Sustainable Reserve Power from Demand Response and Fluctuating Production – Two Danish Demonstrations

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Abstract

The Danish grid is moving from a system based on centralized fossil fueled power plants to a system based on renewable energy where wind is a major energy source. This raises a number of challenges. A main challenge is that the centralized power plants currently are the main providers of reserve power. Alternative sources of flexibility are consequently needed as the conventional power plants are being replaced with fluctuating renewable energy sources. In this paper we present results from two key demonstrations which illustrate that alternative sources of flexibility exist and that this flexibility can be utilized for reserve power. In the first demonstration, a portfolio of inhabited households heated with heat pumps are remotely monitored and controlled such that the aggregate consumption follows a power reference. This experiment is conducted over a full week where an hourly power reference is tracked while the comfort of the inhabitants is ensured. In the second demonstration, an operational wind power plant is regulated to provide a system-stabilizing response. This experiment is conduced over a two-hour period where the wind power plant follows a 5-minute power reference. Together, the two demonstrations illustrate that both consumption and fluctuating production can contribute as sources of reserve power and a sustainable alternative to conventional fossil fueled power plants in the future grid.

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1. Introduction

The Danish electrical system is currently undergoing a major transition. On the production side, distributed renewable energy sources such as wind, solar, and decentralized bio-power plants increase in numbers. Further, the conventional baseload fossil fueled power plants are being replaced with bio power plants which will only operate during peak hours where the electricity prices are high enough to cover the costs of expensive bio-fuels. Changes are also happening on the consumption side: heat pumps are currently an attractive alternative to oil-fired burners and electric cars are becoming a competitive alternative to combustion engine vehicles.

These massive changes are challenging for the stability of the power system. Traditionally, the centralized fossil-fueled power plants have been the main providers of reserve power. As these devices are being replaced with bio-fueled power plants that only operate during peak-hours, alternative sources of reserve power are needed. This is amplified even further because the new fluctuating and non-dispatchable production assets such as wind and solar make the system less predictable resulting in an increased need for reserve power.

Consequently, a strategy is needed for meeting these needs of increased system stabilizing services in a power system where the conventional reserve power providers are phased out. This is the topic of this paper.

This paper is structured as follows. First, in Sec. 2 we describe the transition of the Danish electricity system from the 1980s to today and the expected development the coming years. Following, in Sec. 3 we continue by looking at how the coming transition of the Danish grid will raise a need for alternative sources of reserve power. Finally in Sec. 4 we present a model where flexible consumption and fluctuating production are part of the solution of getting flexibility in the future grid. In Sec. 5 the paper is concluded and in Sec. 6 perspectives are drawn.

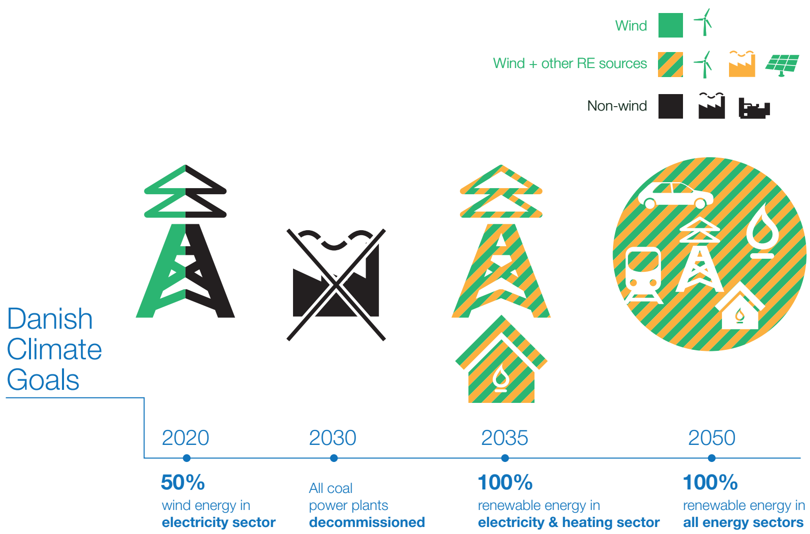

Figure 1: The Danish climate goals towards 2050.

2. Transition of the Danish electrical system towards 100 % renewables

Denmark made a world-record when more than 60 % of the electrical consumption in the entire month was covered by wind in January 2014; yet another record was made the entire year of 2014 when 39.1 % of the Danish electricity consumption was covered by wind [1]. Looking forward, Denmark has a number of very ambitions goals for renewables. These are presented in Fig. 1 and described in the following. The first goal is that 50 % of the electricity consumption should be covered by wind in 2020. In 2030 all coal power plants must be phased out, and in 2035 the electricity and heating sectors must be based on 100 % renewable energy. Finally, in 2050, all energy sectors including the gas and transport sectors must be supplied solely by renewable energy sources [2].

2.1. Power plants shut down

As the share of renewables increases, the wholesale prices for electricity will drop because renewables have zero marginal cost. This causes very difficult conditions for the conventional power plants because the electricity

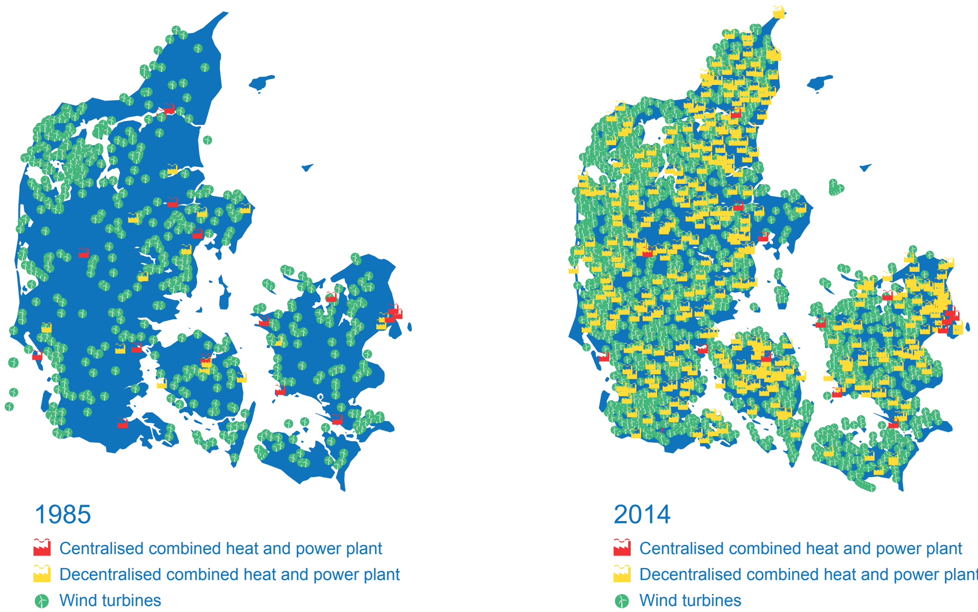

Figure 2: Transition of the Danish electrical system from a primarily centralized system based on conventional production in 1985 to a distributed system based on renewable generation. Figure based on data from the Danish Energy Agency [5].

prices often will be too low to cover costs of keeping coal power plants in operation. Consequently, the renewables will push the conventional power plants out as they are not able to make sufficient revenue to stay in operation according to the plan shown in Fig. 1.

2.2. Decentralization

Another consequence of the transition of the Danish electricity system is that the power system is moving from a system based on fewer centralized conventional power plants to a system driven by a large number of distributed smaller production units [3]. Already today, Denmark has moved from a situation with only 16 central power plants in 1985, to a system which today consists of 16 central power plants, more than 600 local combined heat and power plants and around $5,000$ wind turbines [4]. This transformation is illustrated in Fig. 2.

2.3. Electrification in transport and heating sector

Wind energy is the main sustainable source of renewable energy in Denmark. As all energy sectors must become 100 % renewable by 2050, electrification of the heating and transport sectors are important steps [2]. This electrification has already begun: in recent years, around 50,000 heat pumps have been installed in Danish homes [6] and 5,000 have been installed in the industrial and commercial sector. Additionally 87,000 heat pumps are expected before 2035 [7]. Similarly, electrification of the transport sector is planned: the Danish Department of Transport decided in 2012 on electrification of the railroad in Denmark [8] and a report from 2013 by the Danish Energy Association projects that electrical vehicles will become an attractive alternative to combustion engine vehicles in the following decades leading to an electric vehicle population of 47,000 in 2020 and 221,000 in 2030 [9]. Interestingly, many of these newly introduced electricity consumers are *flexible electricity consumers*, meaning that although these consumers indeed require a certain amount of electricity, they possess some flexibility in exactly when the electricity is required. As an example, some inhabitants in households heated with a heat pump may not experience discomfort if the indoor temperature varies a few degrees. Consequently there will be some flexibility in the operation of the heat pump.

In conclusion, the Danish electrical grid is moving towards a system with a large number of flexible electrical consumption devices on the consumption side and a large number of distributed generators on the production side while the large conventional fossil fueled power plants are being pushed out.

3. Alternative sources of reserve power needed

The ongoing transition from centralized conventional power plants to non-dispatchable distributed renewable generation causes a number of difficulties. A major difficulty is that the system is harder to balance because renewable energy sources by nature have stochastic properties. Already today the effect of having 39 % wind in the system can be seen in the electricity market. In Fig. 3 and Fig. 4 we examine two examples of this.

Usually, the spot price is in the order of 30 Euros/MWh. However on the 7th of June 2013, the price cleared at a value of 2,000 Euros/MWh for a number of hours, see Fig. 3. This happened because of very low wind (around 10 % of the installed capacity) at the same time as there was very limited free capacity on the interconnections. These extreme spot prices represent a system where even the most expensive production units must be activated and thus a system close to its limits. The opposite situation occurred during Christmas in 2013 where a very windy day happened on a day with high CHP

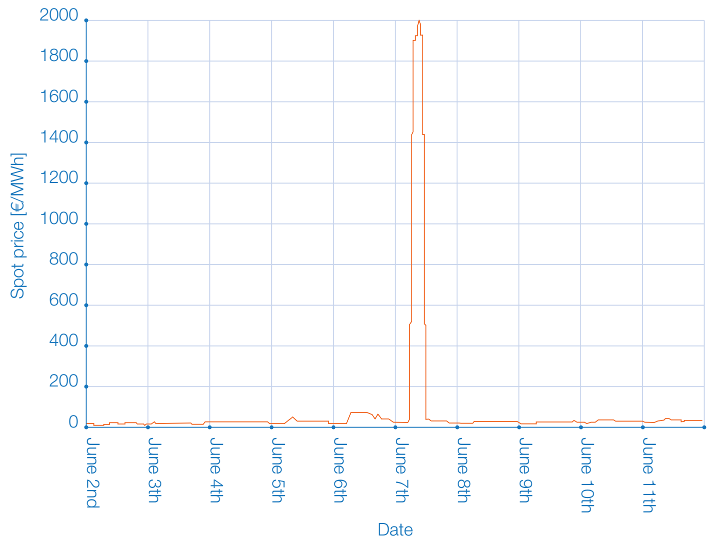

Figure 3: Extreme spot prices due to very low wind generation and little capacity on interconnections.

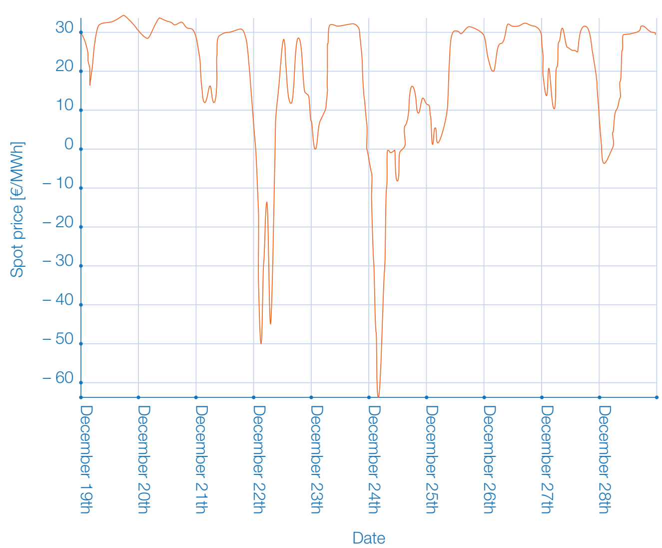

Figure 4: Negative spot prices due to high wind and CHP production and low consumption.

production obligation due to cold weather; further, the electrical consumption was low because of the Christmas holiday. This resulted in negative spot prices as seen in Fig. 4. These instances are indicators of the decreasing amount of conventional flexibility caused by the growth in non-dispatchable renewable energy sources. As a pioneer in utilizing fluctuating renewables such as wind power, Denmark as well as Germany are among the first places to experience these challenges; however, the rest of Europe can expect similar issues in the coming years [10]. It is therefore crucial to examine how flexibility can be mobilized to keep these types of situations from escalating such that it is possible to keep increasing renewables without jeopardizing system stability.

Another issue with non-dispatchable renewables is that they are characterized by highly fluctuating and stochastic power generation and therefore suddenly can increase or decrease production depending on weather conditions. A recent example of this phenomenon took place Denmark on October 28, 2013 where a large number of wind turbines autonomously shut down because of too high wind speeds. This caused a drop from a situation where more than 100 % of the Danish electricity consumption was covered by wind to a situation where this number was less than 45 %. This happened in just 2 hours [11], see Fig. 5. Such rapid production changes can imply severe consequences for grid stability due to the difficulty of accurately predicting the timing of the events [12].

Today, the main providers of reserve power are the fossil fueled centralized power plants which are currently being phased out. The challenge is further increased by the fact that the conventional fossil fuel power plants are synchronous with the grid and therefore provide rotating inertia that supports the system frequency against changes [13]. As renewable energy sources typically interface with the grid via power electronics, they do not directly provide inertia to the grid as the conventional synchronous generators do [14], which further increases the balancing challenges. Although studies show that artificial inertia can be provided by regulating the active power output of the generator according to the system frequency [15, 16], this type of control is generally not implemented in the wind power plants of today.

It is therefore evident that alternative sources of reserve power must be established as renewables replace conventional generation. One approach to obtain reserve power is to purchase reserves in neighboring countries; however, this requires that transmission line capacity is reserved at all times

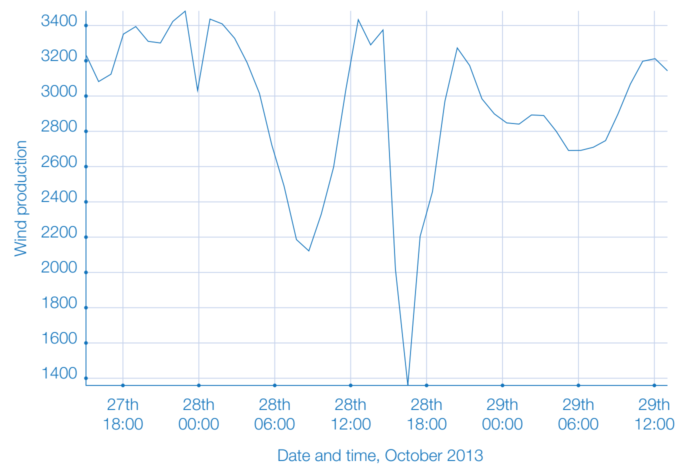

Figure 5: Wind production during 4 days in Denmark in end October, 2013. A storm hits Denmark in the afternoon on the 29th causing a large number of wind turbines to shut down resulting in a production drop of more than $2,000$ MW in just 2 hours.

for the reserve markets which will limit the capacity in the day-ahead spot markets and thereby possibly cause higher electricity prices. Further, the European network of transmission system operators for electricity (ENTSO-E) grid code sets limits on the amount of reserves it is allowed to exchange internationally [17]. Finally, the Danish neighbor Germany is also increasing the wind capacity. Consequently, it may be difficult to purchase reserve power in Germany as they by then possibly will have similar issues as they often will experience similar weather conditions as Denmark.

4. Reserve Power via Flexibile Consumption and Fluctuating Production

Another approach to obtaining alternative sources of reserve power when the centralized power plants are phased out is a concept where flexible consumption and distributed production is utilized [18, 19]. The basic idea is to let an aggregator control a portfolio of flexible devices such as thermal devices, batteries, pumping systems etc. Hereby, the aggregator can utilize the accumulated flexibility by participating in the electricity markets for primary, secondary, and tertiary reserves, on equal terms with conventional generators [20, 21]. This concept is illustrated in Fig. 6 where an aggregator accesses flexibility from some consumers and distributed production, aggre-

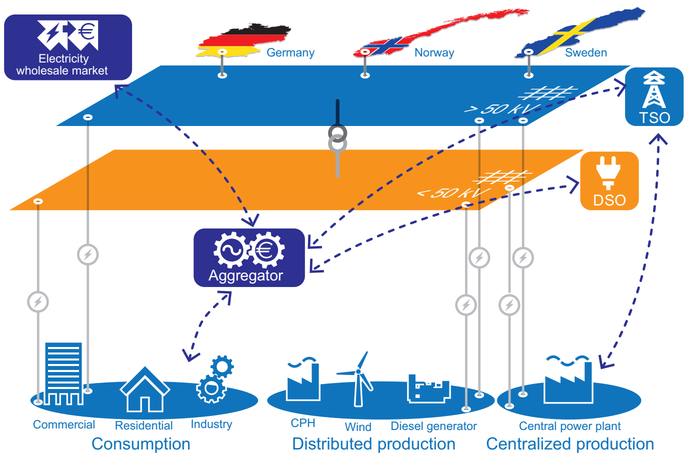

Figure 6: Aggregator collecting flexibility from consumption assets and distributed production to provide flexibility services to the TSO and DSOs

gates this flexibility and utilizes it to provide system stabilizing services to the transmission system operator or possibly to the distribution companies.

The concept of obtaining alternative sources of reserve power is not new. Already in the 1980s the concept of controlling load was discussed [22]. Since, the topic of aggregation and control of distributed flexibility has received much attention from researchers and many different approaches and solutions have been presented. In general there are two major classes describing aggregation of flexibility, namely *direct control* and *indirect control*. Direct control refers to the situation where the distributed devices are directly controlled through two-way communication links. Indirect control refers to a setup where the devices are controlled indirectly by a signal broadcast by a virtual power plant (VPP) or an aggregator [23]. The signal could for example be an electricity price signal, an electricity price forecast signal, or other types of incentive signals.

The concept of demand-response via prices are known from several larger projects. An example is the Dutch PowerMatching concept, which is an agent based method for demand response which was demonstrated on 25 households [24]. Another example is the Danish EcoGrid EU demonstration, where demand response from a large number of customers was obtained via price mechanisms [25]. Two other examples are the Olympic Peninsula Project [26] and the AEP Ohio gridSMART Demonstration Project [27] where the ability to affect consumer behavior through real time prices was demonstrated.

Examples on direct control includes [28, 29, 30, 31] which describe control of thermostatically controllable loads such as air conditioning systems. Other works show how demand can be used to deliver a very fast system stabilizing response, as fast as primary frequency control [32].

This paper deals with how the direct control approach can be utilized to provide reserve power. The results from two real-life demonstrations are presented: One example from the consumption side and one from the distributed production side.

4.1. Global perspective

Although this paper focuses on challenges in the Danish electrical grid, the work has global perspectives: The renewable energy sector is the fastest growing power generation sector worldwide and is expected to keep growing over the coming years [33, 34]. Further, many actions are taken all over the world to increase the penetration of renewables even further: in the US, almost all states have renewable portfolio standards or goals that ensure a certain percentage of renewables [35]. Similarly, the commission of the European Community has set a target of 20 % renewables by 2020 [36], while China has doubled its wind power production every year since 2004 [37]. It is therefore likely that many countries will face problems similar to the ones Denmark currently is experiencing making this study relevant worldwide.

Furthermore, the smart grid model presented in this work is exactly in line with the general IEEE visions for the smart electrical grid which are to utilize information and communication technology (ICT) as a means to ensure a stable, reliable, and sustainable electricity system [38, 39].

4.2. Activation of flexible consumption

In the following, we describe the first of the two demonstrations, namely control of flexible consumption. More details on this demonstration are found in [40].

4.2.1. Demonstration goal

The purpose of this demonstration was to demonstrate how flexible consumers can be aggregated and controlled to provide a response similar to that of a conventional power plant just based on consumption. At the same time, the owner of the consumption device must not experience any discomfort by having their device being used to provide a service.

4.2.2. Demonstration setup

The platform for this demonstration was a portfolio of inhabited households with heat pumps. As previously mentioned, there are currently around 50,000 residential and 5,000 industrial heat pumps approximately corresponding to a capacity of 150 MW. In Denmark, the total need for primary and secondary reserve is in the order of ±80 and ±90 MW, respectively [41]. This illustrates that heat pumps could have a potential as provider of reserve power.

Fifty-four houses with heat pumps were available for the demonstration. The houses were all real life inhabited houses in different locations in Denmark. The houses also varied in size from smaller houses with a total area of 100 m^2 to larger houses with an area of 400 m^2; further, some where old houses built in the 1850s while other houses were newly built.

Also the heat pumps were different with more than 50 different models and types present in the platform. Moreover, the heating systems were also different: all the houses had a heat pump but some of the houses used underfloor heating while others had radiators. Additionally, some of the houses were equipped with other heating sources than the heat pump, for example a wood stove or solar heating. *Consequently, the experiment dealt with a realistic real life heterogeneous household portfolio representative of typical Danish households.*

The households included in this platform all had the heat pumps installed before being a part of the demonstration. The communication- and sensor equipment was therefore subsequently installed as shown in Fig. 7. These sensors included a power measurement of the heat pump, a single indoor thermometer, and various flow meters.

The heat pumps were equipped with a relay so they could be switched between ON and OFF. In the ON-mode, the heat pump acted according to the local embedded control strategy that assured the desired indoor temperature, sufficient hot water, etc. In other words: the ON-mode allowed the heat pump to operate, but it did not force the heat pump to start. On the contrary, the OFF-mode did *force* the heat pump to shut down.

The sensor data and the ON/OFF control commands were transmitted over an Internet connection to a server via a Linux-in-a-Box system (the box seen in the top on Fig. 7). The sampling time of the communication link between heat pump and the server was 5 minutes.

Finally, a control strategy was implemented that regulated the total con-

Figure 7: One of the 54 domestic heat pumps subsequently installed with sensors and actuator that can be accessed over an Internet connection.

sumption to follow a power reference while taking local consumer constraints into considerations. Details on this controller can be found in [40].

4.2.3. Demonstration results

As described, the goal of this demonstration was to follow a power reference. Figure 8 shows this reference (red) over a seven day period. Each night at midnight, an hourly reference was provided for the following 24 hours. The overall controller then regulated the consumption during the day to track this reference.

Fig. 8 shows the results, namely that the heat pumps were able to roughly follow the reference. Further, Fig. 9 shows a closeup of a single heat pump for one day during the demonstration period. The top subplot shows how the aggregator ON/OFF signal respectively allows the heat pump to operate according to the local control law and forces the heat pump off. The second subplot shows that the house was kept within the comfort limits except for a short period. Finally, the lower subplot shows the accumulated hot water consumption during OFF-periods which the controller keeps low to ensure sufficient hot water for the inhabitants. This is simply accomplished by forcing the heat pump ON if more than 30 L of hot water is consumed. These two lower subplots hereby illustrate the very important element that

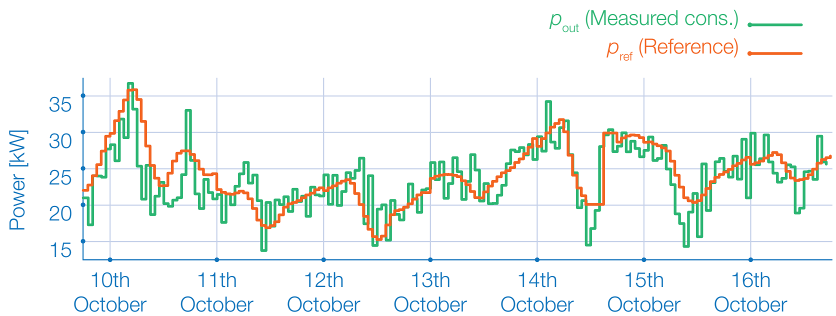

Figure 8: Aggregated consumption of portfolio of heat pumps to follow a power reference during a week in October, 2013.

the local consumer constraints were honored such that the inhabitants did not experience any discomfort.

This demonstration illustrates the first element in the smart grid vision: that load can be aggregated to follow a power reference similar to the way a power plant would do. Furthermore, this can be done while honoring the constraints of the device owner.

Notice that the correlation between power, temperature, and hot water usage in Fig. 9 is heavily influenced by disturbances. This was a phenomenon general to most households, that the indoor temperature was driven more by disturbances than the known parameters such as the power consumption of the heat pump, the water usage, the outdoor temperature, etc.

4.3. Activation of fluctuating production

In the following, we describe the second demonstration, namely control of fluctuating production. More details on this demonstration are found in [42] and [43].

4.3.1. Demonstration goal

The purpose of this demonstration was to show that fluctuating production also can be part of the solution by providing reserve power. The end goal was therefore to demonstrate that fluctuating production also can be managed to follow a power reference similarly to how a conventional power plant would do it.

4.3.2. Demonstration setup

The basis of this demonstration was four newer wind turbines with a total wind power plant capacity of 12.3 MW. The wind turbine configuration

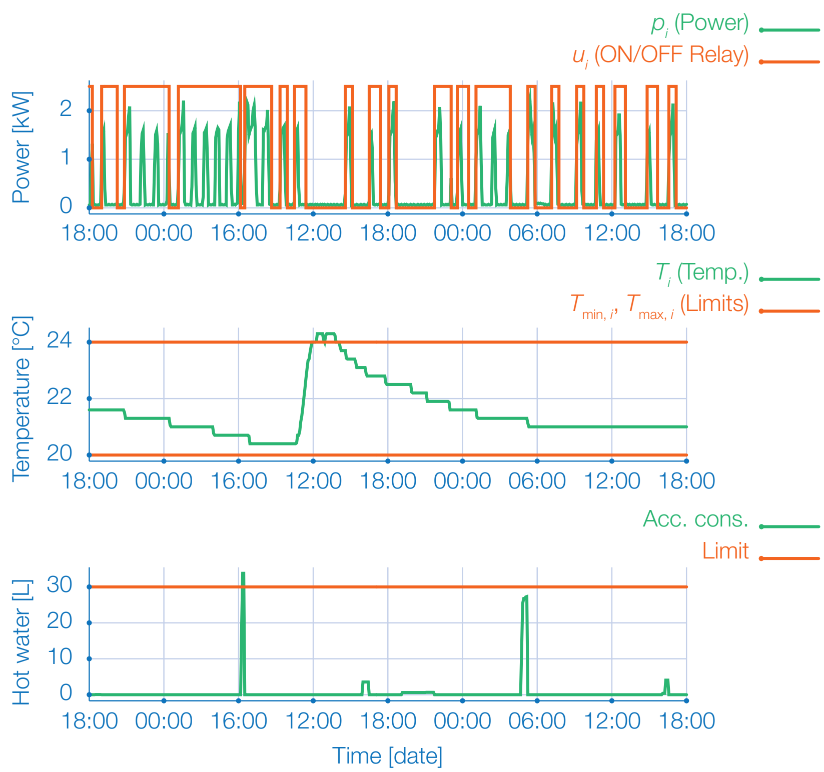

Figure 9: Close-up on single household being turned ON and OFF by aggregator to follow the aggregate reference while honoring local constraints. The indoor temperature is driven by the heat pump but also by events such as opening/closing of doors, additional heat sources, etc.

allowed power setpoint updates every 5 minutes which was used to control the wind turbines to track a power reference. Further, a wind forecasting tool for the wind power plant predicted the possible production.

The demonstration was carried out as follows. First, a forecast production plan was made for the following two hours. The forecast was a point-forecast of the maximum power the wind power plant would be able to produce during the forecast horizon. Following, a baseload was defined as the forecast production plan minus a certain delta. This allowed the wind power plant to provide upward and downward regulation within the delta kept as reserve.

4.3.3. Demonstration results

Figure Fig. 10 shows the demonstration results. The green line represents the forecast power production, the orange line the baseload, the purple line the power setpoint, the black dashed line the realized power production, and the blue line the power that the wind power plant could have produced (only known after the experiment based on measurements).

The forecast shows that the wind farm was expected to be able to produce 11 MW during the first and then 8.5 MW during the second hour. Based on this, the baseload was reduced to a value 2 MW lower than this forecast. This delta of 2 MW allowed the wind power plant to deliver 2 MW of symmetric reserve as the wind power plant could both up-regulate and down-regulate from the baseline within the delta.

The demonstration was carried out by giving the wind power plant a sinusoidal power reference discretized to match a 5 minute sampling time.

Based on this demonstration, it is evident that the wind power plant was able to track the reference with high accuracy by pitching the blades of the turbines into the wind and out of the wind. The local wind power plant controllers could handle this with high precision and fast enough to follow the 5 minute reference. The graph of the measurements from the demonstration (black dashed line in Fig. 10) proves the hypothesis that wind power plants indeed are usable as providers of stabilizing services.

It is, however, important to notice the actual available power in Fig. 10. A first important point is that the area between this curve and the WPP power curve corresponds to "spilled" energy. This spilled energy is a direct cost of delivering this service and clearly illustrates that wind power should only be used for upward reserve when the electricity prices are very low or where the revenue in reserve markets is very high. For example in situations where the available renewable power is higher than the electricity demand,

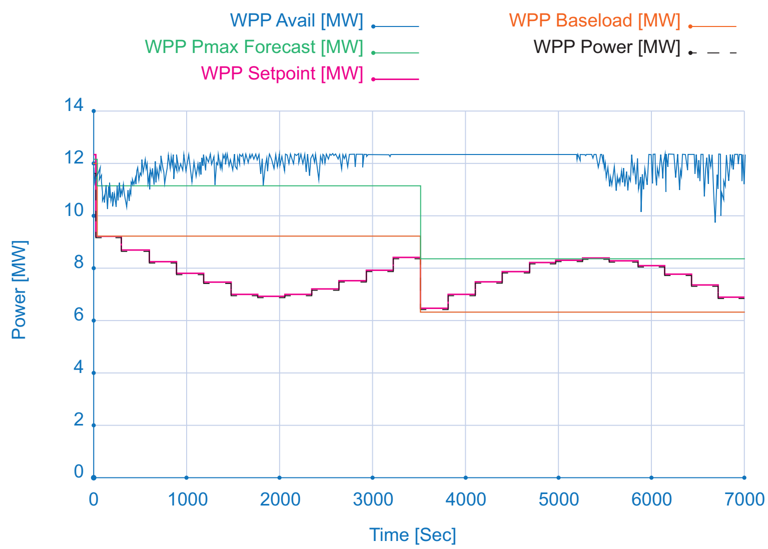

Figure 10: Wind power plant (WPP) being controlled to follow a 5-minute power reference.

it may be beneficial to ramp down power plants and use them for upwards reserve. Further, wind parks can always function as reserve just for downward regulation such that energy is only spilled in the case of activation. For both upward and downward regulation, the wind power plants can design their reserve bids according to the opportunity costs associated with the reserve product in question. Hereby the market will ensure that wind is only used as reserve power when it is indeed the cheapest solution.

Second, notice that the available power in fact is lower than the forecast production plan in the beginning of the demonstration. In this situation, the wind power plant would not have been able to deliver 2 MW of upward regulation in the first couple of minutes. This illustrates that the nature of wind energy makes this a provider of reserve power that is not 100 % reliable. This should somehow be handled, for example by making a separate market for these providers or by requiring that such providers must have a form of backup.

5. Conclusion

In this paper we presented demonstrations of two important methods for supporting an electrical grid based on large shares of fluctuating renewable energy. The first demonstration dealt with electric heat pumps in inhabited houses and demonstrated that a large portfolio of flexible consumers could be managed to provide stabilizing services. The second dealt with a wind power plant and demonstrated that fluctuating production assets were able to provide a system stabilizing response.

We can therefore conclude that both consumption and fluctuating production assets are promising sources of sustainable flexibility and therefore potential providers of reserve power in the future Danish electrical grid.

6. Perspectives

Utilizing flexibility from the demand-side and from fluctuating production is currently in the process of moving from pure research and demonstrations to actual implementation. Already today, wind turbines can participate in the tertiary reserve market in Denmark, and in Germany it is expected that wind will be allowed to participate in 2016 [44]. Also, new special regulations for consumption have made it much easier for the demand-side to participate in the auctions for strategic reserve in the Nordic countries [45, 46].

Currently, a barrier for having demand flexibility and fluctuating production in the reserve markets is the long duration of many of the reserve products. For example, secondary reserve in Denmark is to be delivered on a monthly basis. In Germany, both primary and secondary reserve is on a weekly basis. The stochastic behavior of both fluctuating production and flexible consumption heavily limits the amount of reserve it is possible to sell in markets with such long duration. This barrier is, however, currently being addressed in the German market where the German Federal Ministry for Economic Affairs and Energy recently published a white paper describing how the duration of these markets will be lowered [47]. This trend will help enable the demonstrations described in this paper to be turned into actual implementation.

References

[1] Energinet.dk (Danish TSO), Wind turbines reached record level in 2014 (2015).
URL http://energinet.dk/EN/El/Nyheder/Sider/Vindmoeller-slog-rekord-i-2014.aspx

[2] Danish Ministry for Climate, Energy and Buildings (Klima,- energi - og bygningsministeriet), Smart Grid Strategy - The intelligent energy system of the future, Report (April 2013).

[3] H. Hansen, L. Hansen, H. Jóhannsson, H.-H. Holm-Hansen, H. Bindner, P. Cajar, O. Samuelsson, Coordination of system needs and provision of services, in: Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on, 2013, pp. 1–4. doi:10.1049/cp.2013.0640.

[4] Z. Xu, M. Gordon, M. Lind, J. Østergaard, Towards a danish power system with 50General Meeting, 2009. PES '09. IEEE, 2009, pp. 1–8. doi:10.1109/PES.2009.5275558.

[5] Danish Energy Agency, Wind turbine master data, Website (2014). URL http://www.ens.dk/sites/ens.dk/files/byggeri/anlaegprodtilnettet.xls

[6] Danish Energy Agency, Heat pump statistics, Website (2014). URL http://www.ens.dk/undergrund-forsyning/vedvarende-energi/varmepumper

[7] Danish Energy Association, Energinet.dk and DONG Energy, Heat pumps in denmark (only available in danish: Varmepumper i danmark), report (2013).

[8] Department of Transport, Electrification of the railroad (only available in Danish: Elektrificering af jernbanen mv.) (2012).

[9] Danish Energy Association, Energinet.dk, DONG Energy , Scenarios for electrical vehicle roll-out in Denmark (only available in Danish: Scenarier for udrulning af elbiler i Danmark), Report (March 2013).

[10] K. Hedegaard, B. V. Mathiesen, H. Lund, P. Heiselberg, Wind power integration using individual heat pumps – analysis of different heat storage options, Energy 47 (1) (2012) 284 – 293.

[11] Energinet.dk, Download of market data, Webpage, www.energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/ (August 2013).

[12] A. Chuang, C. Schwaegerl, Ancillary services for renewable integration, in: Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium, 2009, pp. 1–1.

[13] P. Kundur, Power System Stability and Control, McGraw-Hill, Inc., 1994.

[14] G. Joos, B. Ooi, D. McGillis, F. Galiana, R. Marceau, The potential of distributed generation to provide ancillary services, in: Power Engineering Society Summer Meeting, 2000. IEEE, Vol. 3, 2000, pp. 1762 –1767 vol. 3.

[15] C. L. DeMarco, C. A. Baone, Y. Han, B. Lesieutre, Primary and secondary control for high penetration renewables, PSERC Publication 12-06.
URL `http://pserc.wisc.edu/documents/publications/papers/fgwhitepapers/DeMarco_PSERC_Future_Grid_White_Paper_Control_March_2012.pdf`

[16] N. Miller, K. Clark, M. Shao, Frequency responsive wind plant controls: Impacts on grid performance, in: Power and Energy Society General Meeting, 2011 IEEE, 2011, pp. 1 –8.

[17] ENTSO-E, Network code on load-frequency control and reserves, Report (June 2013).

[18] D. Callaway, I. Hiskens, Achieving controllability of electric loads, Proceedings of the IEEE 99 (1) (2011) 184–199. doi:10.1109/JPROC.2010.2081652.

[19] K. Moslehi, R. Kumar, A reliability perspective of the smart grid, IEEE Transactions on Smart Grid 1 (1) (2010) 57–64.

[20] Energinet.dk and Danish Energy Association, Smart grid in Denmark 2.0, Report (2012).

[21] B. Biegel, P. Andersen, J. Stoustrup, L. Hansen, D. Tackie, Information modeling for direct control of distributed energy resources, in: American Control Conference (ACC), 2013, 2013, pp. 3498–3504. doi:10.1109/ACC.2013.6580372.

[22] F. Schweppe, R. Tabors, J. Kirtley, H. Outhred, F. Pickel, A. Cox, Homeostatic utility control, Power Apparatus and Systems, IEEE Transactions on PAS-99 (3) (1980) 1151 –1163.

[23] K. Heussen, S. You, B. Biegel, L. Hansen, K. Andersen, Indirect control for demand side management - a conceptual introduction, in: Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on, 2012, pp. 1–8.

[24] F. Bliek, A. van den Noort, B. Roossien, R. Kamphuis, J. de Wit, J. van der Velde, M. Eijgelaar, Powermatching city, a living lab smart grid demonstration, in: Innovative Smart Grid Technologies Conference Europe, 2010 IEEE PES, 2010, pp. 1–8.

[25] J. Jørgensen, S. Sørensen, K. Behnke, P. Eriksen, Ecogrid eu #x2014; a prototype for european smart grids, in: Power and Energy Society General Meeting, 2011 IEEE, 2011, pp. 1–7.

[26] D. J. Hammerstrom, Pacific northwest gridwise testbed demonstration projects – part i: Olympic peninsula project, Tech. rep., Pacific Northwest National Laboratory (2007).

[27] S. Widergren, A. Somani, K. Subbarao, C. Marinovici, J. Fuller, J. Hammerstrom, D. Chassin, AEP Ohio gridSMART demonstration project real-time pricing demonstration analysis, Tech. rep., Pasific Northwest National Laboratory (2014).

[28] H. Hao, B. Sanandaji, K. Poolla, T. Vincent, Frequency regulation from flexible loads: Potential, economics, and implementation, in: American Control Conference, Portland, USA, 2014, pp. 65–72.

[29] D. S. Callaway, Tapping the energy storage potential in electric loads to deliver load following and regulation, with application to wind energy, Energy Conversion and Management 50 (5) (2009) 1389 – 1400.

[30] N. Lu, M. Vanouni, Passive energy storage using distributed electric loads with thermal storage, Journal of Modern Power Systems and Clean Energy 1 (3) (2013) 264–274. doi:10.1007/s40565-013-0033-z.
URL `http://dx.doi.org/10.1007/s40565-013-0033-z`

[31] T. S. Pedersen, P. Andersen, K. Nielsen, H. L. Stærmose, P. D. Pedersen, Using heat pump energy storages in the power grid, in: IEEE Multi-Conference on Systems and Control, Denver, CO, USA, Denver, CO, 2011, pp. 1106–1111.

[32] J. Short, D. Infield, L. Freris, Stabilization of grid frequency through dynamic demand control, Power Systems, IEEE Transactions on 22 (3) (2007) 1284 –1293.

[33] Department of Energy, Energy efficiency and renewable energy, Tech. rep., U.S. Government, Department of Energy, DOE/GO-102008-2567 (2008).

[34] International Energy Agency, Medium-term renewable energy market report 2013 – market trends and projections to 2018, International Energy Association.
URL `http://www.iea.org/textbase/npsum/mtrenew2013sum.pdf`

[35] K. S. Cory, B. G. Swezey, Renewable portfolio standards in the states: Balancing goals and implementation strategies, Tech. rep., National Renewable Energy Laboratory, NREL/TP-670-41409 (2007).

[36] Commission of the European Communities, A european strategy for sustainable, competitive and secure energy, COM(2006) 105 final (2006).

[37] Y. Yan, C. Xia, Z. Song, T. Shi, Assessing the growth and future prospect of wind power in china, in: Electrical and Control Engineering (ICECE), 2010 International Conference on, 2010, pp. 3391 –3395.

[38] T. Wauters, F. De Turck, C. Develder, Ieee visions for smart grid controls: 2030 and beyond, IEEE Visions for Smart Grid Controls: 2030 and Beyond (2013) 1–12.

[39] M. Amin, A. M. Annaswamy, C. L. DeMarco, T. Samad, IEEE vision for smart grid communications: 2030 and beyond, IEEE vision for smart grid communications: 2030 and beyond (2013) 1–1.

[40] B. Biegel, P. Andersen, J. Stoustrup, M. B. Madsen, L. H. Hansen, L. H. Rasmussen, Aggregation and control of flexible consumers – a real life demonstration, in: Proceedings of the 19th IFAC World Congress, Cape Town, South Africs, 2014, pp. 9950–9955.

[41] Energinet.dk, Ancillary services to be delivered in denmark – tender condition, Tech. rep., Energinet.dk (2011).

[42] J. Hansen et al., Providing flexibility with a virtual power plant, deliverable no: 10.3, Tech. rep., DONG Energy (2013).

[43] S. Børresen, Integration and control of wind power, Tech. rep., DONG Energy (2013).

[44] Sebastian Ziegler, Prequalification of renewable energy within balancing and ancillary services, Presentation, 6th Annual European Electricity Ancillary Services and Balancing Forum (2015).

[45] Energinet.dk (Danish TSO), Strategic reserves in Eastern Denmark (2015).
URL http://energitilsynet.dk/fileadmin/Filer/Internationalt/Hoeringer/Strategic_reserves_in_Eastern_Denmark_v_1.pdf

[46] U. Hammarstedt, M. Nilsson, Demand response in the strategic reserve - the case of Sweden, Elforsk Report 2014.

[47] Federal Ministry for Economic Affairs and Energy (BMWi), An electricity market for Germany's energy transition (2015).
URL http://www.bmwi.de/English/Redaktion/Pdf/weissbuch-englisch,property=pdf,bereich=bmwi2012,sprache=en,rwb=true.pdf