Ready project

SUMMARY OF MAIN FINDINGS - WITH A FOCUS ON MARKET ASPECTS AND LOCAL GRID CONSTRAINTS

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Foreword

This report describes and provides findings from the ForskEl-projekt 10757-2012, ”READY- Smart Grid Ready VPP Controller for Heat Pumps”. It starts with a brief state of the art, before highlighting the READY project’s main results. The current document summarises the findings from the more extensive Danish summary report, though with a greater focus on local grid constraints.

READY is a ForskEL project supported by PSO funds administered by Energinet.dk (the Danish transmission system operator). The project team consists of: Neas Energy (project leader), Neogrid Technologies, PlanEnergi, Aalborg University (AAU), Aarhus University (AU), and Ea Energy Analyses. The project has run from June 1st of 2012 until November 1st, 2014.

READY is a continuation of the previous ForskEL 10469-2010 project, "Intelligent Fjernstyring af Individuelle Varmepumper” (Intelligent remote steering of individual heat pumps), which took place from 2010 to 2012. Four of the five partners from the original project also participated in READY, while two new partners have joined the consortium (Ea and AU).

The idea for the project arose already in the spring of 2009, at which time there were only a few Smart Grid projects underway. Since then, many new Smart Grid projects have been launched, but the control strategies tested in READY are still at the forefront. This is in part due to the advanced models and control strategies utilised, but also due to the real world testing according to spot and regulating power prices. The habits of these end-users have a significant influence on the potential for forecasting heat demand, and both their comfort requirements, and willingness to allow external control of their heat pump must be taken into consideration.

Throughout the project, it is precisely this end-user comfort that has been a top priority. As such, there has been a great deal of contact with many end-users, whom have been exceptionally understanding. We would like to sincerely thank everyone that participated and made their heat pump available. Our participants have been what we referred to as “very friendly users”. Some users had a particularly keen interest in the project, which resulted in periods with almost daily contact.

We would also like to thank a host of actors whom participated in interviews and/or workshops. In particular, we would like to thank Galten Elværk for their time and input.

During the course of the project, there has been knowledge sharing and exchange with a number of other projects, including iPower, TotalFlex, Intelligent Energistyring (Intelligent energy management) and Branchefællesskab for Intelligent Energi (Danish Intelligent Energy Alliance). In addition, the READY project participated in various knowledge sharing seminars (often organised by Energinet.dk) and other relevant conferences.

In addition to this English summary report, the main findings are also found in the extended Danish summary report, as well as five other reports on specific topics and numerous scientific papers. The READY project has also served as foundation for several university student projects and two Ph.D.'s.

1 Introduction

50% wind in 2020

Denmark has a politically agreed target stating that 50% of electricity consumption in 2020 shall come from wind. In addition, by 2035 the heat and electricity sector is to be fossil free, and by 2050, Denmark should be completely fossil free in all sectors. When integrating such a large share of wind production, it will be useful if a significant portion of electricity consumption is flexible. Individual heat pumps with intelligent control can be an important part of this solution. When oil-fired boilers are replaced with heat pumps, this reduces the use of fossil fuels. In addition, heat pumps have the ability to shift their electricity demand without greatly reducing homeowner comfort.

Importance of intelligent control

Intelligent control is necessary in order for heat pumps to better utilise the fluctuating electricity production from wind power. Hours with significant wind power production generally have low electricity prices (and vice versa). Therefore, if heat pumps can increase their electricity consumption when electricity prices are low, this may help to reduce price variation and to reduce potential wind curtailment situations[1]. In this way, heat pumps can help increase the value of electricity produced from wind. Similarly, a reduction of heat pumps' consumption during expensive hours can lower the overall cost of generating electricity, as expensive 'peak load' units may not be required.

For the end-users, intelligent control of their heat pumps can reduce the costs of heating. For the retailers of electricity, an offer of intelligent control can be a way to attract and maintain customers.

End user comfort is paramount

The heat pumps in the READY project are managed according to different principles. The most important aspect of the project was that end-user comfort should not be compromised, at least not beyond a point that had been agreed. I.e., a heat pump normally maintains a constant temperature in a house by following an internal control dictated by the heat pump. Within the READY project, if the heat pump is to be controlled in a manner that deviates from this internal control, it is necessary that this deviation results in a temperature that falls within an acceptable range.

[1] Wind curtailment in this context refers to situations where wind turbines must be shut down in order to avoid the overloading of the grid or because of negative prices in the market.

Control according to spot prices

Within the READY project, there are two main objectives regarding the control of heat pumps in relation to the electricity system. Firstly, electricity consumption should be placed according to the electricity spot price. Prices in the day-ahead spot market are an indication of how electricity supply and demand relate to one another during each hour. High demand and low wind power production will usually yield high prices (and vice versa).

Control according to regulating power prices

Secondly, heat pumps can assist in maintaining the system balance during the operational hour by delivering regulating power. Hourly spot prices that result in a balance between electricity supply and demand are determined at 12 o'clock the day before the operational day. However, a number of conditions can change from this time until the operational hour. In order to maintain the balance during the operational hour, the transmission system operator (TSO) has a number of tools at its disposal, including the regulating power market. Here, electricity producers and consumers can offer to increase or decrease their production or consumption of electricity with 15 minutes' notice. Price variation in the regulating power market is larger than in the day-ahead market, which makes it attractive for demand side participation. The rules for regulating power must be developed to make it possible for small heat pumps to participate. E.g. ex post verification of activation must be accepted.

Direct or indirect control

Generally speaking, there are two ways for end-users to participate in demand response. The first is via indirect control, where a price signal is sent to end-users, and the end-users adjust their demand to this price signal, either manually, or more typically, via automation installed in the home. The second strategy involves direct control, where end-users grant control over selected electrical devices to a centralised actor, an aggregator, for example a balance responsible party, a trading company, or an independent aggregator. In the case of heat pumps, the aggregator guarantees that the temperature in the house may not vary more than agreed. This direct control can result in a more advanced control of electricity consumption, e.g. in relation to regulating power.

Direct control via VPP

Within the READY project, the primary focus has been to develop and demonstrate an advanced direct control solution, a so-called virtual power plant (VPP) controller, for use in the remote control of individual heat pumps. The heat pumps are controlled remotely according to spot prices and the need for regulating power, in order to demonstrate the greatest potential savings for the heat pump owners, all while maintaining the desired comfort level.

The heat pumps within the project receive a signal as to whether there is currently a need for up or down regulation in the regulating power market, and the flexibility present in the heat pump is activated. It should be noted that control of the heat pumps in accordance with the regulating power signal first started late in the final phases of the project, and it was therefore not possible to test this during an entire heating season.

Direct control was demonstrated on roughly 80 houses in Denmark with regular 'real' families. The houses are from a pool of roughly 300 houses that had a so-called 'control box' installed, which collects a variety of data related to the heat pump's operation, and through which the heat pump can be accessed.

Management of control boxes

The control boxes and the associated communication server has comprised the IT platform upon which the READY control system is built on. The control units were installed during 2010-2011 through a project entitled StyrDinVarmepumpe (Control your heat pump), which was led by Energinet.dk. The StyrDinVarmepumpe project has since been taken over by the cooperative "Intelligent Energistyring" (Intelligent energy management). ForskEl has recently pledged to extend the project, thereby ensuring that this platform will be maintained going forward. When the READY project is finished, the heat pumps that were controlled within the project, will in the future be part of the ForskEL project TotalFlex.

Extensive amounts of valuable heat pump data

The control units in StyrDinVarmepumpe have given access to an extensive amount of unique measurement data. One of the objectives of READY has been to test the control of a large pool of heat pumps, and the project has managed to control up to 80 heat pumps at a time. In addition, the plentiful data provided a good overview of the challenges and capabilities associated with different heat pump manufacturers. This extensive data has also provided valuable input to the standardisation work, which was part of the overall project.

Additional project aspects not discussed in detail within current report

As mentioned in the foreword, in addition to the aspects covered in the current report, the overall READY project and Danish summary report also include:

- A detailed description of the READY VPP controller, including findings related to its practical implementation.
- Recommendations and communication requirements for future heat pump installations
- Studies regarding end-user involvement and acceptance.

Focus on markets and local grids

The current report places emphasis on markets and local grids, both in terms of congestions, but also potential markets and options for alleviating these congestions.

A list of all the other reports and papers are found in the back of this report.

2 State of the art: Heat pumps & Smart Grid

Throughout Europe there are numerous heat pump projects researching a broad range of relevant issues including:

- Communication to, and control of, heat pumps.
- Potential value generation for end-users, grid companies and utilities.
- Technical capabilities of heat pumps
- End-user engagement and experiences

The following state of the art provides an overview of a handful of other heat pump projects currently underway in Europe today, but given the numerous projects, should by no means be seen as an exhaustive list.

Linear: Belgium

Increased growth in electricity production from intermittent renewables, accompanied with falling traditional generation capacity in Belgium, has led to the establishment of LINEAR (Local Intelligent Networks and Energy Active Regions). Linear is tasked with looking at the potential for demand side management in households, particularly their ability to adapt electricity consumption to solar and wind production.

Some of the key questions LINEAR is meant to address include (Linear, 2014):

- How do households and industry stand to benefit from a change in behaviour?
- How will the costs and benefits be divided among parties involved?
- Which solutions will provide enough motivation and convenience to prompt a change in behaviour?
- To what extent will households be able and willing to change their behaviour?

The project is not solely a heat pump project, but involves 250 households with various controllable loads, including electric water heaters, heat pumps, smart appliances (i.e. washing machines, dishwashers, dryers, etc.), and electric vehicles (EVs). The field test involves automated demand-side management and smart devices to control electric devices in 75% of the households. These devices are controlled according to four different business cases:

- Rate control – variations in electricity prices
- According to wind production
- Minimisation of peak loads on transformers
- According to the voltage level

Early results indicate that it is technically possible to shift demand of electrical appliances. In addition, DSOs have shown that congestions in the distribution grid can be managed through automated demand side control (Delta Energy & Environment, 2014).

Powermatching City: Holland

The PowerMatching City project started in 2007, with the first phase concluding in 2011, and the second phase scheduled to conclude in 2014. The stated goal of the project is to "demonstrate the energy system of the future with smart energy services, as well as the validation of costs and benefits of this system in order to enable the energy transition" (PowerMatching City, 2014).
This overall project goal is to be reached by investigating:

- The potential for demand side resources to assist in system balancing and grid congestion management
- Customer behaviour, including the identification and design of the most effective pricing/market mechanisms for encouraging customer participation

The project involves over 40 households in Hoogkerk, Holland and includes hybrid heat pump systems (a heat pump accompanied with a natural gas boiler), micro CHP systems, EVs, PVs and battery storage.

As was the case with the LINEAR project, the initial phase of the PowerMatching project found that demand side resources can be utilised to address grid congestion. With respect to hybrid heat pumps, the initial phase found that they are a "cost-efficient cornerstone in balancing networks when intermittent renewable energy sources are deployed on a large-scale." While the first phase found very little economic incentive for end-users to adjust their electricity consumption according to the day-ahead prices, the second phase of the project will involve market prices varying each 5-minutes.(PowerMatching City, 2014).

Customer-Led Network Revolution: UK

Similar to the LINEAR project, the driving force for the Customer-Led Network Revolution (CLNR) project is to prepare UK electricity networks for a future dominated by a larger proportion of distributed and renewable electricity generation. In order to plan for this future, the project aims to better understand the impact (on both load and generation) of large-scale adoption of low carbon solutions such as heat pumps, EVs and PVs. In addition, the project is interested in determining the extent of end-user flexibility, and the cost associated with this flexibility. (Thompson, Foster, Lodge, & Miller, 2014).

In addition to EVs, PVs and other smart appliances, there are 450 heat pumps in the customer trials currently underway. In order to establish a baseline, around 400 of these heat pumps do not face any special tariffs. Meanwhile, in order to investigate the impact of variable prices on consumption, roughly 20 heat pumps encounter a three rate tariff designed to avoid the 16:00-20:00 peak. Lastly, roughly another 20 heat pumps will be controlled remotely in order to monitor their ability to peak shave. (Delta Energy & Environment, 2014).

Smart Electric Lyon: France

Coordinated by EDF in the territory of Greater Lyon, the Smart Electric Lyon project was officially launched in November 2012. It is designed to last 4 years and is divided into three phases (Smart Grids - CRE, 2013):

- Design and development of equipment (2013-2014);
- The integration of equipment and small-scale field tests (2013-2014);
- Deployment of tenders and large-scale services (2014-2015).

The project intends to include 400 heat pumps, as well as hybrids, electric heating, hot water and air conditioning. The project aims to investigate consumer behaviour, i.e. how and why consumers react to different offers, investigate and develop new business models, and work with standardisation for communication between heat pumps and smart meters. (Delta Energy & Environment, 2014).

The project intends to bring together 19 industrial partners from various branches (including energy production, home automation equipment, telecommunications, etc.,) French academia, as well as 25,000 households. 90% of these households will receive detailed electricity consumption data along with benchmarking of their data and personalised recommendations on how to save energy. The remaining 10% of houses, as well as 100 tertiary sector buildings, will participate in field tests involving technical solutions (energy management systems, displays, controllable electric heating etc.) coupled with varying tariffs. (Smart Grids - CRE, 2013).

READY project

While there is naturally a degree of overlap in the research focus of the various projects, with its main focus being the development and testing of a VPP solution for a large group of individual heat pumps, the READY seeks to provide novel findings in this specific area, as well as contribute to overall heat pump research and development.

3 Electricity markets, framework conditions and economy

In order to utilise the flexibility of heat pumps to shift electricity demand to desired periods, and to estimate the cost savings potential associated with this flexibility, it is necessary to understand the markets that heat pumps can participate in today, and the markets they can potentially participate in in the future. As such, this chapter investigates the various electricity markets that formed the basis for the control of heat pumps within the READY project, as well as the framework conditions and economic potential associated with various business models.

3.1 Control in relation to spot and regulating power prices

The table below provides an overview of the various electricity markets in West and East Denmark in 2014, and indicates which markets formed the basis for the control of heat pumps in the READY project.

	West Denmark (DK1)	East Denmark (DK2)
Tested in READY	- Spot market (Elspot) - Regulating power* (energy payment)	- Spot market (Elspot) - Regulating power* (energy payment)
Potential markets for heat pumps	- Intraday market (Elbas) - Regulating power* (capacity payment) - Primary reserves	- Intraday market (Elbas) - Regulating power* (capacity payment) - Frequency controlled normal reserve (FNR) - Frequency controlled disturbance reserve (FDR)
Not relevant for heat pumps at this time	Secondary reserves (LFC)	

*Table 1: Overview of the various electricity markets in Demark.*Regulating power, also referred to as a manual or tertiary reserve, offers both a payment for capacity (payment is received regardless of whether or not the bid is activated), and for the amount of energy delivered (thus contingent on the bid being activated). Within the READY project, only the price for the energy payment was tested.*

As highlighted in Table 1, within the READY project the pool of heat pumps were controlled according to hourly spot prices and a regulating power activation signal. These two markets are described below. A more in-depth analysis of the various markets and how a pool of heat pumps can be controlled according to these markets can be found in an annex report entitled ”Intelligent styring af varmepumper i elmarkeder” (Intelligent control of heat pumps in electricity markets).

Elspot

The vast majority of all electricity in the Nordic region is traded on the Elspot day-ahead market. In order to trade on the market, an actor must be a balance responsible party, or have a balance responsible party trade on their behalf. On behalf of electricity producer and consumers, these balance responsible parties submit offers to buy and sell electricity, with all hourly bids submitted before noon the day before the operational day. Offers to sell (i.e. produce) electricity are related to an electricity producer’s marginal production costs, i.e. they reflect the lowest price the producer is willing to accept in order to producing during a specific hour. Renewable electricity producers (such as wind power) have no fuel costs and therefore very low marginal production costs, which helps to reduce the general spot price. Similar to the production side, electricity consumers can also bid in price dependently.

Spot prices for the upcoming day are formed based on the equilibrium between the supply and demand curves during each hour. Prices vary from hour to hour and during the year in relation to a number of factors, such as electricity and heat demand, wind production, transmission capacity on international connections, electricity prices in neighbouring countries, capacity outages, etc. Via intelligent control of heat humps, i.e. moving electricity demand from high price hours to low price hours, these variations in prices can be exploited by utilising the heat storage capacity of both hot water tanks and the thermal capacities found in houses.

Regulating power market

The regulating power market is a common Nordic market, were once again only balance responsible parties can participate. The balance responsible bids from each country are submitted to the respective countries’ TSO, which in the case of Denmark, is Energinet.dk. Both production and consumption units can deliver regulating power, and it is allowed to pool units in order to achieve the minimum capacity, which is currently 10 MW. Each bid must be able to deliver the full effect of their bid within 15 minutes, and must be able to deliver this effect for up to an hour. The market is a marginal price system, in that the most expensive bid activated within an hour dictates the price received by all activated units within that hour.[2]

[2] This differs for example from a ‘pay-as-bid’ system, where each activated bid receives the price they bid in with.

Regulating power can receive payment for simply being available if necessary (a per MW payment, often referred to as a reserve or capacity payment), and/or payment for the amount of electricity supplied if activated (a MWh payment, often referred to as an energy payment). If an actor's bid is accepted in the reserve portion of the regulating power market (i.e. it receives a payment for making X MW available if necessary), then it must submit a bid in the energy portion for the hours in which it received a reserve payment. On the other hand, an actor does not have to have bid in on the reserve portion of the market in order to submit a bid on the energy portion.

Regulating power - Capacity

One of the primary issues of the READY project was the control of heat pumps in accordance with the energy portion of regulating power, which will be discussed further below. For a more elaborate discussion regarding the potential for heat pumps to participate in the capacity portion of the regulating power market, please see the report "Intelligent control of heat pumps in electricity markets ".

Regulating power - Energy

During the hour of operation, Energinet.dk constantly monitors the state of the electricity grid including the system frequency, and if necessary, 'manually'[3] activates one or more regulating power bids via communication with the relevant balance responsible party. When the electricity system is in need of more electricity, Energinet.dk will activate up regulation. This could for example occur if actual wind production is lower than forecasted, if a power plant falls out, or a transmission connection is compromised. On the other hand, when there is an excess of electricity, Energiniet.dk will activate down regulation. The table below displays what this means in practice for production and consumption units.

Regulation	Production	Consumption
Up regulation	Start	Stop
Down regulation	Stop	Start

Table 2: The signal sent to activated production and consumption units by the TSO depending on whether the electricity system is in need of up or down regulation.

Control according to regulating power in READY

Within the READY project, heat pumps are controlled according to an activation signal. This signal relays the state of the units in Neas Energy's (NEAS') portfolio, i.e. during which hours the units are activated, and in

[3] The term 'manual' is used because there is a person within Energinet.dk that determines whether, how much, and which regulating power bid(s) should be activated. However, within Denmark, all communication between Energinet.dk and the balance responsible parties is done electronically.

which direction. This provides an indication of whether the overall electricity system is in need of regulating power. The actual price of regulating power during the relevant hours is not utilised within the study. This price is settled some hours after the operation hour.

As heat pumps are consumption units, they must already be running, and have the ability to stop running, in order to provide up regulation. Meanwhile, if they are to provide down regulation, they must be stopped, and have the ability to be started. As was highlighted above, the regulation must be maintained for up to an hour. However, by controlling a pool of heat pumps it is not necessary for an individual heat pump to maintain the regulation for the entire period. It is sufficient that the pool as an entirety does so.

Bidding strategies

There are a variety of strategies for how to bid in on the spot market, which will in turn affect how a unit bids in on the intraday and regulating power markets. A number of these potential strategies were analysed within the READY project, a description of which can be found in the Danish summary report and “Intelligent control of heat pumps in electricity markets”. The strategies depend on the expected costs of regulating power and unbalances. If the expectation can be formulated an optimal bidding strategy can be computed. Because regulating power is used to balance unexpected changes, it may be difficult to accurately predict the prices for up and down regulation.

3.2 Current & future regulatory framework for heat pumps

Hourly measurement and billing a must

In order to manage a portfolio of heat pumps intelligently, it is necessary that the individual heat pump has an incentive to shift its electricity consumption, which in turn means that it must be able to measure and bill this consumption on an hourly basis. It is anticipated that by March of 2016 “Flex Settlement” will be introduced in Denmark. Flex Settlement will allow for hourly settlement of small and medium-sized customers, and its introduction should provide incentive for intelligent control of devices in relation to hourly spot prices.

Pooling requires same balance responsible

In order to utilise a pool of heat pumps on the various electricity markets, each of the heat pump owners must have the same balance responsible. Consumers with heat pumps will generally have different electricity suppliers, whom can be associated with different balance responsibles. Heat pump owners interested in participating in these electricity markets will therefore have to group under the same balance responsible, potentially via an aggregator. This can mean that some consumers may have to switch electricity supplier in order to participate.

Minimum bid size

Even with the potential for pooling of heat pumps, given an individual heat pump size ranging roughly between 2-5 kW, it can be challenging to provide ancillary services[4] with minimum bid sizes. Regulating power for example, with its current minimum bid size of 10 MW would require many thousands of heat pumps to meet this threshold. It is possible to pool small consumption devices, such as individual heat pumps, with large electric boilers or large heat pumps, and thus meet the minimum bid size, but for this to be effective requires that the different units have approximately the same marginal costs (i.e. they are willing to bid in at the same price).

The Nordic TSOs have for some time been discussing the possibility of reducing the minimum bid size for regulating power, and it has recently been decided that it will be reduced from 10 MW to 1 MW. It is not certain when this change will take effect, but likely no earlier than 2016 (Parbo, 2014). This change will make it significantly easier for small supply and demand units to participate in the various ancillary service markets.

3.3 Economic potentials of intelligent heat pump control

Within the READY project, the electricity cost associated with managing a heat pump according to spot prices or regulating power prices was compared with how much the electricity cost would be without intelligent control (under both a fixed price and a spot price agreement).

Flexibility is key

One of the most important parameters in determining the potential savings associated with intelligent control, is the degree of flexibility in the house (i.e., the greater the flexibility, the more electricity consumption that can be moved from hours with high prices to hours with low prices). This flexibility is determined by:

- The house’s time constant - a measure of how quickly the house warms up or cools down. A long time constant means higher energy storage and thereby more flexibility.
- The ratio between the heat pumps capacity and the house's heat loss. A high ratio means that the heat pump requires fewer hours to maintain the same temperature, thus providing greater flexibility

[4] Ancillary services in this context refers to primary, secondary and tertiary reserves.

- Comfort requirements in the house – in particular, the spectrum in which the temperature may fluctuate within.

Cost savings associated with intelligent control

In order to determine the potential savings associated with intelligent control of a heat pump, a number of assumptions were made regarding the flexibility values described above, as well as economic (e.g. general electricity price level, as they can vary greatly from year to year) and weather related parameters (e.g. was it a particularly windy, wet, hot or sunny year?). Please see the Danish summary report for a description of the parameters utilised.

The analysis found that for a typical Danish house, the annual savings associated with intelligent control in accordance with hourly spot prices was roughly 300 DKK (€40). By participating in the regulating power market, the annual savings are considerably higher, but also more uncertain. Even if the heat pump only contributes with down regulation, the increase in annual savings can easily be 500 DKK (€67).

3.4 Business models for managing a portfolio of heat pumps

In order for a business model involving a pool of heat pumps to be successful, there must be an economic incentive for heat pump owners to relinquish control of their heating. Likewise, the endeavour must be profitable for the aggregator/balance responsible party. As was indicated above, intelligent individual control of a heat pump can provide the heat pump owner with a financial saving. However, the emphasis of the READY project is management of a portfolio of heat pumps, and it is therefore not the control of the individual heat pump that is in focus.

Settlement challenges

The pooling of a number of heat pumps has the advantage that additional ancillary services can be provided. However, this pooling of heat pumps also presents some challenges in relation to the settlement of heat pump owners. Simple hourly settlement would not be optimal for a number of reasons. One concrete example would be situations where only some of the heat pumps are delivering regulating power at favourable prices (despite the fact that other heat pumps also had the ability to do so).

Valuing flexibility

Another challenge related to the distribution of benefits is that of flexibility. Those heat pumps in a pool that provide the greatest flexibility (either through a broader acceptable temperate spectrum, an/or due to physical characteristics) also provide a greater potential for revenue generation in the various ancillary services market. The degree of flexibility could be incorporated into the business model.

Recommended business model

After considering a number of alternatives (please see the Danish summary report for an extended discussion), for a portfolio of heat pumps it was concluded that the most appropriate form of settlement with the individual heat pump owners would be payment for energy consumption over a period. This could for example be via a fixed kWh price that includes a discount, with this discount depending on the degree of flexibility the individual heat pump and house provides. This discount could be specified in advance, but could also be adjusted periodically in order to reflect the actual flexibility and/or value of services provided.

4 Demonstration

The demonstration portion of the READY project has shown that a larger number of heat pumps can be managed successfully. However, this is not to say that there have not been a number of practical challenges related to a number of the individual heat pumps.

A previous project, StyrDinVarmepumpe (Control your heat pump), had roughly 300 houses with heat pumps and control boxes allowing for remote control. There were a number of different elements that could be measured within the project, including:

- The heat pump's electricity consumption, both to the compressor, internal pumps, electric heater, and control device.
- Heat consumption for space heating, by measuring flow rates and two temperature measurements at 5-minute intervals.
- Heat consumption for water heating, measured in the same fashion as space heating.

The control boxes were developed by Liab, and are coupled to communication server that they also developed. This server allows for users to access the measured heat pump data. The VPP server is connected to the balance responsible party's IT system, and provides the communication server with prices forecasts from the balance responsible party. An overview of the platform utilised in the project is displayed below.

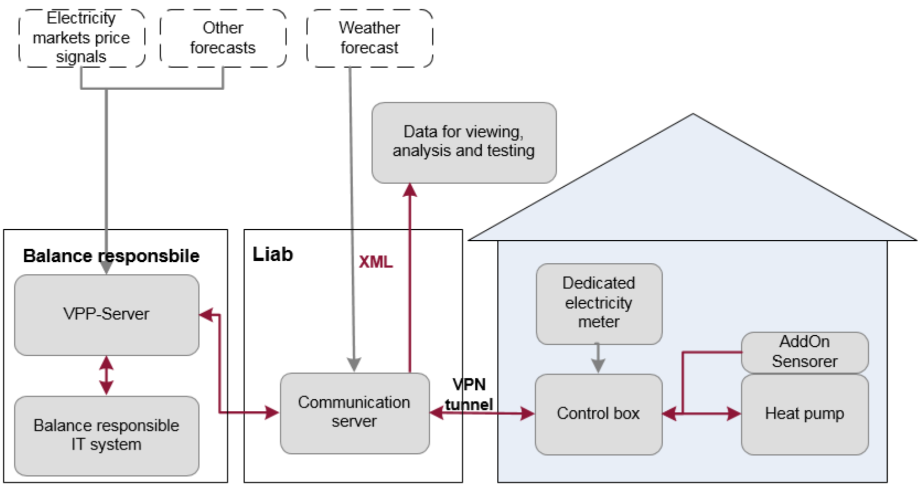

Figure 1: Overview of the platform utilised

The READY project had access to the above-mentioned 300 heat pumps, however, a large number were not utilised for various reasons, including:

- The heat pump model is one that cannot be effectively controlled
- The installation was defective or not completed
- The house is so poorly insulated, thus resulting in the flexibility being too volatile to control
- The homeowner has their own timer control for their hot water
- The house is not occupied at all times or vacant for extended periods
- The homeowner controls the heat pump themselves
- The homeowner does not want to relinquish control of their heat pump
- Projects other than READY are controlling the heat pump.

As a result, there were roughly 80 heat pumps that the READY project utilised for portfolio management. This is deemed to be enough to reduce the 'interference' associated with unanticipated actions by individual home owners, and thereby a sufficient number to evaluate the potential for control of a pool of heat pumps. For a more in-depth description of the demonstration phase of the READY project, please see the Danish summary report, and the reports "VPP control" and "READY – Heat pump installations in Smart Grid".

5 House modelling and control strategies

Within the READY project, methods were developed to make it possible to centrally control the energy consumption of heat pumps in a group of houses in a fashion that minimises costs without sacrificing end-user comfort. The thermal energy storage capacity found within houses is used to shift energy consumption in accordance with spot prices in the day-ahead electricity market. A short summary of these findings follows below, while a more comprehensive description can be found in the following reports: (Nielsen, Andersen, & Pedersen, 2014), (Nielsen, Andersen, & Pedersen, 2013), (Biegel, et al., 2013a), (Biegel, et al., 2013b), (Biegel, et al., 2014), (Andersen, Pedersen, & Nielsen, 2014), (Pedersen, Nielsen, & Andersen, 2014).

House model

A model was established which describes the relationship between the indoor temperature and power from the heat pump, weather data and house parameters. The parameters were estimated based on measurements from 6 different houses, but this proved difficult because the heat pumps in place maintain an almost constant indoor temperature, and the residents in the house introduce large disruptions, for example by using a fire place, opening or closing a window or door, etc.

Optimal energy purchase

In order to determine when it is optimal to purchase electricity on the spot market, a performance function based on the house model, spot price forecasts and weather data from DMI (Danish Meteorological Institute) were used to estimate and optimise energy consumption 36 hours into the future. The algorithm has made it possible to plan increased energy consumption during times with lower electricity prices.

Via simulation, and on single-family houses, it was tested whether the optimised energy purchased can cover the individual houses' heating needs during the day of operation. The simulations show that the energy consumption can be moved and the energy plan can be kept. However, “interference” from residents (i.e. opening of windows, etc.) and weather changes mean that it is not always possible to employ precisely the same energy plan if the house comfort requirements are to be respected.

Control strategy algorithm

Due to the potential for individual interferences, it is difficult to forecast the future energy requirement for a single house. However, in reviewing data from a large group of houses, it is apparent that these interferences are largely independent from one another, and it is therefore assumed that they will largely even one another out. Therefore, a control strategy was developed in which a collection of houses must comply with an overall energy plan comprised of a number of individual plans. The control system is a scheduling algorithm, which ensures that the overall energy plan is maintained, while at the same time also ensuring that the temperature within all houses is between their respective comfort limits, and that the individual heat pump operational conditions are respected. The algorithm has been tested on a large number of houses and revealed positive results.

Comparison of control strategies

As highlighted above, within the READY project, various forms of control strategies were considered and evaluated. These are summarised below.

Type	Description
Spot prices and individual modelling and control	Relies on a model that computes a house's individual heat needs. Spot prices are utilised to generate a plan for the heat pump. This could for example involve altering temperature set points in accordance with spot prices. Does not deliver regulating power.
Portfolio modelling and direct control	Critical measurements from the various houses are received centrally and combined with historical weather data, and price and weather forecasts. Based on this, an overall plan for the next day is generated. Direct central control ensures that the overall plan is followed, while also respecting the individual constraints. Can deliver a range of ancillary services.
Price signal control	Could for example be in the form of 5-minute electricity prices based on the regulating power price, received by the individual heat pump owners. Requires home automation in order to react to the price signals. Requires an aggregator in order to deliver ancillary services.

Table 3: Overview of the three main forms of control strategies

The first of the above three can utilise direct or indirect control, while the second, which is the primary focus of the READY project, relies on direct control. Lastly, a price signal system could also utilise direct or indirect control, and a variation that relies on indirect control is described in another ForskEl project, "FlexPower" (FlexPower, 2013). Between these three are a number of variations that combine various aspects of each, e.g. individual vs. pool modelling, local or central control, etc. Please see the Danish summary report for an extended discussion and comparison of these variations.

Utilisation of flexibility

The indoor temperature in an individual house may vary within the predetermined comfort limits. The difference between the actual temperature and this comfort limit temperature therefore represents a potential energy storage, with the current state of the individual heat dump determining the exact quantity. A balance responsible party can utilise this storage either for internal balancing, or in the ancillary services markets (e.g. regulating power). Within the READY project, an algorithm has been developed to optimise the amount of energy that can be utilised. The algorithm has been tested on realistic data.

5.1 Effect of variations in heat pump & hot water tank size

The extent and value of the flexibility provided by a heat pump is dependent on the size of both the heat pump and the accumulation tank (and on the hot water tank and the heat capacity of the building). As such, an analysis was carried out to determine the effects of increasing the size of heat pump or accumulation tank, seen both from the house owner's perspective, as well as from an overall grid perspective.

To assess the economics associated with the various alternatives, a number of assumptions were made regarding additional costs of larger heat pumps and hot water tanks, electricity prices, interest rates, etc. Please see the report "Varmepumpeinstallationer i Smart Grid - Undersøgelser og anbefalinger" for a more detailed description of the analysis.

Main findings

Generally speaking, the analysis found that given the current tax and tariff framework, there is no incentive for end-users to optimise the size of their heat pumps or water tanks according to anticipated spot prices. On the other hand, for the electricity system as a whole, there is a positive benefit associated with home owners optimising the size of their installation. This is particularly the case with respect to regulating power, as larger pumps and heat tanks provide a greater capacity, therefore increasing the ability to produce heat when electricity prices are low.

Additional observations

There were a number of additional interesting observations:

- Heat can be accumulated in a buffer tank and/or in the building mass, and there are advantages for the electricity system associated with both types.
- The most effective form of accumulation is houses with floor heating in concrete floors, but even for these houses it was not worthwhile to invest in a larger heat pump.

- Solar heating in conjunction with a heat pump is a fine approach that saves electricity. However, compared with hourly price settlement of an electric heat pump, the additional investment cost associated with solar heating is not economically attractive.

6 Managing congestion in local grids

6.1 Future markets and tariff regimes

Increased future electricity demand

In the future, electricity demand in residential areas may change quite dramatically. Heat pumps may be introduced in large numbers to reduce oil consumption and individual heating costs. Electric vehicles may in the same way be introduced to reduce gasoline and diesel consumption, and both of these trends will increase electricity consumption. For example, a typical single-family Danish household (without electric heating) uses 4,000 kWh/year today, and this may be increased by 5,000-10,000 kWh if a heat pump is installed, and by another 2,000-3,000 kWh/year with an electric vehicle.

Traditionally, small end-users were not exposed to variable electricity prices, and thus had no incentive to regulate electricity usage according to wholesale hourly prices. This will change in Denmark in the near future, as it is expected that by March 2016 end-users will be able to select the option of being metered hourly, and enter into agreements to be billed hourly. (Parbo, 2014).

Heat pumps (and also electric vehicles) may potentially create overloading of electricity lines. Distribution grids in particular may be challenged if a large number of these units draw electricity at the same time. This challenge can be amplified when heat pumps (and other price responsive units) react to price signals. **The economic optimisation of the heat pump operation may result in an increased correlation of their electricity demand.** The price signal may lead to a loss of diversity in the on/off cycles of the control.

Different grids: different stories

Each distribution grid has a different history, and in some cases, congestion is first expected to emerge in the medium voltage grid, while in other grids the low voltage grid is considered to be more critical. Congestion can be related to the cables or the transformers. Most grid companies in Denmark report that they expect to be challenged in their 0.4 kV grid in relation to the expected rise in consumption from EVs and heat pumps. However, the largest grid company in Denmark, Dong Eldistribution, reports that they expect challenges in the 10 kV grid. The solutions analysed in this report will be relevant for both of these voltage levels.

Solutions to congestions

DSOs essentially have two options for grids with potential problem areas:[5]

1. Increase grid capacity by investing in additional grid infrastructure, or
2. Investing in demand response tools i.e. smart grid tools that can shift and/or reduce demand.

In a recent study where the above two options were investigated, it was concluded that relative to simply investing in the expansion of transmission and distribution grids, savings of over 6 billion DKK could be realised by investing in smart grid technologies (Energinet.dk and Danish Energy Association, 2010).

Different tariff signals

How future signals from the DSO to the consumer would work in practice is open to discussion as there are a number of potential options, each which vary with respect to their geographic scope, timing, notice, and price level. Table 4 displays four of the more discussed options.

	Time-of-use tariffs (TOU)	Critical peak pricing (CPP)	Variable tariff	Dynamic tariff
Notice	Before spot			After spot
Activation	Weekly pattern regardless of needed relief	Activated when relevant		
Timing of price determination	Year ahead	Year ahead + day ahead	Day ahead	Intra day
Tariff characteristics	Tariff fixed one year in advance	Fixed low and high tariff for one year. Announcement of use the day before	Varying tariff for each hour. Announcement of use the day before	Varying. Announcement up to actual operation time
Price variations	Moderate	Typically large		
Advantages	Simple to use. May help to activate e.g. manual control or simple clock control	Can be designed to limit end-user risk, e.g. with a maximum number of times the high prices can be activated	More flexible than CPP because of hourly tariff. Greater incentives for those targeted	Can be used if congestions are motivated by calls for regulating power
Disadvantages	TOU tariffs are general in nature and do not target specific problems	More complex. Would typically require automated control.		
Open questions		Risk for DSO?		How to coordinate with spot market?
Geographical scope	DSO area	Tariff for whole DSO area or only congested grid?		

Table 4: Examples of potential tariff regimes for the use in distribution grids

[5] A third 'option' for the DSO could be to invest in and utilise additional metering equipment, thus allowing the DSO to reduce their safety margins. This is possible due to the greater knowledge regarding the capacity usage in the local grids.

As seen in Table 4, the various options have different advantages. In addition, they also have varying investment and operational costs.

Preliminary findings

Our initial findings indicate a number of issues that appear to be clear:
The signal indicating a potential congestion in distribution grids must originate from the DSO, and this signal will be directed to the retailer/aggregator/balance responsible, which will pass it on to end-users.

- Ideally, the signal with grid tariffs should be sent to all end-users (not only heat pumps) in the congested area (i.e. possibly a small fraction of the DSO area). However, with more than 10,000 potential grids this may not be practical. It is an open question how detailed the geographical scale in practise should be: Can price signals solely be sent to the end-users contributing to a congested line; or must the price signal be sent to larger areas?
- Simple time-of-use tariffs can be an important first step in the direction of dynamic tariffs. Time-of-use tariffs can motivate behavioural change, i.e. computers and communication are not a requirement. It has not been analysed in detail how far in the direction of the ideal dynamic tariff it is relevant to go. Many practical aspects may lead to the result that very simple solutions, such as time-of-use tariffs, will be preferred, particularly in the short to medium term.[6]
- Via the use of modern techniques that are already available today, substantial investments in metering equipment may not be necessary and grid investments may be reduced. DSOs can use these techniques to predict potential congestions. These techniques include state estimators, load flow estimators, and other methods that utilise a variety of information types. For example, meter reading of hourly demand holds a rich amount of information that is particularly useful when combined with grid topology.

Direct or indirect control

With respect to how to activate the end-user, demand can be controlled by a computer in each home that responds to a price signal that originates from the DSO (indirect control), or it could be controlled by a centralised system, e.g. a virtual-power-plant (VPP) setup. The VPP set-up is in focus in this project, but the signal from the DSO should likely be useable in relation to both control solutions.[7]

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[6] TOU tariffs are expected to be standard for Danish grid companies in the future.
[7] This assumption is meant as a compromise between the decentralised and centralised control schools. It is the authors' point of view that the DSO should not take side in this discussion. By sending

6.2 State estimation

State estimation

The above section described potential market set-ups and/or tariff regimes that could be utilised. However, a number of these require that the DSO has knowledge of the state of the grid in order to send out the appropriate signal. State estimators use maximum likelihood methods to compute the state of the grid. The method can use measurements of varying quality, use information of the physical topology of the grid, and utilise user profiles for consumer groups to calculate the most probable state of all grid elements. State estimators are often used in relation to transmission grids, but could also be developed for distribution grids. Some DSOs already have projects developing this method. In a transmission system, there are sufficient measurements[8], while in distribution systems the measurements are usually much sparser. However, the installation of new interval meters will change this, as they will provide a number of new measurements.

6.3 State estimator and demand control strategies.

To illustrate the potential of using a simplified version of a state estimator we have been permitted access to actual demand data from Galten Elværk (GE Net A/S – now a part of "Aura Energi"). This data was used to analyse and compare two demand control strategies, namely a 'kW maximum, and a VPP solution.

Galten Elværk

Galten Elværk is a grid company West of Aarhus with 24,000 customers. The grid includes 10 kV (638 km) and 0.4 kV (899 km) distribution grids – all utilising underground cables. Total annual consumption in the area for 2011 was 293 GWh. In 2011, the utility started rolling out smart meters to all of its customers. Galten Elværk is able to read all meters with a notice of 3-4 hours and a hit-rate of approximately 90% of all meters. After 7-8 hours, the hit-rate rises to ca. 99.9%. Reading of e.g. 50 meters can be completed in 3-10 minutes with a hit-rate of 99.9%. The sampling period for the meters is typically 1 hour, but can be 5 minutes if needed. Currently it is only kWh/h data for each meter that is collected, but meters are capable of transmitting more information, e.g. consumption per phase and voltage (however, the phase ID (L1, L2, L3) is not synchronised for all installations). (Rasmussen, 2012 & 2013).

a price signal both methods can be used – and they can compete for end-user interest. Examples of the centralised approach can be found in (Sundström & Bidning, 2012).

[8] In fact, in transmission systems there are often more measurements than degrees of freedom, which essentially means that not all measurements can be used.

Galten - kW max solution

One of the measures that is often cited as being a potential option for reducing congestions in distribution grids is a ‘kW maximum’, which places a limit on the amount of electricity a customer may draw at any one time. The current contract allows each private end-user in Denmark to draw 17 kW, and more for some user categories. To test the effect of a kW maximum limit, end-user data from late June of 2011 to October of 2012 from station 52 within the Galten network was utilised.[9]

Station 52 consists of 62 end-use customers with a combined hourly load of 113 kWh/h during the hour of the year with the highest load. Of these 62 end-users, 40 are regular single family houses without heat pumps, electric heating or PV installations, which combined have a load of 48 kWh/h in the hour of the year with the highest load. It is interesting that none of the house had their individual maximum in the hour of the combined total maximum.

The primary scenario investigated involved a simulated situation where eight of the forty houses in Galten have a heat pump installed[10], thus increasing their daily electricity demand during the heating season. Their total combined load in the hour of the year with the highest load thereby increased from 48 kWh to 70 kWh. In the analysis, a fictional kWh/h maximum was then placed on these 40 units to see how this affects the congestion on lines and transformer boxes under station 52.

Results

The implementation of a kW maximum on single-family houses without electric heating in an area such as Galten would have to be considerably lower than the current maximum (roughly 17 kW) before it would have any noticeable effect on the peak demand hour. When eight of the forty houses in Galten have a heat pump installed, the maximum feasible hourly limit is deemed to be 6.0 kWh/h.[11] In this situation, the annual peak demand is reduced by roughly 3 kWh/h (corresponding to approximately 4.7% of single family houses usage). Meanwhile 25% of all houses would see their consumption reduced in at least one hour during the year as a result of the maximum.

[9] Raw data for the months March-June did not have individual readings and was therefore not used.
[10] With data from real heat pumps from the "StyrDinVarmepumpe" project.
[11] Whether a limit this low is reasonable given that it requires a shifting of electricity demand for one of the house over 125 hours is in of itself highly debatable.

Galten: VPP

In order to reduce overall system demand, an alternative option to the above kW max limit is a virtual power plant (VPP), where end-users agree to allow an aggregator control a certain portion of their electricity demand. In practice, there are number of ways this could be carried out, both via indirect (i.e. sending of price signals to end-users), or direct, control strategies. A plausible first generation VPP would likely be given permission to regulate particular devices in the house given agreed upon parameters. Non-heat related usages could include washing machines, dryers, dishwashers, electric vehicles, etc., all of which can often have their use postponed resulting in little or no reduction in customer comfort. In addition to this is heat-related electricity use, for example from heat pumps, freezers or direct electric heating, where electricity usage can be altered with little or no loss in customer comfort.

As was done in the previous kWh/h maximum case, data from 40 Galten end-users under sub-station 52 was utilised to simulate the implementation of a VPP given current electricity demand, and the same eight houses received a fictional heat pump. In practice, the amount of electricity that will be able to be shifted forward will depend on a number of factors, including: the hour of the day, day of the week, time of year, weather, and will vary greatly from user to user. For the sake of simplicity, in this exercise it was assumed that for each of the 40 houses without electric heating, 30% of their hourly electricity demand is flexible, and that it can be shifted a maximum of 3 hours forward into the future. In addition, it is assumed that 50% of the additional demand from heat pumps is flexible, and can be shifted up to 3 hours.[12] Given the aforementioned restrictions, the goal of the exercise was to minimise electricity usage in the hour with the highest overall system demand.

Results

After eight users have electricity demand from heat pumps added, the implementation of a VPP on 40 end-users in Galten reduces the maximum system load by more than 15 kWh/h during the maximum system load hour.

Conclusions: kW max vs. VPP

The analysis is clear that if a VPP can be successful in shifting a particular amount of demand forward, then this is a significantly superior solution

[12] In practice, heat pumps generally operate 100% on or off, however, this 50% figure is an average for the eight heat pumps, and is also an hourly average, so they could in principle run for 30 minutes of a given hour in this modelled scenario.

than that involving a kW maximum. In addition, the VPP has the added benefit in that it does not result in lost welfare for the customer at other times during the year, as is the case with the kW maximum, which reduces electricity usage for a number of users in hours where there is no need for a reduction. The VPP solution is however not without its drawbacks, as it requires infrastructure and communication technology in order to function properly. How large these required investments are relative to the costs associated with having to expand the capacity of the distribution system will ultimately determine the viability of a VPP in local distribution grids.

7 Additional reflections

Possibility to compel heat pumps to start

The heat pumps within the study have been controlled in a manner that ensures that the indoor temperature remains within an agreed upon temperature spectrum. However, one limitation of the current control platform is that the heat pumps can be stopped, but they cannot be compelled to start. When the heat pumps received a signal to start, this signal came from the heat pump's own control unit, which had determined that it was time to start. This contributes to a less precise management of the heat pump, and therefore increases the potential for imbalances (i.e. the heat pump's actual electricity use is more likely to deviate from the planned usage within an hour). In addition, this has greatly lessened the potential for storing heat in the building mass. The possibility to also compel heat pumps to start should therefore be a priority going forward, as it would allow for the full exploitation of the flexibility within the house, and thereby increase the possibilities in the various electricity markets. One rather simple solution, assuming that one can gain access to the heat pump control unit, would be to adjust the temperature set points, a concept that has been tested in the aforementioned FlexPower project. This would be a step in the right direction.

Role of the aggregator

In the future, when thousands of devices are to be managed, it is assumed that there will be a business entity that will gather the various signals (prices from various markets, weather, etc.), submit the flexible consumption bids to a balance responsible (whom buys and sells electricity on the wholesale market as well as participates on the various ancillary services markets), and have responsibly for the technical and communication platforms. Here and in other projects this entity has been referred to as an aggregator. Within the current project, it has been assumed that this aggregator can be a balance responsible party or a separate entity. Which of the two approaches is likely to be the most appropriate has not been considered within READY.

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