join us on a journey to a future scenario with 50 % wind power in the Danish power system. This is not just a vision or science fiction - the Danes are starting designing and building tomorrow.



Preface

How should the Danish power system be designed to securely handle 50 % wind power generation? What technical solutions can offer necessary system services in such a system? And how can the electricity market be designed to support the power system? Can Denmark expect neighbouring countries to provide the present or even an increased contribution to our growing need for resources to balance supply and demand? And what can we do to mitigate the dependency on neighbour resources and interconnections?

These were some of the very challenging questions Energinet.dk asked leading Danish researchers and energy experts. Energinet.dk received several relevant project proposals, many of which overlap other research activities. Instead of funding many individual projects, Energinet.dk decided to invite a group of researchers and specialists to be part of a common EcoGrid.dk programme. The EcoGrid.dk team should develop a common project proposal with one common goal, which is to provide ways of meeting the demanding challenges the Danish energy system will face several years ahead.

Phase I was initiated in 2007, and in March 2009 the EcoGrid.dk research team delivered its Phase I report Steps Toward a Danish Power System with 50 % Wind Energy. The phase I report is the first part of a 3- phased EcoGrid.dk project that will run into 2012 introducing new thinking and targeted research into the future power system and analyse further integration between electric power, heating systems and transport systems.

The ambition is that it will contribute to a wider EU EcoGrid demonstration project, which will merge the best international and Danish capabilities. The Phase I report compile existing knowledge of systems and measures and outlines the challenges in managing an increasingly complex power system with international dependencies. System design and analysis should be part of EcoGrid.dk Phase II, together with the planning of the Phase III demonstration involving 1 % of the Danish power system.

The EcoGrid project team acknowledges Energinet.dk for initiating and facilitating the EcoGrid.dk project. The support and information provided by Energinet.dk through Phase I is highly appreciated.

Kjeld Nørregaard

EcoGrid.dk
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Introduction

In the EcoGrid project phase I a unique combination of scientists, experts and industry stakeholders with different backgrounds and experiences were put together to work towards one common objective:

Develop new long-term technologies for the power grid and system that can contribute to realizing the Danish Energy Policy goal of 50% wind energy by 2025.

The specific task of the EcoGrid phase I report was to make a general description and analyses of demand and development of the Danish power system with increased volumes of renewable energy. The report describes different solutions with respect to new power system architecture; examine the consequences of future market developments and identify new measures ("building blocks") to support the overall goals and functions of the future power system. The main report includes five work-packages:

- **WP 1**: The EcoGrid Programme and Communication
  (Work Package leader: Jeanette Møller Jørgensen, R&D Coordinator, Energinet.dk)

- **WP 2**: System Architecture
  (Work Package leader: Morten Lind, Professor, Centre for Electric Technology at DTU)

- **WP 3**: International scenarios
  (Work Package leader: Berit Tennbakk, Director Econ Pöyry AS)

- **WP 4**: Survey of new measures
  (Work Package leader: Poul Ejnar Sørensen, Senior Scientist, Risø at DTU)

- **WP 5**: Activities for EcoGrid phase II
  (Work Package leader: Jacob Østergaard, Professor, Centre for Electric Technology at DTU)

The target group of the EcoGrid summary report is not only industry specialists, but also stakeholders and politicians who want to take part in the discussion about how to develop a sustainable future power system. The EcoGrid project team hopes the summary report will be an "aperitif" to TSOs (i.e. Energinet.dk and other system operators), local grid companies and any other stakeholders with interest in this field, and that it will inspire the study of the main report in further detail. All reports can be downloaded from: www.ecogrid.dk

This summary report will give insight into the EcoGrid project through interviews with the work package leaders and its main contributors. In brief, it describes the future challenges of the Danish power system and the EcoGrid.dk team's overall conclusions and recommendations.

Future Challenges of the Danish Power System

In Denmark, there is a common understanding among politicians and the public about the need for a sustainable energy system with a high share of renewable energy sources. Without this consensus, Denmark would probably never have experienced the wind power industry "adventure". Neither would Denmark have achieved its ambitious national energy policy target of wind power.

Development of wind power in Denmark goes well beyond 1,500 MW in 2005, which was the first Danish national target of wind power[1]. In 2000 the total wind power capacity was approximately 2,200 MW. Today the installed wind power capacity in Denmark has increased to 3,180 MW and wind power generation corresponds to approximately 20 % of the total Danish electricity consumption in 2008. In the Governments "Energy Strategy 2025" a new target of 30 % renewable energy in 2025 is set out, implying a doubling of wind power capacity.

In the opening remarks, the authors of the EcoGrid phase I report (WP2) have a clear message to the public:

Increasing the use of wind energy is not only a matter of deciding to install new wind farms. Providing technical solutions to enable these goals is a complex undertaking. High penetration of wind energy will influence the security of supply and the efficiency of the power system as a whole if not accompanied by major changes in system architecture and operation

This is the experts' first appeal:

- Do not limit the discussion on wind energy penetration to the challenges concerning cables and wind power locations
- Start thinking of the Danish power system as a whole
- Denmark is a part of an international power market

One consequence of the Danish renewable energy policy target is that existing thermal power generation must give way to wind turbines in an energy future where wind power generation covers 50 % or more of the Danish electricity consumption. Increasing wind power generation has implications for the development of the rest of the power system as well; the grid, operation of central and decentralized power plants, energy flows, investment decisions, etc.

By nature wind power is variable and partly unpredictable. It is variable because the electricity production depends on wind speed, and the predictability is limited in the sense that it depends on the accuracy of wind power forecast tools. The variability of wind power means that systems are needed to utilize the wind power in an economic way, and that other types of generation are needed when no wind power is available. An increase of wind power

[1] Formulated in the Danish Energy Action Plan "Energi 2000" from 1990



generation means that more balancing resources such as ancillary services should be available[2]

The central power plants are currently important domestic providers of flexibility and balancing resources, especially to balance demand and supply in critical situations. The key challenges of the future power system are that

- The need for balancing resources will increase because the installed wind power capacity will reach 6,000 MW in a power system with a load in the range of 2,100 MW to 6,300 MW (2008). At present wind power already covers the entire demand in many hours. In the future this will happen more frequently and increase the need for downward regulation or absorption of the surplus of electricity

- The balancing capacity must be provided by other sources because there will be less capacity of thermal power plants currently providing these resources available in the future. Old thermal units will be phased out of the system and not necessarily be replaced.

So far, Denmark has to a large extent benefited from the provision of significant amount of such services to come from import and export managed by the electricity markets, in particular the connection to the Nordic power system dominated by hydro generation. This means that access to foreign resources (import/export) helps Denmark to balance the power system due to variability and forecast errors of today's wind power generation. More wind power will increase the imbalances in the Danish power system and new local resources must be activated.

Hence a crucial question is whether Denmark to the same extent can rely on the electricity markets to cover its increased need for system services or to what extent Denmark has sufficient domestic solutions available in a future with 100 % more wind power capacity installed. That is: what should replace the current central power generation units that provide this support to the system?

The increase in Danish wind power is likely to take place in an international market context where other countries also increase their own wind power generation. This may also increase competition for the balancing resources offered by the Norwegian and Swedish hydro power, and increase the cost of these resources. Increased competition and higher prices may require:

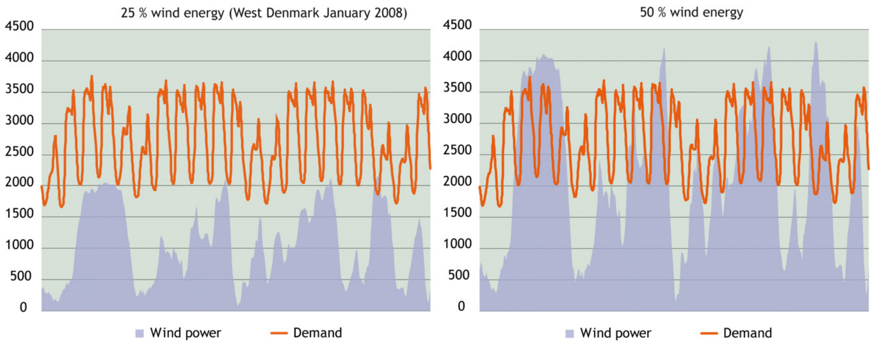
[2] Ancillary services are needed to maintain the physical balance and safeguard the quality of electricity in an interconnected electricity supply system. A balance will be maintained by regulating the actual exchange by means of ancillary service in Denmark or by adjusting the planned exchange in the form of electricity trade with neighboring TSOs. The approach taken depends on the operational situation in question and on what is the most cost effective solution. The need for ancillary services will in reality vary according to the operational situation and the mix of electricity production and electricity exchange. The need for ancillary services for individual 24 hours can be assessed one day ahead on the basis of production and trading plans etc. Resources for system balancing may be offered by sources both on the supply and demand side.



- Increased market integration and development of common market solutions;
- A greater need for new domestic sources of system services
- Development of end-user markets

All which provide increased flexibility and balancing resources from additional sources. Other regulatory conditions such as environmental concerns, emissions of green house gases, and a ban on new overhead lines, etc. will further influence the size and magnitude of the Danish power system challenge. Still, it is clear that solutions have to be found via a combination of international markets and agreements, and domestic means and measures.

Illustration of the "Danish Power Challenges"



At present wind power already covers the entire Danish demand for electricity in many hours. In the future, this will happen more frequently and increase the need for balancing resources significantly. At the same time, there will still be several hours where wind power is not able to meet demand, and other resources must be put in operation to make up the energy and capacity deficit. New sources of system services have to be found, both to meet an increased demand for system services and to replace the services offered by current suppliers. The extent to which Denmark will have access to international provisions depend on grid developments (congestions and capacity investments), market design, international obligations and market developments in surrounding areas.

Overall Conclusions and Recommendations

In 2025, wind power capacity in Denmark is expected to reach 6 GW or approximately twice as much as today. Consequently, the power system will be required to increase the balancing capacity correspondingly.

At present, the Danish wind power challenges are amplified by the increasing wind power installed in our surroundings. In total 29 GW wind power was installed in Denmark and Germany (2008)[3]. Hence, Denmark and Germany benefit from balancing resources supplied from Norway and Sweden. There is currently competition for scarce balancing resources due to limited HVDC transfer capability between the two regions limited to 4.2 GW.

In the future, these problems become more acute. For example the generation of wind energy in Germany has been estimated to reach between 32 and 59 GW in 2025 in the scenarios developed in the project (WP 3). Most of the German wind power generation is planned to be located in North Germany, reasonable close to the Danish border. This means that the total German and Danish wind power capacity could increase from today's 29 GW up to 38.5 GW or from 29 GW up to 65 GW depending on the scenario. The required domestic balancing resources in Denmark would be very different in the two cases.

Without new steps the operation of the Danish power system will become challenging and there is no simple solution to handling the future challenges with 50 % wind power. Denmark will enter an undiscovered territory where no other country has shown the way.

The Need for a Redesign of the Danish Power System

Doubling the share of wind power is likely to require a profound redesign of the power system architecture within the next 10-20 years. Development shows that consumers are becoming more aware of the environmental impact of the energy and transport system and seek greater ability to manage their own electricity use and contribute to system flexibility. New distributed energy resources such as solar, micro generation and storage allow the consumers to produce their own "green" electricity as well as selling excess electricity.

Today, the grid is primarily a vehicle for moving electricity from generators to consumers. Tomorrow's power system should include diverse and distributed energy resources[4] as well as accommodating electric vehicles. This will require two-way flow of electricity and information as new technologies enable new forms of electricity production, delivery and use. New solutions, including a wider use of ICT[5] and automation will be necessary, as well as a reinforced grid and improved trading opportunities. Without this, there is a risk of

[3] European Wind Integration Study (EWIS), 2008

[4] Distributed energy resources are generation, storage and demand response connected to the distributions system

[5] Information and communication technology

insufficient system security and reliability, as well as inefficient utilization of new wind power capacity.

In EcoGrid phase I, WP 2 discusses possible challenges and requirements to the future power system in more detail. According to the experts, a robust power system (organisation, distribution of responsibilities, information and IT solutions) must enable active involvement from large wind power farms and distributed energy resources, electric vehicles to take (more) active role in market balancing and supply of system services. The changes required in the current system architecture will depend on several factors, e.g. expected development in international markets, development of competitive domestic balancing resources and customers' demand for new energy management services and clean vehicle transport solutions.

To what extent should Denmark rely on international balancing resources in 2025?

All four scenarios described in WP 3 show that it is unlikely that Denmark can rely on international markets to provide operating reserves and sufficient balancing capacity to the same extent as today in a power system with 50 % wind power. However, the availability and cost of balancing resources from neighboring countries are likely to differ significantly depending on the future development.

The challenges related to international developments include:

- The availability and cost of balancing capacity from neighboring areas
- International security rules, including shared reserves and system services
- International market design rules, including market coupling
- International market prices paid for excess Danish wind power generation
- Demand for transit through Denmark – which affects grid operation and frequency of internal bottlenecks

To what extent these challenges related to international development will have an impact on the Danish need for additional system support from domestic solutions is uncertain, but considering different international future development scenarios makes it possible to identify the relative importance of some of the above challenges.

Four scenarios with different challenges are considered:

- *The Grønnevang scenario*, characterised by ambitious renewable targets, weak international coordination and significant reductions in electricity demand seems to be the most challenging scenario (in terms of wind power surplus and need for domestic balancing resources). In this scenario, international market solutions are not provided and the general flexibility of the systems is low.
- In *the international green scenario, Greenville*, more market based solutions and more international coordination should be anticipated, but also this is coupled with increased competition for the shared balancing resources. Increased competition means higher prices and the availability



of balancing capacity from surrounding areas will depend on the competitiveness of domestic solutions.

- It is generally easier for Denmark to accommodate wind power in *the two blue scenarios (Blåvang and Blueville)*, where the development of renewables in other countries is moderate, and especially in the Blueville scenario where international market development is encouraged.

The scenarios in EcoGrid phase I show that the extent to which resources will be available from surrounding markets, and the extent to which the challenges on Danish system operation is amplified by developments in neighboring systems, may be very different in 2025 compared to today. Planning for the accommodation of 50 % wind should take into account that the future is uncertain; we simply do not know which scenario will unfold in the end. Planning for the worst case may be unnecessarily costly. And planning for the best case may seriously compromise system security and make it impossible to reach the renewable energy target. Hence, a flexible strategy should be a key concern.

New domestic sources should be implemented for commercial reasons and for security reasons. The amount should be sufficient to form national alternatives to foreign commercial services and to form national backup during future international crises.

Many measures with high potential

The experts' general conclusion is that penetration of 50 % wind energy in Denmark is possible, but will require profound changes in the power system architecture.

The EcoGrid project, WP 4, has identified a number of promising measures with high potential. In different ways, these can contribute to system security and to meeting the increased requirements of balancing resources and technical reserves. Hence, the technical solutions exist but they have to be put together in a smarter way.

Among the solutions are:

- **Further integration of different energy systems and technologies (e.g. heat, gas and bio energy) can improve flexibility of the energy system**, i.e.
    - There is a significant potential to use existing heat storage capacity in the Danish district heating system (combined heat and power or CHP), and the cost of additional heat storage is reasonable. Most of the Danish CHP plants are equipped with heat storage in order to make electricity generation less dependent on heat demand. The possibility for indirect storage of electricity in off peak situations is good (e.g. in periods where wind power production is high). Surplus electricity in 2025 can be absorbed in the district heating systems for at least 12 hours. As a rough estimate between 20 and 30 GWh energy can be stored as useful heat.
    - Dynamic use of other heat production technologies in the district heating system (e.g. electric heaters, large heat pumps and heat boilers) are important measures to make the energy system more flexible. Use of these measures makes it possible to utilize electricity production when prices are low or electricity production exceeds



demand. At low electricity prices, an option is to stop the CHP production and produce heat on other production technologies. There is a significant potential of installing heat pumps combined with buffer heat storage outside district heating areas. The investment cost of large heat pumps is high relative to electric heating (dump load). On the other hand, the operation costs are low and a high frequency of low electricity prices can make heat pumps profitable.

    - In situations where an immediate increase of electricity is needed investment in new gas turbines, cooling towers can be attractive options. Micro generation/CHP provides a promising future solution as well.

- **Further integration with transport**, i.e.

    - The accelerating transition towards cleaner transport using plug-in hybrid and battery electric vehicles will create a new type of electric consumers with integrated energy storage in the traction batteries and ability to take only electric energy when it is more convenient for the electric system. Even though the plug-in vehicles will become an important measure in the integration of much more wind power the vehicle owners will do the major investment. Thus, the only additional cost to the electric power system associated with this measure will be building up new dedicated communication and control infrastructures.

    - There are estimations that up to 10 % of the passenger car and small van fleet in 2025 could be Plug-in Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV). This corresponds to a total number of about 200.000 vehicles with plug-in functionality in 2025. Just a quarter of these vehicles, represent more than 100 MW flexible demand. The control system must prepare also for future vehicle to grid applications, i.e. vehicles that can export power from the battery to the grid (on long term).

- **Need for new markets services to activate local small multiple resources**, i.e.

    - The potential for increasing flexibility of the power system through demand response solutions is significant up to 1.3 GW. A challenge is to activate not only a few energy intensive industry end-use customers, but also the many small electricity end-use customers. Measuring electricity by smart meters will allow the provision of prices that vary with time-of-use. This can for example allow small electricity consumers to benefit from in-home energy displays, home energy management system etc.

    - Currently the Nordic regulating power market is in practice limited to suppliers that can send plans and guarantee to be able to supply the balancing service. Further, the participants must bid minimum of 10 MW into the power regulating market. Many potential suppliers (wind power and micro generation) are in practice prevented from being active. In a well-designed real-time market, any producer (and consumer) who is able to adjust production or consumption should participate and get paid the prevailing prices. Subsidies for small generation could be changed and exposed to market prices, i.e. reducing the barriers for supplying balancing capacity.

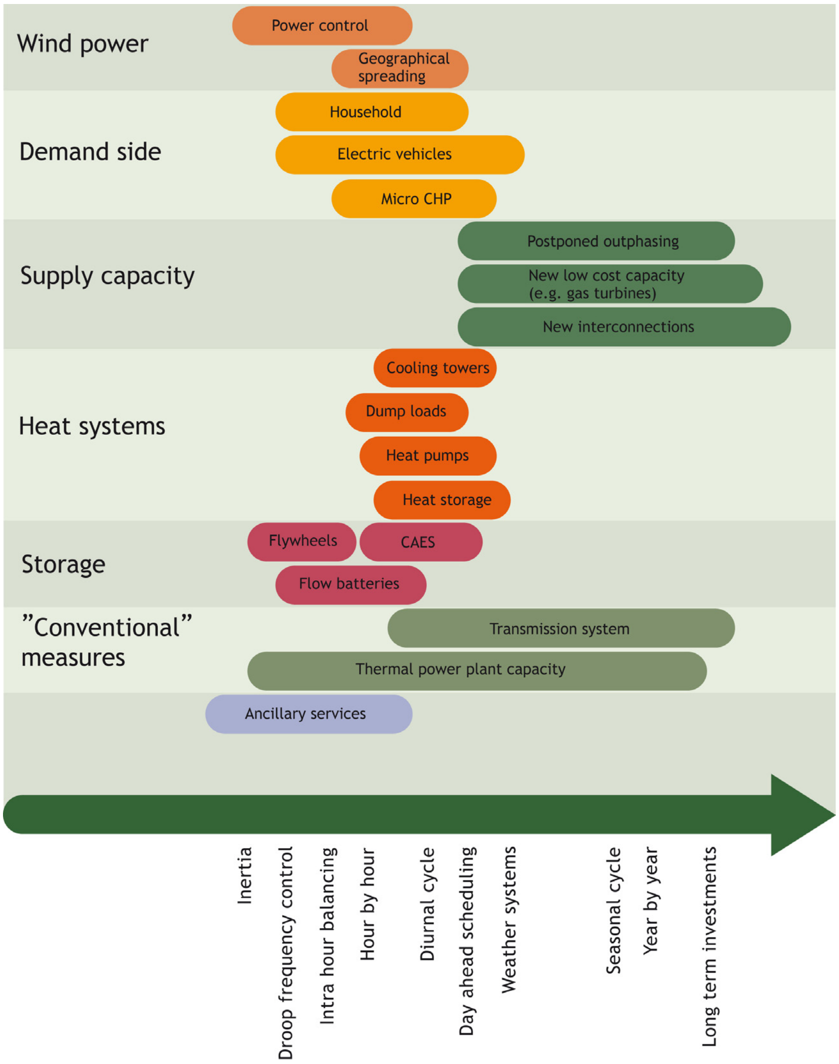
- **Several options exist for grid connection of modern wind turbines.** Modern wind turbines (technology proven) can increase the flexibility (and value) of wind power in the power system. Thus there is no single technology, but rather a number of competing options for individual wind turbines and for wind power plants/farms (auxiliary equipment and flexible AC/DC interconnectors).

The first steps towards integration with heat demand have already been taken. After 2005 all CHP about 5 MW can sell electricity at market price. The subsidy has been maintained, but it has been made independent of the generation. This has helped to improve the timing of the generation, and has reduced power production when electricity prices are low. The technological challenges are manageable, but legislation, communication and operational procedures may need improvements. Financing problems and risk distribution could also form barriers.

The new measures associated with a wider activation of local small multiple resources will not be possible without fundamental changes in regulation and infrastructure. Serving electric cars and other measures in end-user installations will require more comprehensive changes as the power system must be able to interconnect with hundreds of thousand cars, which should be charged to fulfil customer needs, but can also support power system operation when required by providing balancing power. An update of the power system architecture will be a necessary preparation. The main purposes will be to improve customer service and to activate resources of active and reactive power in local grids.

The new infrastructure will require smart meters and two-way communication for all customers. The communication systems that the utilities are currently developing for smart meters will probably not be adequate to support a system with millions of end-user devices and installations. The communications needs associated with the collection of meter data are different from those of grid operation, e.g. additional bandwidth and redundant services will be needed for grid operations because of the large quantity of operational data. New (cyber) security issues will arise, as the installation of smart meters will create many new and potential access points that connect into grid operation system. In addition, grid code required for new distributed generation as well as all new wind farms need to be adjusted to the new power system architecture.

The EcoGrid experts point out that there is no “silver bullet” or “winning solution”. The challenge posed by doubling wind power capacity in Denmark has to be understood along several dimensions. Solutions must be found along different dimensions as well and also depends on international development. New sources of system services have to be found and identified, both to meet an increased demand for system services and to replace the services offered by current suppliers. It will be necessary to provide the necessary infrastructure and incentives to create an environment, which will enable and encourage stakeholders to develop competitive measures. Moreover, initiatives must be taken to ensure that the need for flexibility in future power systems is understood and integrated correctly into the development of all new solutions.



The power measures described in WP 4 (highlighted in red, orange and yellow colours) have different time scale of balancing capacity. The power must be balanced on all time scales in order to ensure stable system operation and security of supply. In the figure below the time scales are illustrated, pointing out different technical and market issues and solutions, including so-called conventional and supply capacity measures (green colour). In Appendix 6 the different terms of balancing characteristics are further described.

Recommendations

The specific task of the EcoGrid phase I report was to make a review of possible new power system architecture, international perspectives and available technologies. Furthermore, the report proposes a selection of relevant future research and development activities for the next phase of EcoGrid.

The EcoGrid group also recommends activities that put emphasis on general strategic future activities, which could support the process towards a Danish power system with 50 % wind energy and a system with a high share of local and distributed energy resources. These recommendations are closely lated to Energinet.dk's own research, demonstrations, planning and operation strategies. The EcoGrid proposals and recommended activities could provide important contributions, but Energinet.dk is supposed to take the overall leadership.

Development of a Danish EcoGrid Strategy 2025

A Strategy Task Force group led by Energi.dk should be created. The group should involve government authorities as well as representatives from the industry, energy sector (customers, distribution, retail service providers and generation), energy experts and universities.

Recommended activities are:

- Coordinating Energinet.dk activities with other energy and transport related activities, which influence power system operation, reliability and security

- Developing a strategy of coordinated research, innovation, demonstration and system operation, including an educational programme to define the future needs of skills and competences

- Initiating the establishment of a forum for discussion of issues related to responsibilities, legislation, regulation, taxation, subsidies, standards or other means that facilitate the deployment of a coordinated EcoGrid strategy

- Further development of Energinet.dk's scenarios. Energinet.dk's own scenarios could be supported by assessments including:

    - International scenarios and their impact on the Danish power system

    - The future technology development and demand of distributed generation, storage and plug-in electrical/hybrid vehicles, energy management solutions/installations.

    - The development of smart meters and two-way communication and consequences of wider end-user participation in electricity markets

Management of an energy system in transition

The recommended activity could take place as EcoGrid phase II work shops (for example four per year). It could be seen as a first step in constructing a process that lays out the strategy towards a successfully integration of increased wind capacity in Denmark. The suggested activities have parallels to the so-called Change Management concept used in Systems Engineering, which is a process of requesting, determining attainability, planning, implementing and evaluation of changes to a system. The activity should be led by Energinet.dk with relevant external collaborators or consultants.

Recommended activities are:

- An analysis of the existing workflow at Energinet.dk used for handling system requirements, evaluation of new technologies and reporting of operating experiences.

- Developing a process to support the transition of the Danish Power System. Energinet.dk is facing ambitious goals regarding the accommodation of wind power and other renewable energies, the continuing development of power and information technologies and an uncertain future regarding international connections. It is doubtful if the present planning criteria will be valid for the future power system with a high share of wind power and sometimes only with a few conventional power plants connected to the grid.

- Energinet.dk needs a running process for identification and continuous revision of the power system requirements and monitoring of system performance, including continuous monitoring of the development in the surrounding markets.

Strengthen the international efforts

Through international co-operation with other TSOs in Northern Europe, Energinet.dk should continue its efforts to:

- Develop efficient market(s) , which allows active participation of local generation and end-users in the spot, intraday and regulating power markets

- Improve the integration of the Nordic electricity market with surrounding markets, including the reinforcement of interconnections

- Push for international standards for SmartGrids installations/appliances

Selected EcoGrid phase II project proposals

The Ecogrid team recommends Energinet.dk to take an active role in the next EcoGrid phase II research and development activities, in particular with reference to the development of adaptive planning tools and preparation of demonstration of new technologies and solutions. Specific project proposals described in WP 5 include:

- Development of a tool for optimal operation of system with new balancing measures described in phase I

- Development of new market functions for participation of distributed energy resources in system balancing

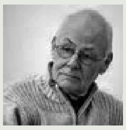
- Development of new coherent control architecture based on sub grids

A need for new power system architecture(s)

Interview of Morten Lind and Paul-Frederik Bach

The overall objective of WP 2 was to “provide a synthesis of alternative system architecture for the future Danish electric power and transmission system” as formulated in the main report. Soon the EcoGrid project team experienced that this was no trivial task.

Morten Lind, Professor of Control Engineering and Automation, Centre for Electric Technology at DTU was project manager of the EcoGrid project WP 2: *System architecture*.



Paul-Frederik Bach, has been one of the key contributors to the work package. With over 40 years' experience with power system operation tasks in West Denmark Paul-Frederik Bach takes the academic discussions closer to the practical problems and challenges a TSO is facing every day.

What is power system architecture?

Explaining the concept of “power system architecture” is difficult. – However, you can use a very simple analogue to the architecture of buildings, which includes the design and construction, primarily with the purpose of pro-viding shelter. The focus is on the design of the building as a whole, its functions and not every single building block (Roofing tiles, bricks, cement, etc.). These are just means, says Morten Lind. However, the architecture of a power system is much more complicated because of the many technologies involved and the influence of the market on its operations. To get a better analogue we could extend the notion of building architecture to include also energy standard requirements, the water and electricity supply and the air conditioning systems, which are required so that the house as a whole satisfies the comfort needs of its users.

One aspect of power system architecture is therefore to make the physical design of the power system, i.e. the composition of grid and cable structure in the power system. Another important aspect is to design the system functionality, e.g. how to organise the use of physical measures for system operation, monitoring and controlling in order to fulfil the future requirements and need for more back-up capacity services. In addition there is the physical and functional aspect of design of IT and communication system that make it possible to provide the power system services.

Power system architecture is - like building architecture - a matter of finding the principle of how you build a system so that it does not collapse and deliver its services as efficiently as possible, i.e. comply with the requirements to the system. – In a modern society we expect that supply of electricity is reliable and available whenever needed. If the TSO delivers this “product”, nobody will complain. It seems so easy, but it is not!

The public will normally not worry about the system requirements needed to ensure a reliable electricity supply. According to the EcoGrid experts, it is time to reconsider the power system requirements which will be much more complex in a future dominated by wind power and local and distributed energy resources.

Development of the Danish power system towards a carbon neutral energy future is synonymous with new system requirements. In 2025, and beyond, the increased need for regulating power and ancillary services can no longer be expected to be delivered by the same sources/ resources as today, says Morten Lind.

The new challenge

In the main WP2 report, the authors wrote, “One of the challenges in Denmark is that the change from centralised production to the present situation with a considerable share of distributed generation already has occurred without major changes in the basic power system architecture”. Does that mean that the Danish power system architecture in its current shape is not “up-to-date”?

- We consider the balancing problem as being the most significant new challenge associated with an expected doubling of wind energy by 2025. It is difficult to imagine how the present Danish power system could be balanced without access to international markets. A power system with 50 % wind energy will require approximately twice as much regulating power capacity. Maintaining system security and market service will be other important future challenges, says Paul-Frederik Bach.

Cross-border interconnections provide most of balancing of wind power in the current Danish system. This is possible due to high flexibility in the Nordic hydro power system. At present approximately 70 % of wind power variability is balanced through export, which means that 30 % is balanced through “domestic” measures.

There will be increasing international competition for a limited balancing capacity in the future. Therefore it is unlikely that future demand for regulating capacity can be met without a significant increase of domestic resources (internal power balancing capacity), and the current power system architecture is not designed and equipped to offer these services, says Morten Lind.

Lucky Denmark

Since World War 2, the Danish power sector has been centralised, dominated by few large oil- or coal-fired power plants and few control rooms. – The electricity supply system was a vertical one-way system. Electricity was generated and delivered to customers. Transparency and control of the system was a relatively simple task, explains Paul-Frederik Bach.

The structure of electricity generation was decisively changed during the 1990s. Following a political decision, a large number of local CHP and wind power plants were established. – In the last 20 years Denmark has installed 900 local CHP plants and many thousands wind power plants, the market share of the central power plants was reduced by more than 40 %. Fortunately, the introduction of the Nordic power market came and rescued the Danish power system from a likely collapse, says Paul-Frederik Bach.

- No person is able to dispatch more than 1,000 power plants as efficiently as the market can and the Nordic hydropower system makes it possible to optimize the physical balancing. Since the Skagerrak Cable was build in 1976 Denmark has used these opportunities.

Many claim that the system has worked with 25 % wind power, why should the Danish power system not manage 25 % more?

The Danish achievements so far could be seen differently. It has to be taken into account that Denmark is strongly interconnected to the neighbouring markets. In 2008 Germany and Denmark had 29 GW wind power. Wind power output and spot prices in Germany and Denmark were strongly correlated. The market share of wind energy for both countries taken together was 7 %.

There is still a long way to go from 7 % to 50 %.

However, local CHP are successfully participating in the Nordic power market (both in the day-ahead market and in the market for regulating power). Estimates in the WP 2 study shows that the wind power variability balanced trough export in West Denmark has fallen from 85 % in 2004 to approximately 70 % in 2008 - probably because of increased CHP participation.

According to the EcoGrid project team similarly activating end users and local power generation, can improve the power system flexibility and increase the value of wind power. This could also make the Danish power system less dependent on foreign balancing resources, but will require significant effort in development of new market rules and communication systems.

A smarter way

One conclusion from WP 2 is that interconnections play a decisive role in balancing current Danish wind power. Therefore it is essential to maintain and, if possible, to increase this flexibility. Taking into account the plans for wind power development in Denmark and its neighboring countries, presently limited capacity and expected future interconnections, it must expected that the current share of export will decrease in 2025, i.e. other options are needed.

The Danish EcoGrid project team does not believe that the best answer to handle the challenges is to build on “a back to basic approach”.

- It is unlikely that the challenges of the future can be met by only extending the existing power system with more of what you already have, i.e. more thermal generation, stronger grids and more cables and interconnection (transmission), says Paul Frederik Bach. He continues:

- In the EcoGrid project we asked our self if we could face the new challenges in a smarter way, i.e. use modern IT and communication technology to ensure system balance and reliable and secure power supply (system security). Using IT and communication technology “intelligently” will enable local distributed energy resources, currently passive or not properly integrated in the power market, to contribute to system balancing and system security.

- The idea of activating resources in the local grids and combine it with modern information technologies is not new and the concept of so-called Smart Grid[6] has it origin in the US and is today an integrated part of the EU energy policy[7] The big challenge is to add an intelligent information and communication infrastructure to the power system infrastructure with same mesh density as the grid. This new infrastructure is a condition for active participation of small scale CHP units and end-users in system balancing and system security, explains Paul-Frederik Bach.

- The smart solutions will be necessary in addition to reinforced grids and improved trading opportunities. Congestion on the grids will continue to be a major problem, no matter what we do, Paul-Frederik Bach says.

The main drivers for developing smart grids or new power system architectures in Denmark is to increase the ability to accommodate intermittent generation from wind power and other variable generation. Thus, increasing reliability, efficiency and safety of the power

[6]Smart grid is referred to by other names including Smart Electric Grid, Smart Power Grid, Intelligent Grid/Intelligrid, and FutureGrid, SmartGrids (EU),

[7] See: www.smartgrids.eu



grid will prevent outages. The WP 2 main report includes a review of innovative power system solutions in other countries. In the US the motives behind the development of smart grid solutions are typically driven by the need to use the current energy system more efficiently in order to prevent “brown-outs” in the existing grid. The example of innovative system structures described should be considered as building blocks or possible solutions, which can be used as elements for future power system architecture.

- The important lesson learned from the review was the experiences with and methods used for the design of new power system solutions (or sub systems). We did not find one single power system solution able to address the Danish future challenges and power system requirements, says Morten Lind.

What is the “added value” for Energinet.dk – what to learn from these examples?

- I think the review in WP 2 can help the TSO to choose methods and tools to define solutions for the future power architecture. We do not give any solutions rather methods and inputs to a strategy discussion, says Morten Lind. He continues:

- Being an engineer myself, I find that engineers have a tendency to focus directly on solutions without really discussing the problems, needs or requirements. In WP 2 we suggest that Energinet.dk or system operators in general start to make detailed requirement specifications of the expected future system operation needs and develop means of evaluating the success of new technologies and reviewing requirements so that they can handle the challenges in the future evolution of the Danish power system.

Major Technology Development Needs

According to Paul-Frederik Bach and Morten Lind there is no easy way to build up new power system architecture.

- In my 40 years experience in the power sector and from work with system operation tasks the biggest challenges was when Denmark joined the Nordic power exchange (Nord Pool) in 1999. The future challenge Denmark (and other countries) faces have other dimensions. When Denmark joined Nord Pool we could look to the Norwegian TSO (Statnett) and learn from them. No country has taken similar steps before, i.e. developed a system that can manage wind power and distributed energy resources of these proportions, says Paul-Frederik Bach.

Morten Lind agrees: - We are probably facing some of the largest technology development in the Danish power sector so far, in particular because the system changes are expected to involve major implementation of modern information and communication technology, which has not been used in the power sector before. It is not enough to build upon what we already have.

Paul Frederik Bach: - To what extent we choose to change the power system architecture will depend on how much Denmark wants to rely on system support from our neighboring countries. All international scenarios considered in the EcoGrid project, suggest that Denmark also have to develop their own, i.e. domestic, solutions. Our conclusion is that it is an unrealistic and dangerous strategy to expect that Denmark will have access to the Nordic hydro power system to an extent that can offer the double back-up capacity to the Danish power system.

Challenging the traditional mindset

One of the main tasks in WP 2 was to give a clear picture of the possible new future system requirement – a so called “requirement capture” analysis. Many people work with



"solutions" but very few are considering the power system requirements or needs, Morten Lind claims.

According to the authors of WP 2 there has been an evolution of the power sector, which so far has not required dramatic system changes. – We will probably need a tool to prepare the system for major changes. In contrast to the power sector the pharmaceutics industry has constantly been under pressure of development of new medicines/products. This industry has developed very advanced tools for designing and building new production plants because the requirements are tough and the markets of pharmaceutics industry are changing very fast, says Morten Lind. He continues:

- I think similar tools and methods are needed in the power sector. It may not be appropriate to solve the problem gradually as they arise. The solutions required must be considered in a broader context. This is the only way to analyse alternatives. If you start with the solution without looking at the context, there is a big risk of implementing measures that do not solve the problem.

Paul-Frederik Bach and Morten Lind are aware that this discussion can be considered too academic for many, in particular for the people sitting with the practical and daily responsibility of the overall power system operation. - Nobody wants to loose control. Many operation people do not like the idea of delegating control to the local distribution level. They fear that this will cause more instability than stability. The conservative mindset is that the national system operation should control and have access to sufficient regulation capacity. Many do not believe that more decentralized control would work, says Paul-Frederik Bach.

- In a power system with different sub systems, decentralized control and responsibility of the system operation seems reasonable. The high penetration of distributed generation speaks for itself and is an argument for further assessment of opportunities to decentralize system operation and control. However, it is understandable that the idea of splitting the system in subsystems not only technically but also organisationally will meet resistance.

- The WP 2-synthesis and review probably contain more questions than answers. We have initiated a process, which can start an open dialogue and discussion, says Paul-Frederik Bach.

Denmark is not an Island

- The Future Development of the International Power Sector

Interview of Berit Tennbakk

The Work Package 3 leader, Berit Tennbakk, director, Econ Pöyry and her project team were asked to look at scenarios for the development in the market areas surrounding Denmark (in particular Norway, Sweden and Germany).

The challenges for the Danish TSO, Energinet.dk, given that Denmark will achieve its national goal of at least 50 % wind energy in the year 2025, is highly related to the developments in the surrounding systems since Denmark is a small open electricity market. Berit Tennbakk wants to emphasise: - Do not consider Denmark as an (electrical) island. International market developments provide opportunities and influence the challenges!

To what extent local/domestic balancing resources are required, and to what extent flexibility and services can be supplied from other countries, depends on development outside Denmark, i.e. the development of the international power market. For example, the current development of wind power in Denmark would probably not have been possible without access to balancing capacity in the Nordic hydro system, particularly Norwegian hydro. In the future, other countries have ambitious renewable targets as well, and the competition for those resources is likely to increase. At the same time, the increase in wind power generation in Germany, close to the West Danish border, has implications on the system security and operation in Jutland. Changes in power balances, trade patterns and international obligations affect the development of the Danish system as well.

Scenarios - a tool for better understanding of an uncertain future

- The international scenarios give Energinet.dk (or the TSO) a tool to get better grip on an uncertain future and provide a basis for creation of robust and flexible strategies. In addition, the scenarios can give a clearer picture of the nature of challenges the TSO should give special attention to, and make it possible for the TSO to respond adequately to different futures, says Berit Tennbakk.

The market developments in the areas surrounding Denmark differ substantially between the scenarios. Let us look on the four international futures considered in WP 2 named “Greenville”, “Blueville”, “Grønnevang” and “Blåvang”. The basic stories of these scenarios correspond to the scenarios Energinet.dk has developed for the Danish system. The main scenario dimensions are market development and environmental focus. The Greenville and Blueville scenarios are both driven by increased co-operation and power interconnection between the EU member states. However, the drivers behind the scenarios differ. In Greenville, the member states are coordinated with respect to the European climate policy and targets. In Blueville, the main driver for co-operation is associated with security of energy supply.

In contrast, national uncoordinated solutions are dominating in the “Grønnevang” and “Blåvang” scenarios. The highest environmental focus among the four scenarios is in “Grønnevang” where global climate agreements and ambitious national climate targets set the policy agenda in the EU member states. The answers to meet the ambitious targets in the Grønnevang society build predominantly on national solutions and a local self-sufficiency “mindset”. In Blåvang preservation of national security is the main driver - and the answers to these challenges are domestic in nature as well.

Can you give an example of how these international scenarios could make a difference for Energinet.dk or other TSOs in their decision making related to strategies and future investments?

- In the Greenville scenario there is a very high penetration of wind power, particularly in Norway, Sweden and Germany, which results in a substantial (international) transit demand and a high (international) competition for balancing power. This means that the requirement for domestic solutions is much higher than in the Blueville scenario where the demand for transit capacity and regulating power is relatively low, explains Berit Tennbakk.

The need for and cost of providing balancing resources differ

Higher competition (i.e. in the Greenville scenario) for balancing power may also mean higher prices for the balancing resources in an international regulation power markets, but at the same time provide better access to foreign balancing resources. From the society’s point of view, however, the costs of regulating power can be a challenge. Even though the access to balancing resources will be easier in an international market, the associated costs may be high. Hence, even in this scenario it makes sense for the Danish TSO to develop competing domestic measures.

In contrast to Greenville, the need for domestic regulation power in the Blueville scenario is moderate. The transit demand increases, but the international demand for balancing capacity is low due to the lower focus on environmental and climate change issues. Compared to Greenville, the share of wind /intermittent power generation is therefore relatively low.

Among the four scenarios analyzed Grønnevang seem to be the “worst case” scenario for Denmark in terms of the *very* high need for domestic regulation power. In Grønnevang expansion of transmission capacity is generally not prioritized. In addition there will be a substantial reduction of electricity demand, which means that the share of intermittent generation capacity will be much higher in the international power system. To put it simple: Denmark cannot expect to have access to balancing resources from Germany, and will rely more on Norwegian hydro power for “back-up”. Norway will, however, develop a large surplus and may be less willing (or willing to pay less) to be a receiver of Danish overflow generation. In other words, the frequency of zero prices is likely to increase. The result may be that Danish wind power generation has to be curbed in high wind periods. Put differently, the value of Danish wind power is low and sometimes negative.

The Danish challenge to be seen in an international market context

Berit Tennbakk wants the reader to bear in mind that the scenarios described in WP 3 have not yet been integrated with different scenarios for the Danish energy system that for example consider different mix of renewable energy resources or analyze the impact of different geographical diffusion of the wind power in Denmark. One of the conclusions of WP 3 is that to achieve the full understanding of the challenges and possible solutions, the development in Denmark should be included in the picture. In order to study the full impacts on the markets and system developments, model simulations including international markets have to be carried out. This has not been a part of the task in phase I of the EcoGrid project.

- Although the international scenario descriptions do not tell us the full consequences for the Danish system Energinet.dk and other TSOs can use the scenarios as a method to gain valuable insights and make reflections about the future challenges, and shed light on the potential need for specific domestic solutions or actions, says Berit Tennbakk.

Denmark relies on international markets in all scenarios

One thing is for sure: In 2025 Denmark cannot rely completely on the back-up capacity through their access to international market, especially the Norwegian hydropower, when there is little or no wind. Neither is the international market expected to capture all the Danish surplus of generation, i.e. in periods when there is a lot of wind.

- I want to emphasize again that all scenarios indicate that Denmark will have a need for internal balancing resources to stabilize their power system, says Berit Tennbakk. On the other hand, it is unlikely that the Danish system can fully accommodate the wind power on its own – international solutions are needed – and will probably be available to some extent in all scenarios.

It is a magnificent task to create a system which can accommodate 50% wind power generation, and the system costs are likely to increase substantially even in an ideal market situation. Although domestic resources can be found, they have to be intensified to be available, and it is unlikely that it is desirable or even possible to rely completely on internal resources for system services and balancing. If one emphasizes domestic solutions too much, the result may be that wind power itself must be significantly used for down regulation. This implies that it may actually be difficult to utilize the full energy potential of the wind power.

New Measures for Integration of Large-scale Renewable Energy

Interview of Poul Sørensen

At Risoe, DTU, Professor Poul Sørensen's field of research is integration of wind energy in the electricity system with focus on simulation, control, power quality and power fluctuations. In EcoGrid.dk he was project manager of the comprehensive work package 4: *New Measures for integration of large-scale renewable energy*, including very wide-ranging measures.

- The main task of WP 4 was to establish an overview and description of measures that could help us to manage the future challenges of the energy system with very high penetration of renewable energy, in particular wind power. Apart from the more traditional power measures we also looked at the opportunities to use market solutions and new control/IT systems, says Poul Sørensen.

It was not an easy task to determine which measures to include in the survey. This decision was taken together with 20 experts representing universities, consulting companies and industry.

Integration with the heat system - a Danish speciality

The main conclusion of WP 4 is that Denmark is in a very good position to increase the intermittent wind power that goes far beyond the current share of 20 % of the Danish electricity consumption. - In the short term, integration with the current Danish heat and power system provides the most promising measures. The survey shows that technologies are already available and economically reasonable. In addition, several interesting pilot projects have been started. In principle, we could use these measures from day one, says Poul Sørensen.

According to the energy experts, realising the potential "heat-integration-measures" primarily depends on the Danish regulatory regime. –Assessment of the barriers concerning taxation and legislation were not a part of the EcoGrid phase I study, but this is a very important issue to follow-up, says Poul Sørensen.

While large scale implementation of known electricity storage technologies would be very expensive at the present development stage (e.g. flow batteries etc.), storage of heat requires much less investments. Denmark is already using their district heating systems/CHP plants for load management in the power system, but the storage capacity can easily be extended and used also to balance large scale wind power. No matter how increased flexibility in the energy system is attained, there are costs involved. –Although the integration with existing district heating (i.e. heat storage) and better utilisation of the current CHP units in interconnected heat systems are probably the most efficient measures, it is important to accept that it implies increased costs, says Poul Sørensen.

Flexible demand

In the short to mid term, activation of electricity customers/demand can offer a significant source of flexibility. The key challenge is to engage a large number of end-users and make it possible for them to respond to real-time price signals. –



This requires some investments in IT- infrastructures (meters etc.) but we do not know exactly the amount of investments. Often it is about the “chicken or egg” dilemma. Some measures are necessary to make other measures work.

Transport (i.e. Electric and hybrid vehicles) is another mean that can provide a significant flexibility to the electricity system – Here we rely on what is happening outside of Denmark. The opportunities will largely depend on the development in the car industry – there must be an international market for the car manufactures. We do not know how fast the penetration of electric and plug-in hybrid vehicles is going to happen. This depends highly on whether the policy focus on environmentally friendly cars is on a European or global level. In contrast to the Danish wind power “adventure” we cannot control the development in the transport sector to the same extent, says Poul Sørensen. On the other hand, Poul Sørensen does not recommend Denmark to adopt a "wait-and-see" attitude: - We have a great opportunity to demonstrate in Denmark how electric vehicles can be used to support the integration of renewable energy, especially wind energy. It is also very important to prepare for the integration of electric vehicles into the power system, e.g. we could prevent people from charging their electric cars immediately after work and there after walking into their home to turn on all their other electric appliances. In this case, we will have created another "peak" load.

"Added value"

Compared to previous analysis the EcoGrid.dk project has a wider focus. - Popular speaking the objective of WP 4 was to point out so called ”smart grid” technologies that go beyond the catalogue as we know from the Danish Energy Authority (The Danish technology catalogue 2005).

WP 4 is more a survey than a traditional research project. - It was not expected to provide new research results. The WP 4 should rather be seen as an “up-to-date” status picture of relevant smart grid measures, including direct links to latest research, pilot test and demonstration projects. WP 4 should be used as a “book of references”.

An unsolved problem

The future need for new power generation capacity is another key challenge that the WP 4 group highlights in their concluding remarks. The measures described in WP 4 work on a time scale to maximum a couple of days and do not provide back up capacity in longer periods. – Through “demand response” measures it is possible to reduce electricity consumption instantaneously. On the other side, it is possible to increase electricity consumption in a limited period, for instance through storage of heat or charging of electric car batteries.

– The challenge is how the Danish society should deal with several days without wind (i.e. electricity generated from wind) which we know will happen. In the long term we expect current thermal generation capacity to close down because of wear and tear. It is not likely that commercial investors have the incentives to build new capacity, to be used in very limited periods of the year.

One option is to subsidize future back up capacity. Everything is about how much you are willing to pay for security of supply. Who can afford to be without electricity for days? – I do not know anyone – and certainly not if it happens every time we have a couple of days without wind, says Poul Sørensen.



A vision of a real-time market

Interview of Mikael Togeby

Doubling generation capacity from wind power requires a more dynamic electricity market and mobilisation of many more resources that today are either passive or insufficiently integrated into the energy system.

Adequate design of the electricity market is pivotal in relation to increasing dynamics and mobilesing new resources like demand or micro-generation, says Mikael Togeby, Ea Energy Analyses and editor of *Market measures* in WP4.

- The day-a-head market at Nord Pool was originally constructed to attain a better utilization of flexible hydropower generation. Coal power plant does not have the similar ability to regulate supply on an hourly basis. To meet this problem the market was developed to include block bids. Each technology has its own favorite market design. - The current market is not properly designed to include wind power, micro-generation and demand response. The point is that different technologies have more or less favorable conditions in a certain market design, says Mikael Togeby and he adds:

- A problem with integrating wind power in today's power market is that the wind power is difficult to predict. As the amount of wind power increases, the need for flexible power resources is increased. A crucial question is how the electricity market could be developed to manage a system dominated by wind power generation and many players. According to Mikael Togeby an important part of the answer could be to design a real-time power market, better tuned for future technologies and more market participants.

- The current Nordic regulating power market is a kind of real-time market, however other designs are likely to be more appropriate when the focus is on including new resources, e.g. demand, which could respond better to a true real-time price signals, says Mikael Togeby.

The Nordic regulating power market is traded with a 15 minutes notice, and in much smaller volumes than the day-ahead spot market. The market is in practice limited to suppliers that can send plans and guarantee to be able to supply the balancing resources. Further, the participants must bid minimum of 10 MW into the market. Competition in the regulating power market is limited and many potential suppliers are in practice prevented from being active. With a well designed real-time market, any producer or consumer who is able to adjust production or consumption can do so and get paid the prevailing prices.

A new and innovative market for regulating power

Before mentioning all the obstacles and barriers to overcome, Mikael Togeby wants to start with following description a vision for the design of a future near real-time market:

A real time power market could be based on broadcasted price signals. Regulating power is motivated by offering an "adder" to the spot price. The TSO (or DSO) could change the adder, e.g.

every five minutes. If the system could be run as planned in the spot market the adder would be 0. If more generation (or less demand) were needed to obtain a secure operation, then the adder could be positive, and vice versa.

With such a market design small distributed energy resources could be active in the regulating market. In principle, all market players could choose to participate in the real-time market and be exposed to the adder, Mikael Togeby says. New potential suppliers could include electricity demand (both industry, and households) and micro generation. Also existing wind power and local CHP could respond to actual prices. Crucial for this vision is that participation is voluntary and no plans must be submitted beforehand. Such a system can be highly predictable and secure if a large number of actors are active.

Too good to be true?

Technology needed to make it happen is the installation of interval meters and broadcast of the actual price added per area (for example over the internet or radio). - The meters do not need to be "smarter" than being able to measure data in five minute intervals, claims Mikael Togeby. In Denmark many (also the energy authorities) seem to be sceptical to installing remote metering facilities in all customer sites, and who should pick up the bill for the meters. Is their reluctance understandable? - I think the social benefits of installation of meters are underestimated. Remote metering is only a tool to enable a more flexible system work. The value of increased flexibility in the energy system can be high. Activation of distributed generations and consumers has the potential to mitigate congestion in transmission lines, control price fluctuations (misuse of market power), strengthen energy security, and provide greater stability to the electricity grid. The use of interval meters may also lead to energy savings due to improved feedback of metered data to the end-user.

The research team in WP 4 believes that the main barrier against a new and more flexible market is in general not the cost of the needed IT systems, but the fact that several organisations must agree, e.g. all Nordic TSOs or the UCTE. Further many system operators doubt that a real-time market should be voluntary based – Alternatively the cost of running a system with hundred thousands of market participants (i.e. local generation as well as customers) will be too high, says Mikael Togeby.

The fear of loosing "control" is understandable. Therefore, it is important to define a critical mass of participants that can ensure that the balancing service is available when needed. In that respect, "automation" is the key. Practical experiments with demand response from houses with electrical heating shows that SMS/E-mail of prices have little impact, while automated control based on individual preferences and broadcasted prices can lead to predictable and significant results.

When do we have a real-time electricity market? Who knows? - But ten years ago the electricity spot market was not yet introduced in Denmark. Today it is a dominating market for electricity and is considered a success, says Mikael Togeby and he adds: - The development of communication and IT systems make it possible to use demand and for example micro generation with very fast response features in the dispatching of the power system.

Step-by-step approach

In WP 4 the main conclusion is that integration with heat power systems provides the most promis-



ing and mature measures, from a technical as well as an economic point of view and in the short term. In the short to mid term, demand response could be another important source to achieve increased flexibility. The potential of demand response in Denmark has been estimated to 1290 MW. This estimate includes electric heating (in households and businesses) and industrial processes and back up generation.

Mikael Togeby recommends a step-by-step approach that gradually adjusts the market to respond to more dynamic prices:

- More interval meters
- Reform of the subsidy scheme to wind power, so they can react to market prices.
- Experiments with real time pricing for losses, local congestion and regulating power, including practical demonstration to prove the predictability of such systems.

What is a smart meter?

Traditional electrical meters only measure total consumption per year and consequently provide no information about when the energy was consumed. Smart(er) meters provide an economical way of measuring this information, allowing price setting agencies to introduce different prices for consumption based on the time of day, the season or even daily spot prices.

If generation is constrained, prices can rise significantly as more expensive sources of power are purchased. When wind is high electricity prices can drop. In general it is believed that billing customers by how much is consumed and at what time of day will motivate some consumers to adjust their consumption habits to be more responsive to market prices. The central feature of smart meters is the ability to record the consumption at small time intervals, e.g. hourly. The price signal can be send by the meter or (probably better) by other channels, e.g. internet or radio.

In the EcoGrid phase I project, WP 4, it is noted that a number of Danish grid operators are working with smart-metering and most of them are able to make measurement of electricity, gas, water, heat etc. on an hourly basis (or less). A lot of research within demand response and other related topics has been done, but the break through is still before us. In the long term it is expected that remote meter will be found at all customer sites. *"Remote meters are a tool to make the flexible energy system work"*. The researchers advocate for the development of so-called Energy Flow Control (EFC), which has the functionality not only to measure the consumption of electricity, gas, water or other energy sources in real-time, but also to optimise the usage of energy sources in accordance with the needs of the power system, society, market and end-user. Major bottlenecks/barriers for further development/utilization of EFC solutions relates to standardisation within all communication and data protocol issues.



Tomorrow's wind turbine is available

Interview of Thomas Ackermann

Thomas Ackermann, CEO of the German company Energynautics, was project manager of the WP 4 *Control and IT measures.*

In summary, Thomas Ackermann considers that the main lesson to be learned from this comprehensive research project is that in the (near) future distributed energy technologies such as wind turbines and micropower generation will be expected to be much more flexible in the way they can be operated and to be capable of providing system services. The key to this development is modern IT and communication tools that enable, for instance, wind farms that are connected to the transmission system to contribute ancillary service functions that are similar to those of conventional power plants. In addition, distributed wind turbines as well as new microgeneration technology is today able to provide much better support to the operation of the local grids.

- It is quite amazing how wind power control technology has developed within the last five years. The offshore wind turbines at Horns Revn in Denmark are quite advanced. The wind farm can be operated as a single power plant that is able to offer a number of ancillary services that the TSO needs to operate the overall power system, says Thomas Ackermann.

Wind farm control measures

Future power systems that will be dominated by (offshore) wind power and a large number of local power plants - including microgeneration, such as solar panels, micro wind turbines, fuel cells, micro CHP etc. will play a significant role in supporting the operation of the future power systems.

Already today, the wind turbines of the Horns Rev offshore wind farm have advanced control modes such as delta control. Delta control can be used to support the power balancing (secondary control) and frequency control (primary control) in the Danish power system. And wind farms can adjust their power output very fast - even faster than many conventional power plants: For frequency control, the maximum power rate of change allows to reduce the production from 100 % of rated power to below 20 % within 3-4 seconds. In addition, the wind farm - if operated in Delta Control mode – can also increase production, i.e. the actual power generation of the wind farm is decreased by a delta below the theoretically possible power production for balancing or frequency control purposes, the power output of the wind farm can now be increased by the mentioned delta whenever needed. Delta control results in a certain waste of energy, but the point is that wind turbines can be regulated up and down if required. These new control options increase the value of wind power and reduce the need for other spinning resources. However, you still need wind to ramp up a wind farm, says Thomas Ackermann.

Development of new black-start capabilities

One of the new control measures analysed within the framework of WP 4, is the capability of wind farms to support grid control in combination with other available generation. In cases of emergency,



future wind farms will be able to offer black-start support to the grid, i.e. start up from a shut-down state and help to energise part of the grid. - This type of wind-farm-controlled black-start requires support from other available generators (CHP etc.), though. New grid control structures will be needed in order to be able to utilise this new wind turbine/wind farm control function at least at distribution level. Wind farm black-start systems are associated with more complex (and costly) wind turbine technologies, as well as more advanced control and communication systems, says Thomas Ackermann.

Micro production support

Micro production (MP) or micro generation is home-based and local energy production, i.e. solar panels, micro wind power and micro CHP with an installed capacity of less than 10 kW. The electric power interfaces that are typically used for connecting microgeneration plants to the grid can quite easily perform additional power support functions, such as:

- Ancillary grid supporting services, such as local voltage and frequency control
- Uninterruptible Power Supply (UPS) for houses, ensuring power supply in emergency situations/blackouts – thus improving reliability of the grid
- Operating as regulating reserve

The local grid support function is a well-proven technology and provided by “MW-range” wind power plants with electronic grid converters. Applying this technology to micro production is only a matter of down-scaling it to the “kW range”. Such features can be included into existing software without requiring the installation of additional hardware. UPS systems as such are also an established technology, however UPS used in relation to micro generation plants is still at the R&D level.

Lack of standardization is a major challenge

Currently, a common challenge to the implementation of many of the described support and control measures is a lack of standardised communication protocols which allows the TSO to remotely control the various wind farms of different suppliers and the new micro-production units when needed for power system support.

- One of the major challenges is the lack of standardisation of IT and communication technology used in the power industry. Today communication protocols are vendor dependent and the components have different levels of automation. This means that they are often unable to communicate with each other, says Thomas Ackermann.

- Development and implementation of a communication standard is in certain areas at a very early stage and is crucial for the reliability of future power systems. Requirements regarding IT and communication in the power system are different from the development of the internet. In “the early internet days”, nobody would notice if the internet broke down for a day or two. If the same thing happened to the power system it would be unacceptable.

Real-time state estimator “matters”

Real-time state estimators are tools that can give the TSO a better and more complete understanding of the current status in the power system. State estimators are today already used by power system operators. However, the new kind of state estimation can better filter redundant data, eliminate incorrect measurements, produce reliable state estimates, and - to a certain extent - allows to determine power

flows in the parts of the network that are not directly metered. The real-time estimator relies on the availability of data measurements from the electric network. The newer versions of state estimation are based on *phasor measurement units* (PMUs), a device that provides synchronized measurements of real-time phasors of voltages and currents along with measurements of the frequency. In typical applications, phasor measurement units are sampled from widely dispersed locations in the power system network and synchronised from the common time source of a global positioning system (GPS) clock.

- It is all about power system security. Improved state estimators and other tools using for example PMUs will help the system operator to detect critical situations in the power system earlier and to evaluate possible solutions much faster than before, Thomas Ackermann explains.

IMPORTANT: Be careful regarding the implementation on power systems

According to Thomas Ackermann, the Danish network operator was very successful in incorporating 22 % wind power into the Western Danish system, a unique situation worldwide. Increasing the wind power penetration level in Denmark to 50 %, however, is certainly a much larger challenge than integrating the first 22 %. The key issue is to foresee the necessary problems and to start making the relevant changes in time.

- I think that it is certainly possible to develop a power system that can handle a 50 % energy production coming from wind power, but it is not without major challenges. Historically power systems engineers had time to learn how to deal with critical system states that occur once in a while, and this learning often included learning from blackouts. However nowadays blackouts are not really acceptable anymore, hence it is all about foreseeing the issues and developing solutions well in advance, says Thomas Ackermann.

The Danish case has shown that it is possible to manage 22 % wind power with the existing infrastructure - partly thanks to the access to Norwegian and Swedish hydropower resources. 50 % wind energy will also work, but this will require a major redesign of the current power system, including additional IT control and infrastructure.

The aircraft industry is used as an analogy for describing the challenges posed by the incorporation of new IT-based control systems into power systems: Until the early 1980s, most airplanes used cable-based control systems, i.e. the pilot used a cable system for controlling the hydraulic control networks that ran all of the major mechanical systems of the aircraft. The system is known as ”fly-by-cable” system. Today most large airplanes use fly-by-wire systems, i.e. they use electronic communication for controlling all onboard systems. Hence, including more IT-based control systems into power system operation is often compared to changing a “fly-by-cable” system in an airplane to a “fly-by-wire” system while the plane is flying, because it is not possible to shutdown a power system to install new control systems. Thomas Ackermann, however, prefers to put it another way: There are always risks associated with the installation of new IT-based control systems. It is possible, however, to prevent serious incidents if you install the new equipment without removing the old systems.

Communication standards and wind turbine codes

The communication standard IEC 61850 will be the key standard for the design of substation in the near future, which is crucial in order to maintain an efficient and reliable electrical infrastructure. This standard is currently tested in some substations and demonstration projects. Recently the standard has been extended to different distributed energy resources, among others local CHP units. This development has among others been facilitated by a Danish research and demonstration activity.

The IEC 61850 standard defines, among other things, a common system language for the configuration of electrical substation devices that make interoperability possible (e.g. facilitates data exchange over the internet etc.) between different components/substations and ease the communicating with the overall TSO monitoring and controlling systems, SCADA (Supervisory Control And Data Acquisition system). A related communication standard for wind power is IEC61400-25 the standard will provide a critical measure to manage the rapidly growing wind power penetration – such a standard can really make a difference. Through communication standards the current state of the individual wind plant can be controlled and monitored when required, and counter measurements can be enforced if needed, in order to meet the changing demand for energy and to provide support to the overall power system operation.

Preparing for Large Scale Demonstration

Interview of Jacob Østergaard

Jacob Østergaard is Professor and Head of Centre for Electric Technology (CET) Department of Electrical Engineering, Technical University of Denmark.

Work Package 5 *Activities for EcoGrid phase II* embrace the EcoGrid experts' view on high priority research and development activities recommended in the next phase of EcoGrid (2009-2011).

- The objective of EcoGrid Work Package 5 is to suggest future research and development activities recommended for next phase of EcoGrid. Thus, it is a key input to Energinet.dk when formulating EcoGrid phase II (2009 – 2011), says Jacob Østergaard, project leader of WP 5.

EcoGrid phase II paves the way for large scale demonstration

Crucial for the selected topics for future EcoGrid activities is that the technologies and solutions included must have high impact to the overall EcoGrid goal of enabling 50% wind power and other renewable energy sources in the grid (i.e. following the national target of renewable energy). Furthermore, future activities should provide technologies and solutions, which are robust for different future developments. This means that the solutions should be able to handle "worst case" situations. Finally and very important is that the activities shall focus on research and development enabling demonstration and implementation of smart grid technologies and system solutions which is not covered by other national research programs.

- The proposed future EcoGrid Phase II activities will be a part of Energinet.dk's own internal research and development programmes. Therefore, the proposals are closely related to Energinet.dk's current design activities and system planning, says Jacob Østergaard.

- We recommend that Energinet.dk plays an active role in the project, to ensure maximum benefit by combining internal and external knowledge and in particular because the activities should provide the basis for large-scale demonstration. Jacob Østergaard refers to the ambition of an EcoGridEU demonstration project on Bornholm merging best Danish and international knowledge and competences and expertise within the area of SmartGrids.

High priority EcoGrid phase II proposals

So far the current national research programmes (e.g. PSO and EUDP) cover environmentally friendly generation, energy savings and demand response solutions separately. According to Jacob Østergaard and his colleagues the new system architecture, new market designs, and new control measures should have much more attention in the future.

- The system challenges are important for the development of the future system with high share of renewable energy resources. It is therefore suggested that the selected future EcoGrid activities



focus on the energy system as a whole and utilise the broad national competence established in the ongoing EcoGrid activity to develop new system level solutions, says Jacob Østergaard

The activities suggested are seen as important elements within a strengthened emphasis on the development of smart energy solutions. A future strengthened emphasis can for example be established by development of focus areas in this field within the public funding programmes such as ForskEL and EUDP.

The EcoGrid team has carefully selected specific research and development activities within the next 2-3 years, which are considered as important contributions to future research and development activities with expected special interest of Energinet.dk.

Three activities are suggested within the following non-prioritised order:

- Develop tool for optimal system operation with new balancing measures (Activity A)
- Develop new market functions for DER participation in system balancing (Activity B)
- Develop new coherent control architecture based on sub grids (Activity C)

Jacob Østergaard describes the proposals briefly in this interview and he suggests the reader to find a more detailed description in the WP 5 report.

Tool for optimal system operation with new balancing measures

The purpose of this activity is to develop a new tool to support operation of the power balancing in a power system area with large share of renewable energy (primarily wind). - The key issue is how the new, flexible power measures we have identified in WP 4 can supplement the traditional power balancing measures provided by controllable thermal units and interconnections, says Jacob Østergaard. The group of new measures includes:

- Integration with the heat sector
- Integration with transportation
- Consumer demand response
- Wind farm control

Power system simulations are the core activities in this proposal. The target is to provide the operator with the available information to support allocation of the relevant resources to ensure system security and balancing.

Outcome of “Activity A” New tool for optimal system operation with new balancing measures:

- A power system balancing awareness tool, which will help the system operator to (better) quantify the available balancing resources as well as the need for these resources.



New market functions for DER participation in system balancing

Near real-time adjustments of the electricity system is crucial for an economic and safe operation of a power market dominated by small power plants and participants. Through improved market dynamics the administrative overhead can be minimised.

The purpose of this activity is to develop and analyse a new market and operational set-up. It will focus on ways to activate new resources for the normal operation for intra hour regulation. – We are not talking about hundred, but hundred thousands – potentially millions of new market participators and a variety of different types of technologies and resources, says Jacob Østergaard. In this activity, different designs are studied, including different time intervals. Critical issues like stability, predictability and the possibility of misuse of market power will be analysed for different market designs.

Examples of tasks include:

- Review of existing real-time markets, including those in Australia and the US.
- Optimal response to near real-time markets from a single technology perspective
- System modelling of a system with hundreds of active market participants

Outcome of “Activity B”, New market functions for DER participation in system balancing:

- A complete and documented design of demonstration project with near real-time markets with highly improved short term dynamic
- Together with the elements from development of new coherent control architecture (Activity C below) the results will provide a valuable starting point for the planned EcoGridEU project.

New coherent control architecture utilising DER for flexible, secure and efficient system operation

This proposal focus on development of a consistent control architecture, which enables participation of resources in the distributions networks, e.g. activation of thousands or even millions of local power and heat plants, electric vehicles and consumers.

- The purpose of this activity is to develop, evaluate and optimise a new power system architecture for a target system with focus on real-time balancing and reactive power/voltage control. The activity includes development and analysis of solutions for managing grid operation tasks (e.g. congested lines, optimum response to security and stability issues, dynamic tariffs for losses, voltage quality etc.) through market interaction, says Jabob Østergaard.

The near real-time market model developed in the above-mentioned proposal concerning new market functions (Activity B) will be used for the development and analysis. Further, development and analysis of voltage control/reactive power control build on an integrated sub-grid approach considering reliability issues and sub-grid interface.0

Outcome of "Activity C", New coherent control architecture utilising DER for flexible, secure and efficient system operation

- Development of a coherent control architecture based on sub-grids
- Development of a simulation tool enabling analysis of architecture design for a variety of power system aspects.

Other prioritised research

Along with the above activities the EcoGrid project team has identified an additional number of highly relevant research and development topics. They recommend six research activities either to be followed up as part of a future EcoGrid.dk activity or supported by other national research programs:

- **Capacity market**. Most of the present base load power plants are likely to be replaced before 2025. The future operating mode of CHP units will be far from base load operation. Therefore a new generation of CHP units for more intermittent operation will be required. Phase I did not include recommendations on the replacements. It is doubtful if the present market can provide sufficient incentives for development efforts and investments in new capacity. An update of the market design should therefore be considered. Daily peak power could be a separate element of the market while energy might loose its dominating role.

- **Electric vehicles-storage technology**. The electric vehicles will probably play an important role in the economic and reliable operation of the Danish electricity grid with 50 % wind power penetration. From the electricity grid perspective, it will be mainly a storage device for smoothing the power fluctuations from renewable resources especially wind power. In this context, it is necessary to develop optimal architectures to facilitate intelligent charging and discharging. As a spin-off activity of EcoGrid phase I this research challenge has been addressed in the separate project Edison[8].

- **Utilisation of PMU measurements in system operation.** PMU installations worldwide bears witness to a general expectation in the value of the additional phase information in the voltage and current measurements. The exploitation of this information is under development but need much more attention to develop optimal solution to support opera-

[8] **EDISON** (**E**lectric vehicles in a **Dis**tributed and **I**ntegrated market using **S**ustainable energy and **O**pen **N**etworks). On February 2008 the announcement of EDISON took place. Electric vehicles (EVs) provide a unique opportunity to reduce the CO_2 emissions from the transport sector. At the same time, EVs have the potential to play a major role in an economic and reliable operation of an electricity system with a high penetration of renewable energy.

Project partners: Dansk Energi, Centre for Electric Technology at DTU, IBM, Siemens, Rittal, Østkraft and Dong Energy

tion of the power system with large share of wind power.

- **Ancillary service market.** Provision of ancillary services will be a critical element in a power system with 50 % wind power. To ensure sufficient resources and enable overall economic optimal solutions proper market incentives should be provided to system users (both generation and demand). Possibilities for market based solutions should be exploited, e.g. related to reactive power/voltage control, system inertia etc. Such new markets could potentially be coherently developed with a near-real time market for active power. Ancillary service markets and new market functions for DER participation in system balancing (activity B) can be developed as an integrated framework.

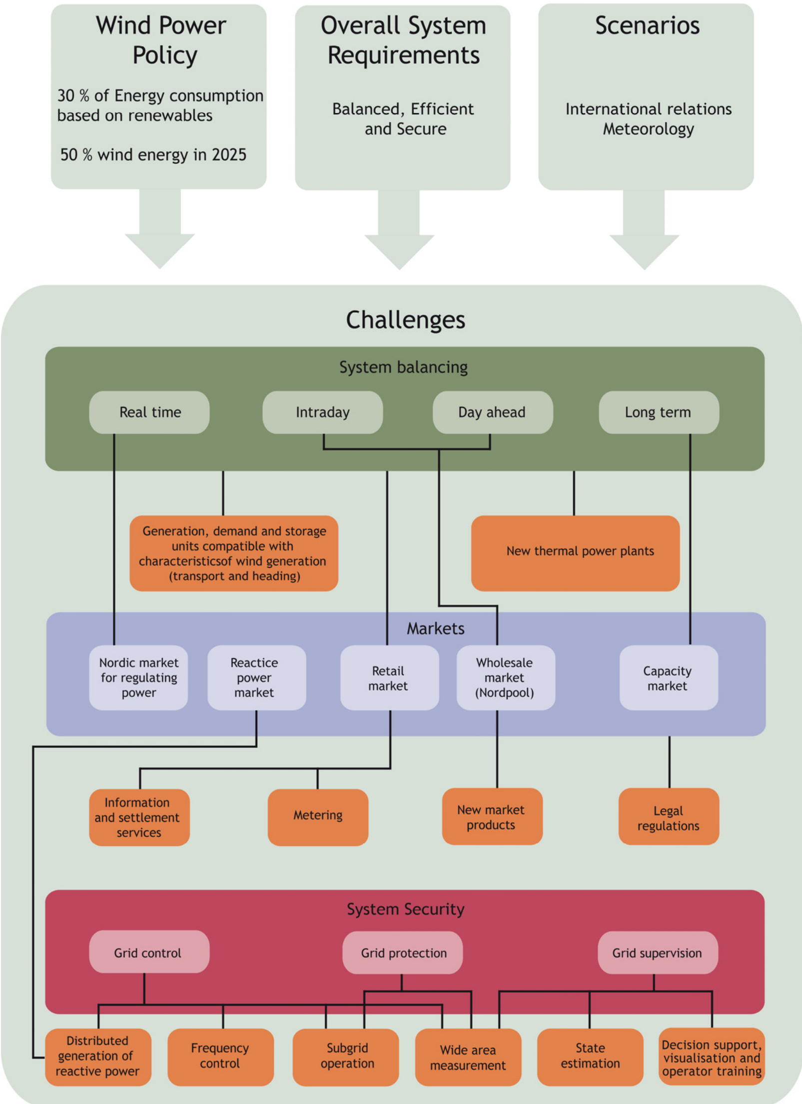
- **System awareness related to active distribution networks.** Methods for increased system awareness of distribution networks should be developed to obtain better awareness at transmission level about the overall system state. This will contribute to reliable operation of a power system with high DG penetration. This can e.g. be based on new system identification and online measurements at the interconnection points

- **Optimization of transmission system operation with distribution systems with islanding capability.** Work is ongoing in Denmark and in the international power engineering community regarding intentional island operation of distribution systems (e.g the Energinet.dk cell project). To maximise economic and reliable operation of the system, methods should be developed, which optimize the system operation, and in an intelligent approach utilize the different capabilities of the different distribution grids.



List of Appendices

Appendix 1: The future power system architecture (WP2)



The figure includes an overview of EcoGrid WP2 conclusions and recommendations. It is shown how the proposed system solutions and measures (orange) relate to the overall challenges, requirements, scenarios and policies (light green). The overview illustrates the link between the new proposed system solutions/measures (orange) and the current system (system balancing, markets, system security).

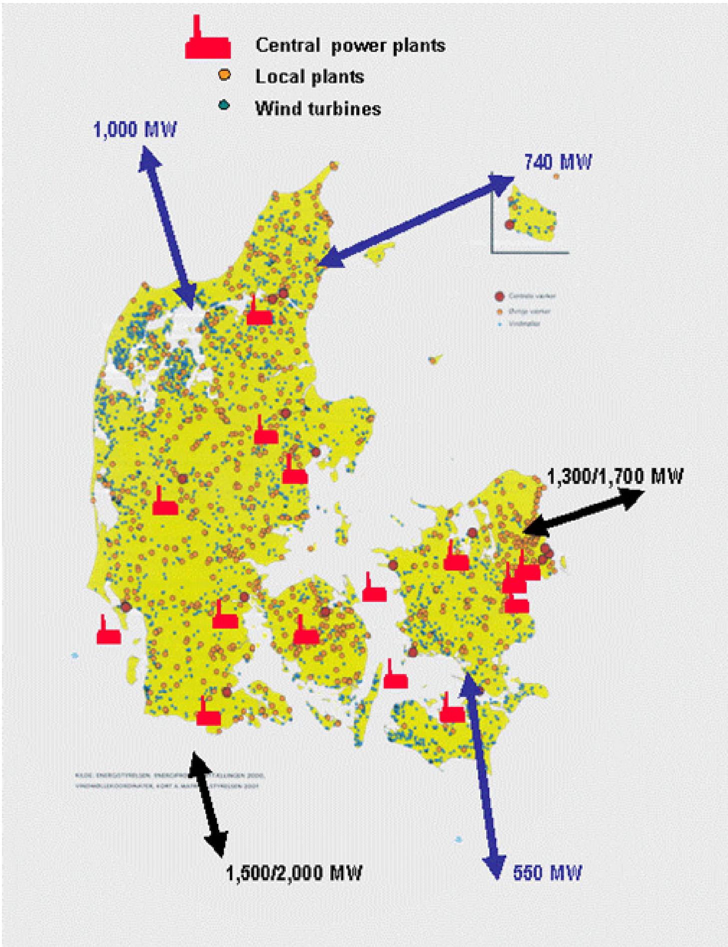
Appendix 2: Power Balance in Denmark 2008

Western Denmark

Peak load	1.250 - 3.700 MW
Central power plants	3.400
Local CHP	1.700
Wind Power	2.400

Eastern Denmark

Peak load	880 – 2.600 MW
Central power plants	3.800
Local CHP	650
Wind Power	750



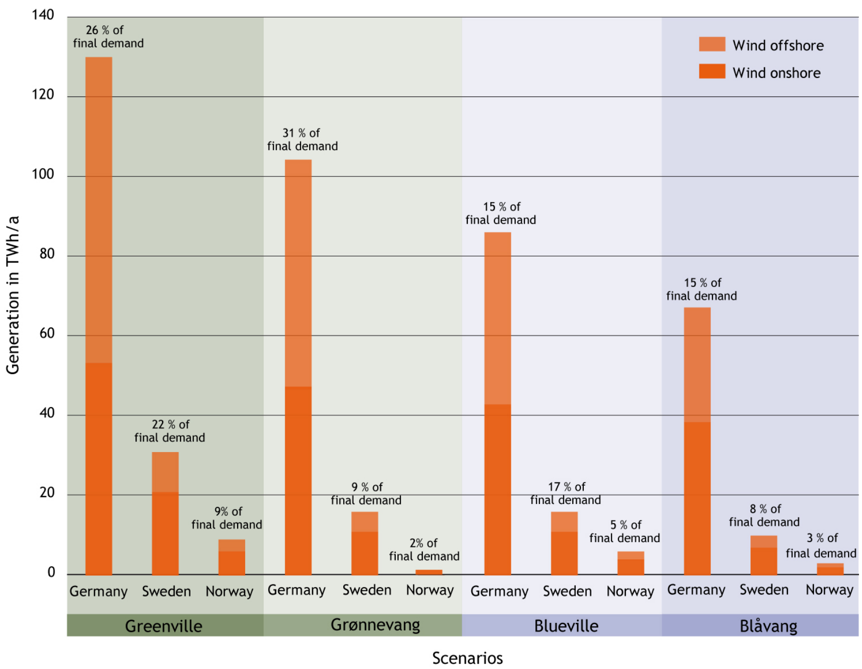
Source: Energinet.dk

Appendix 3: International scenarios (WP3)

Summary of annual generation, demand and trade in 2005 and 2025, all scenarios, per country, TWH

TWh/year	2005	Greenville 2025	Grønnevang 2025	Blueville 2025	Blåvang 2025
Germany					
Final demand	508,87	491,17	344,47	596,59	463,57
Gross generation	556,22	509,02	376,68	617,56	517,06
Net generation	500,60	458,12	339,01	555,80	465,36
Net exports	**-8,27**	**-33,06**	**-5,45**	**-40,79**	**1,79**
Sweden					
Final demand	136,65	144,07	95,02	177,35	129,19
Gross generation	152,21	153,55	113,06	186,48	171,75
Net generation	136,99	138,19	101,75	167,83	154,57
Net exports	**0,35**	**-5,88**	**6,73**	**-9,52**	**25,38**
Norway					
Final demand	112,66	98,33	64,76	127,29	98,55
Gross generation	125,92	143,81	131,04	140,83	136,37
Net generation	113,32	129,43	117,94	126,75	122,73
Net exports	**0,66**	**31,11**	**53,18**	**-0,54**	**24,18**

Summary of total wind deployment in 2025, all scenarios, TWh/year





Appendix 4: TSO concern: Planning on different time scales

Simplified, the main task for TSO (i.e. Energinet.dk) is to keep the system running, i.e. make sure that "the lights stay on". This means that electricity demand and supply must be equalized at all times, and that the network must be adequate and operational. In order to carry out this responsibility, the TSO must plan ahead: It must make sure that available generation capacity can always match demand (and that the system can supply the necessary system services). Most TSO make plans or system studies with different timescales:

- Long-term system plans
- Annual assessments
- Day-ahead planning
- Short term balancing.

The basic planning challenge for the TSO and the different timescales is not new, it applies to the system regardless of the capacity mix, demand levels, and market design. Wind power introduces new and increased challenge associated with the variability of wind power generation (MW), limited predictability of wind generation and inflexibility of wind generation (i.e. it is not possible to increase wind power generation within the available capacity if the wind is not blowing).

Long-term system planning (down to one year ahead). Usually, the TSO is not "responsible" for investments in new generation capacity.[9] TSOs are, however, responsible for the development of the grid including interconnectors with other TSO areas. The development of the grid and investments in interconnectors are based on long-term market assessments: developments in demand and supply, and how these developments impact the system balance. Usually, the TSOs look at both the energy and effect capacity balance.

Day-ahead market. The day-to-day planning consists of making production plans to ensure that supply meets demand at every hour. In principle, all loads and all generation must submit their production and consumption plans to the TSO within a specified deadline the day before the fact, i.e. day-ahead. After the electricity market reform, a large part of this day-ahead planning is determined in the day-ahead market.

Elbas – intraday trading. The day-ahead system plan balances expected demand and supply for every hour of the next day (24 hours). The market equilibrium is found based on forecasted demand and market bids. However, realized generation and consumption will not be exactly according to plan. Reasons for is typically prediction errors for wind power, unexpected consumption variations and trips in generation and grid. The Elbas market offers participants an opportunity to adjust their hourly positions by additional trading up to one hour before the trading hour.

[9] Some exceptions exist, e.g. Norwegian Statnett's investments in reserve gas turbines in a particular deficit area in Norway.

Ancillary Services. Planning/balancing within the hour. Ancillary services are needed to maintain the physical balance and safeguard the quality of electricity in an inter-connected electricity supply system. A balance will be maintained by regulating the actually exchange by means of ancillary service in Denmark or by adjusting the planned exchange in the form of electricity trade with neighboring TSOs. The approach used depends on the operational situation in question and on what is the most cost effective solution. The need for ancillary services will in reality vary according to the operational situation and the mix of electricity production and electricity exchange. The need for ancillary services for individual 24 hours can be assessed one day ahead on the basis of production and trading plans etc. Resources for system balancing may be offered by sources both on the supply and demand side (See also appendix 5: 50 % wind energy increase the need for ancillary services).

Appendix 5: 50 % wind power increases the need for ancillary services

Ancillary services are needed to maintain the physical balance and safeguard the quality of electricity in a power system at all times. Four main categories of ancillary services can be distinguished:

- **Balancing market**

- **Frequency Control Ancillary Services** (FCAS) are used to maintain power system frequency, i.e. to keep supply and demand in balance. Energinet.dk defines two different FCAS services:
  - **Normal operation reserves**, which are used to maintain normal operation at all times. The normal operation reserves are used, for instance, to balance the difference between forecasted wind power production and the actual wind power production, or the difference between forecasted demand and actual demand.
  - **Operational disturbance reserves**, which are only used in emergency situations i.e. to restore the electricity system to a secure state of operation within a reasonable time of a disturbance such as a trip of a power line or power plant. The operational disturbance reserves are defined based on the worst-case fault, i.e. loss of one of the largest production units or the loss of an interconnection with full imports (the so called *n*-1 principle). In Denmark the breakdown of any of these can be in the order of 550-620 MW.

- **Network Control Ancillary Services (NCAS)** which are related to aspects of quality of supply other than frequency, e.g. voltage control. Most of NCAS is a service that can only be supplied locally close to the point of voltage distortion, therefore it is useful to distinguish between NCAS provided in the transmission systems and provided in the distribution systems. In distribution systems, this service is, typically, entirely performed by specifying equipment, e.g. voltage control by special transformer or capacity banks. In the transmission system large conventional power plants nowadays are typically the only providers of NCAS, see table below.

- **System Restoration Ancillary Services (SRAS),** which is related to system restoration or re-start the following major blackouts. Denmark currently uses large conventional power plants to provide the SRAS, see table below.

Example of "short-term" balancing challenges with increased wind power capacity:

Need for normal operating reserves could increase as the difference between forecast wind power production and the actual wind power production could increase. Thisin particular will have a significant effect on regulating power reserves.

- With large offshore wind farms the worst-case fault situation might increase, hence the requirements for operational disturbance reserves will increase, which could affect the whole UCTE or Nordel area.

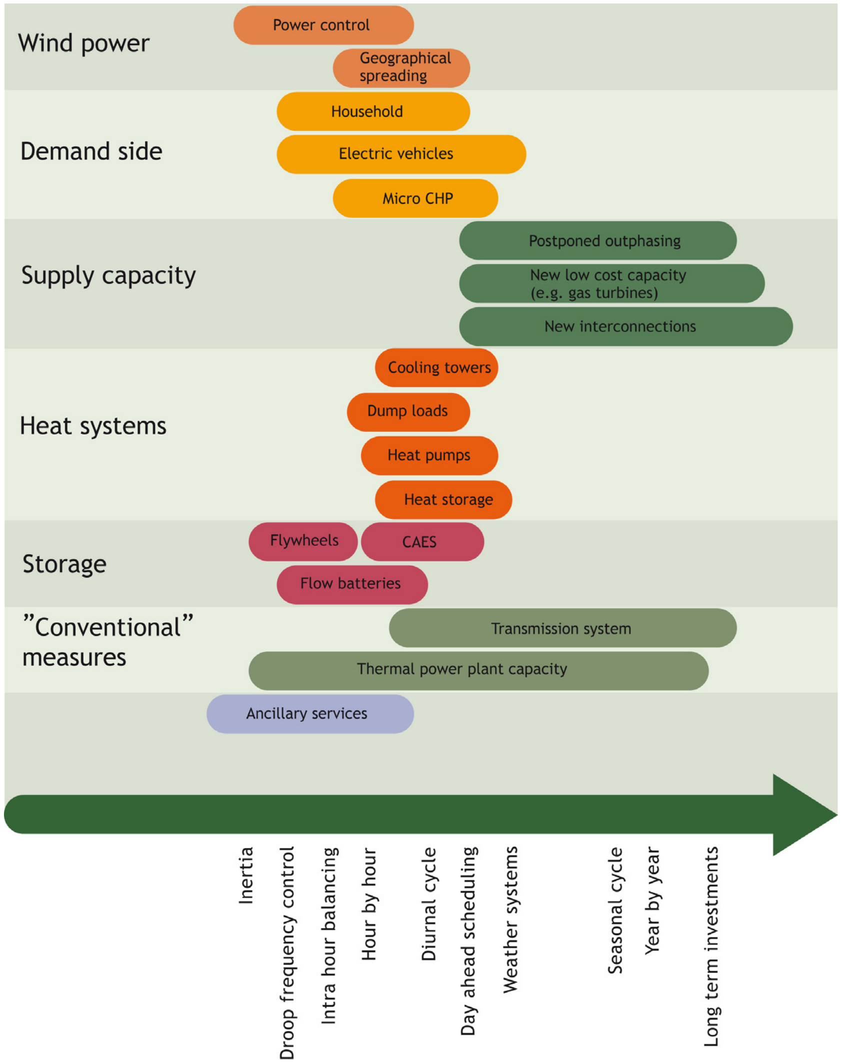
- With increasing wind power production less conventional generation assets will be online which typically provide ancillary services such as primary regulation reserves, automatic reserves or fast operational disturbance reserve. However, FCAS can in principal also be provided by wind power plants as loads, as long as they can adjust production or demand by a specific amount within the required time frame. Generally, wind power can be down regulated very fast. Up regulation is also possible with wind power if Delta control is applied to a wind power plant, i.e. a wind farm is first downregulated down by a certain delta, and this delta is the upregulation potential. In this case, wind farms can supply upregulation faster than many conventional power plants.

- With increasing wind power penetration alternative suppliers of network control ancillary services must be found as it will be uneconomic to operate the conventional power plants just for providing NCAS.

- With increasing wind power penetration alternative solutions for system restoration ancillary services must be found as conventional units might not be in operation during a black-out, i.e. they first need to be heated up to be able to provide fast restoration services. Hence, other, fast black-starting strategies must be developed to avoid long periods of black-outs. Wind power could be part of such a new black-starting strategy.

Appendix 6: Definitions and dimensions of balancing resources

The power measures described in WP 4 (in red, orange and yellow colours) have different time scale of balancing capacity. The power must be balanced on all time scales in order to ensure stable system operation and security of supply. In the figure below the time scales are illustrated, pointing out different technical and market issues and solutions, including so-called conventional and supply capacity measures (green).



- *Inertia* is a very important parameter for the power system stability, as it limits the rate of change of frequency, and thus ensures that the system can respond to the frequency changes before they become too big. Inertia is active for a few seconds, depending on the system size.

- *Droop frequency control*, which is often denoted primary frequency control, is the automatic frequency control provided today by central power plants that change generation depending on the frequency. The typical time scale is from a few seconds up to 10-30 seconds.

- *Intra hour balancing*. This is to limit the area control error, i.e. the deviations from scheduled exchange with AC connected neighboring countries.
- *Hour by hour*. Energy companies can trade balancing power to modify the day ahead scheduling.
- *Diurnal cycle*. Especially the demand varies in the diurnal cycle. Wind power diurnal variations are relatively small in Denmark, whereas PV obviously varies significantly in this time scale.
- *Day ahead scheduling* is close to the diurnal cycle, looking 36 hours ahead.
- *Weather systems*. The time scale of weather changes typically varies form days between front passages to several weeks with low wind due to stable high pressures.
- *Seasonal variations*. Load (electric and heat), wind power and PV varies significantly during a season
- *Year by year*. Wet and dry years are important for the ability to provide supply from Nordic hydro
- *Long term investments*. Investments in new transmission systems and new generation capacity are based on long term planning.

Appendix 7: District Heating – a Danish Speciality

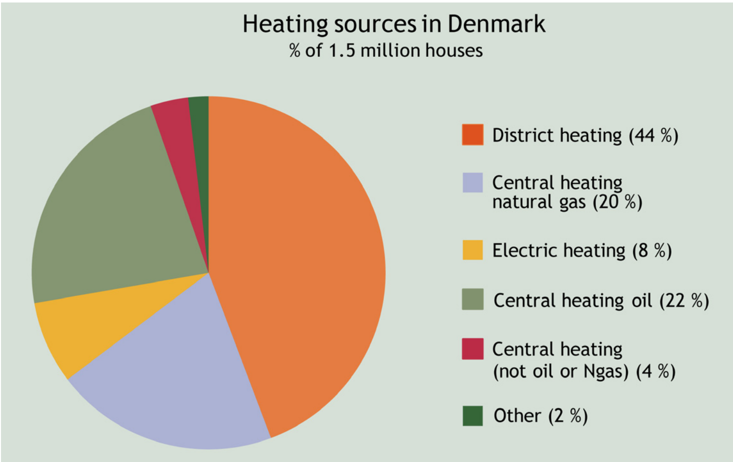
44% of the Danish buildings are heated by district heating, where treated water is heated centrally and circulated in large areas through a couple of pipes with thermal insulation. The pipes are normally buried in the ground to avoid freezing problems. District heating infrastructure is always considered in new build areas. The hot forward temperature is so high that hot water for households can be heated through a simple heat exchanger. When the heat is taken out of the water it is returned to the heating plant. The majority of heat for district heating is produced in Combined Heat and Power plants A combined heat and power plant is a plant where heat is produced in combination with electricity. See illustration below of District Heating with CHP.

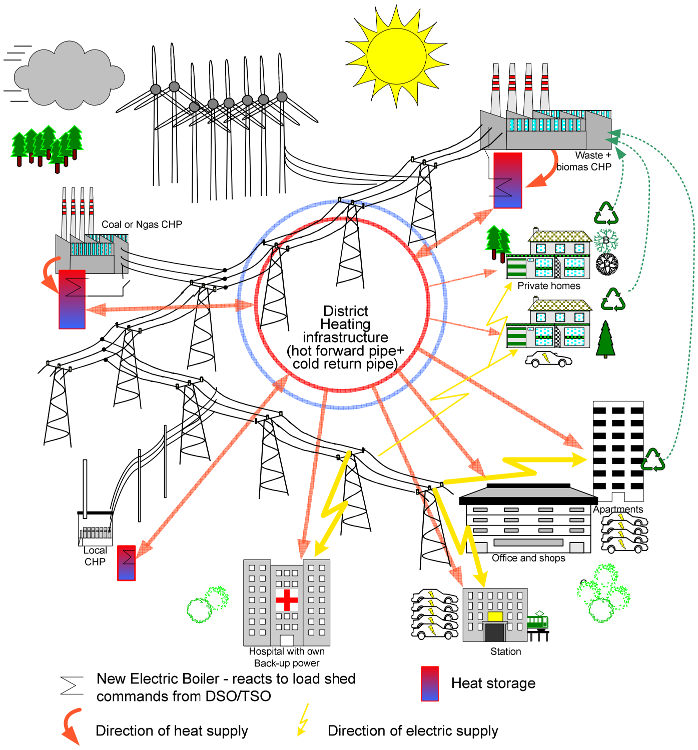
Denmark's major cities have city-wide district heating schemes where most of the heat is produced in large CHP plants fired by coal, natural gas, biomass or waste.

Smaller cities, communities and even small villages typically also have a district heating system powered by a small-scale CHP plant, utilising typically natural gas or biomass and operated with rather high power-to-heat ratio. The size of the CHP plants varies from around a few 100 MWe in larger cities to 0.5-10 MWe in small communities and villages.

The CHP systems combined with a district heating system installed all over Denmark are unique in their design because most district heating systems are equipped with a hot water storage tank to allow efficient production of electricity when there is less heat demand. The heat storage tank is, if filled completely, typically capable of supplying the heat demand in the district heating system without any support of the CHP plant for hours up to more than a day depending on the actual load and weather situation.

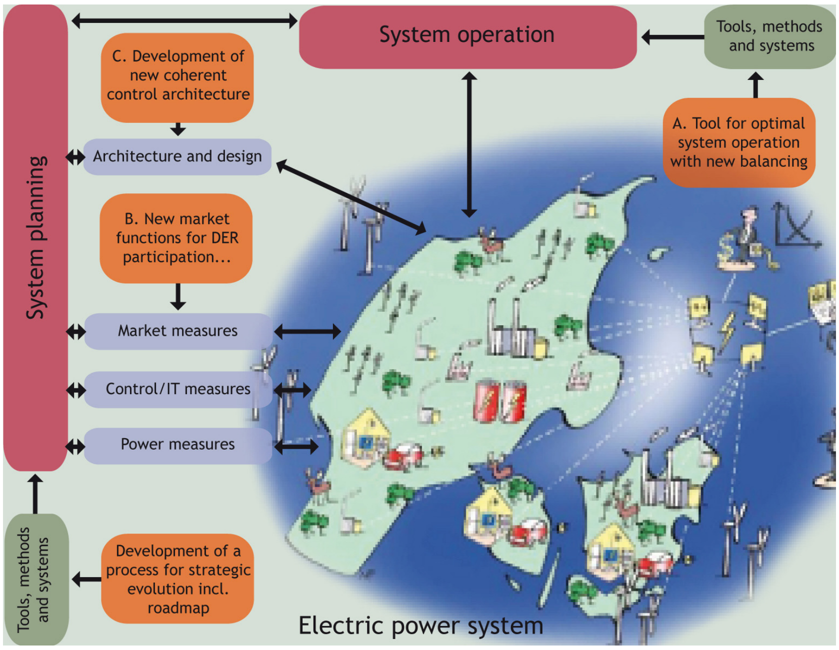
In addition, most CHP systems are also equipped with boilers, which can produce heat without producing electricity for periods with high share of electric energy from wind. Recently legislation has been changed so that it will be allowed to use electricity for heating the district heating water. Use of heat pumps is encouraged but also simple fast reacting electric boilers are allowed. I.e. electricity supplied via the Danish power system can be converted to heat which can be stored and distributed via the already today exiting infrastructure of the district heating systems. Hence, surplus electricity generated by wind power, for example during times with high wind speeds and low loads, can easily be converted to heat and stored in the existing heat storage tanks. Hence, instead of "spilling" in case of over supplied it can be used to replace naturally gas usually used in CHP stations for producing heat and save biomass for periods with less wind. An important additional benefit is the new means of fast up and down regulation of electric load.





llustration of integrated district heating with CHP and heat storage.

Appendix 8: Overview of relations of the suggested EcoGrid phase II activities (WP 5)



Appendix 9: Persons involved in EcoGrid phase 1

Names are organised in random order

DTU CET (Elektro)
Divya K Chandrashekhara
Jørgen Peter Horstmann
Hjörtur Jóhannsson
Arne Hejde Nielsen
Preben Nyeng
Tonny Wederberg Rasmussen
Zhao Xu
Jacob Østergaard
S. You
I. Vlachogiannis
Arhad Saleem
K. Heussen
M. Gordon
R. Garcia-Valle
Y. Chen
M. Lind

DTU IMM
Henrik Madsen
Pierre Pinson
Bjarne Poulsen
Niels Kjølstad Poulsen

Risø DTU
Tom Cronin
Anca Hansen
Stine Grenaa Jensen
Peter Meibom
Per Nørgaard
H. Bindner
Kenneth Karlsson
Poul E. Sørensen

AAU (IET)
Remus Teodorescu
Birgitte Bak-Jensen
Florin Iov
Lasse Rosendahl
Robert Weissbach (guest from Penn State University, USA)

ECON Pöyry
Berit Tennbakk
Klaus Skytte
Kristin Munthe
Anne-Franziska Sinner

Energynautics GmbH
Thomas Ackermann

EA Energianalyse
Mikael Togeby
Jesper Werling
Anders Kofoed-Wiuff

EC Power
Jens Otto Ravn Andersen

Danfoss
Bruno Lund Pedersen
Per Balslev
Thomas Ritz Nissen
Uffe Borup

DONG Energy
Lars Bai Jensen
Tommy Mølbak

Vattenfall
Preben Jørgensen

kk-electronic
Paul Bach Thøgersen

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