Final report

1. Project details

Project title	OPSYS 2.0
File no.	64108-0581
Name of the funding scheme	EUDP
Project managing company / institution	Danish Technological Institute
CVR number (central business register)	DK 5697 6116
Project partners	Neogrid Technologies ApS, Aalborg University, Wavin A/S, Bosch A/S, Danish Technological Institute
Submission date	13 June 2023

2. Summary

English summary

Both the EU and the IEA see energy flexibility of buildings as an important resource for facilitating the coming transition of energy grids from fossil fuels to renewable energy resources (RES). Today, heat pumps may be switched off during periods with a low amount of RES in the grid, but it is not possible to store excess heat and thereby prolong the duration of the possible switch off period. However, this may be done using the OPSYS concept where the heat emitting system is controlled in such a way that the set point of the thermostats in the rooms may be increased within the comfort range of the room air temperature allowing for the storage of heat in the thermal mass of the house. Another possibility is to increase the set point of a water tank, e.g., the domestic hot water tank of the house, in order to store heat when there is a surplus of production from RES in the grid or a surplus of local production from an individual PV system installed on the house.

With basis in these ideas the project showed how surplus of electricity from a PV system on the house could - by the OPSYS controller - be utilized for an increased self-consumption in the house, and, thus, increase the economic benefit of individual PV systems as less electricity needs to be sold to the grid at a very low tariff. The predictive controller was used to forecast peak production and save storage capacity for such periods, so that no or little PV electricity was wasted. Integration of heat pump and floor heating was also demonstrated in practice and investigated theoretically. During the project several obstacles has been overcome, especially regarding communication between the different components, but in the end a functional setup that could demonstrate energy flexibility was found.

Thus, the OPSYS concept can help the transition of the Danish energy system from being mainly fossil fuel based to mainly being based on renewable energy resources as the utilization of the OPSYS concept will decrease the demand for primary energy for heating of houses with heat pumps. The solution can also provide energy flexibility services to the electricity grid, increase self-consumption of PV generated electricity and decrease curtailment of PV electricity.

Dansk resumé

Både EU og IEA anser energifleksibilitet fra bygninger som vigtig for at kunne gennemføre den kommende omlægning af energisystemerne fra fossile brændsler til vedvarende energi (VE). I dag kan en varmepumpe stoppes i perioder, hvor der er lidt VE i nettet, men det er ikke muligt aktivt at lagre varme og dermed forlænge det tidsrum, hvor varmepumpen kan slukkes. Dette kan gøres med OPSYS-konceptet, hvor varmeafgiverne styres, så rumtemperaturen kan øges (indenfor komfortbåndet) før en periode med lidt VE i nettet, så der lagres varme i bygningens interne konstruktioner. Varme, som afgives, når varmepumpen efterfølgende slukkes, gør det muligt, at varmepumpen kan være slukket i en længere periode. En anden mulighed er at lagre varme i en vandbeholder, f.eks. brugsvandstanken, ved at øge temperaturen af denne før en periode med lidt VE i nettet. På den måde kan OPSYS-konceptet tilbyde energifleksibilitetsservices til elnettet, som kan være med til at stabilisere dette.

Med udgangspunkt i disse ideer viste projektet, hvordan overskud af elektricitet fra et solcelleanlæg på huset - med OPSYS controlleren - kunne udnyttes til et øget egetforbrug i huset og dermed øge den økonomiske fordel ved individuelle solcelleanlæg. da der skal sælges mindre strøm til nettet til en meget lav tarif. Den prædiktive controller blev brugt til at forudsige spidsproduktion og spare lagerkapacitet i sådanne perioder, så ingen eller lidt PV-elektricitet blev spildt. Integration af varmepumpe og gulvvarme blev også demonstreret i praksis og undersøgt teoretisk. I løbet af projektet er flere forhindringer blevet overvundet, især hvad angår kommunikationen mellem de forskellige komponenter, men i sidste ende blev der fundet et funktionelt setup, der kunne demonstrere energifleksibilitet.

OPSYS-konceptet kan således hjælpe med til at muliggøre omstillingen af det danske energisystem fra fossile brændsler til vedvarende energi, da OPSYS-konceptet kan reducere energiforbruget til opvarmning, tilbyde energifleksibilitetsservices til elnettet, øge egetforbruget af PV-strøm og mindske spild af PV-strøm.

3. Project objectives

The original aim of the project was:

- To increase the efficiency of both existing and new heat pump installations by developing a control kit that can optimize the forward temperature from the heat pump and the flow rate through the heat emitting system.
- Based on the above, to develop control software capable of:
  - Creating flexibility services for the stabilization of the electricity grid.
  - Optimizing the self-consumption of PV generated electricity on private houses and/or avoid curtailment of the production.
  - Minimize the total cost of electricity and heat by developing and using an advanced predictive control system (MPC).

The project should demonstrate this in practice (in inhabited buildings and on a test rig at Danish Technological Institute (DTI)) and document the results via detailed measurements.

Technology

The project aims to develop a control kit for both new and existing heat pump installations which can improve the efficiency of the installations by optimizing the forward temperature and the flow rates throughout the heat emitting system and thereby - for existing installations - upgrade poor heat pump installations to good installations. In this way, the heat pump and the heating system can be optimized as a whole which is not the case today. The control kit should be tested in a test rig as well as in real households.

In addition, the project should develop advanced control strategies for improved grid flexibility (demand side management). Today, heat pumps may be remotely switched off during periods with a low amount of RES (renewable energy sources) in the grid, but it is not possible to store heat upfront (by boosting the heat pump) and thereby prolong the possible switch off period. With the OPSYS concept, the heat emitting system is controlled in such a way that the set point of the thermostats in the rooms may be increased within the comfort range of the room air temperature allowing for the storage of heat in the thermal mass of the house. This paves the way for more grid flexibility and better use of available RES. Another possibility is to increase the set point of a water tank e.g., the DHW tank of the house in order to store heat when there is a surplus of production from RES in the grid.

Another system advantage is the ability to use surplus of electricity from an individual PV system to partially power a heat pump, thus increasing the economic benefit of the PV system as less electricity needs to be sold to the grid at a very low tariff. This should be done and demonstrated by increasing the floor temperature in daytime with solar peak production and stop heat production during electricity peak hours. The advanced MPC controller collects data from weather services and Nordpool electricity price in order to predict the most economic way to heat the house. A mathematical model of the house is used to predict the heating demand.

The following figure shows the principal design and interaction between the different elements. More details on the technology and results can be found in Annex 1.

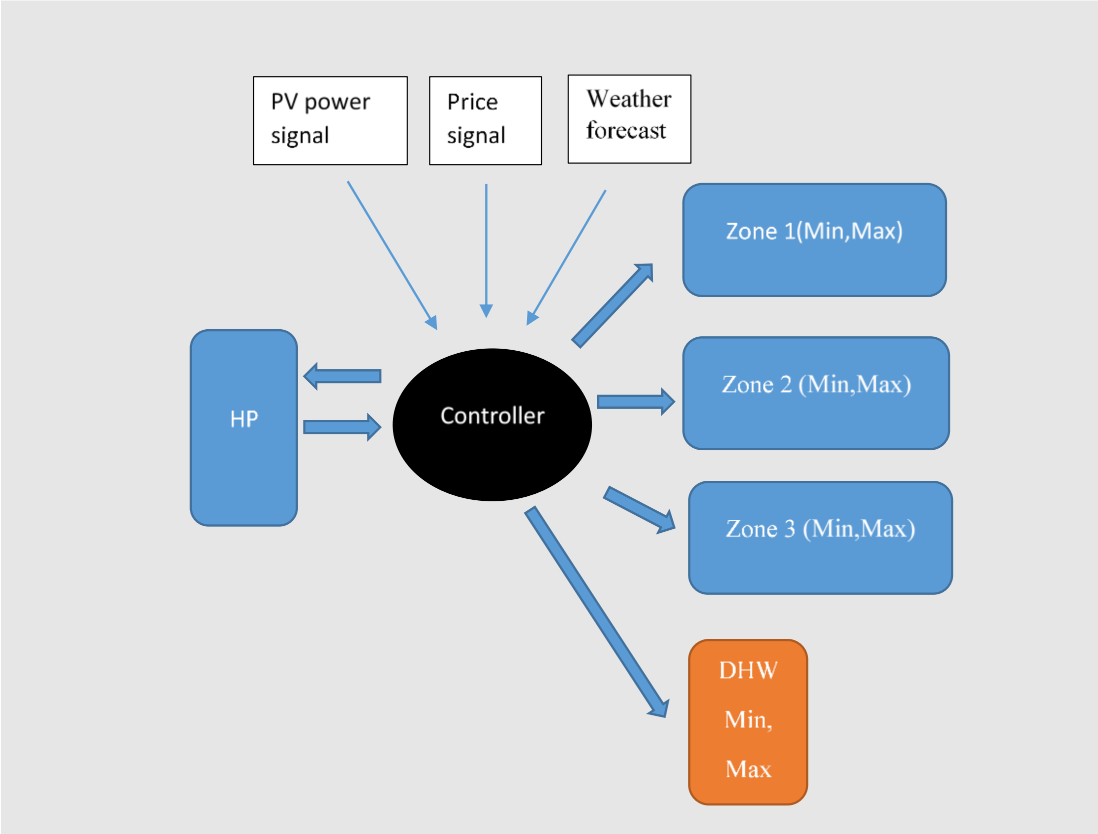


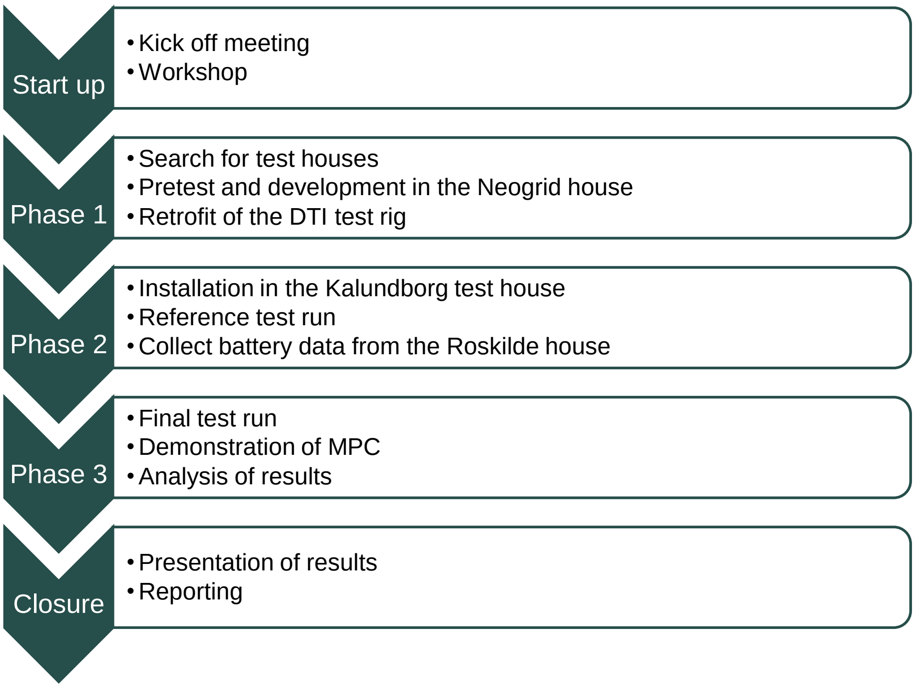
Figure 1 Principle of the developed controller. The weather forecast and the price signal is gathered from external cloud services whereas the predicted PV power is calculated from plant data and weather. The predicted heating demand for the next 24 hours is used to publish an "action plan" for the various valves and the pump

4. Project implementation

Project evolvement

The project included industrial and academic partners with the following roles: Bosch as heat pump expert and supplier, Neogrid as developer of the new controller, Wavin as expert in floor heating, Aalborg University as Ph.D. student and DTI as project manager and test platform developer.

Like many other activities of the time, the project was severely affected by the Covid-19 pandemic which made physical meetings difficult. Instead, Microsoft Teams was used with regular intervals to keep the work ongoing. None the less, limitation of visits to the test house and other practical teamwork caused problems and delays. The workflow is illustrated below:



The project team included three important industrial partners – Bosch, Neogrid and Wavin – and they were all supposed to contribute to and benefit from the project with respect to hardware development. The idea was that the Neogrid box and the Wavin floor heating controller should work together symbiotically so that the signals to and from the floor heating telestats could be transferred to the Neogrid controller via MODBUS protocol, and this part was successfully implemented.

When the project started, there was some uncertainty regarding the possibilities for control of the valves in the Wavin manifold, and an experimental study was done to clarify this. It was concluded that the benefit of "pulsed operation" resulting in semi open or closed valves was very limited compared to the simpler on/off control. Therefore, the incentive for Wavin for specific product development of their manifold and integration with the controller became lower than expected. Nevertheless, it was successfully demonstrated how an external override signal to the manifold and control valves could activate the floor heating as an active heat storage element. The continued cooperation between Neogrid and Wavin is still possible if a consensus regarding market share can be found between the partners.

The work consisted of the following work packages and tasks:

WP1 – Development of control kit for heat pump/heat emitter systems

1. Establish test and demonstration installations – two to three houses with floor heating and a heat pump.
2. Further development of the flow controller from the OPSYSv1 project (balancing floor heating circuits – a non-linear MPC task).
3. Implementation of a flow controller in the Neogrid platform.
4. Development of an aggregated model with a heat pump and a floor heating system for joint optimization.
5. Connect the control to the power grid conditions using price signals or CO_2 intensity in economic MPC – in combination with WP2.
6. Building a simple model of the heat pump (e.g., COP = f (ambient temperature, supply temperature, runtime), minimum runtime, …).
7. Collect external price and weather signals to the Neogrid platform.
8. Demonstration and documentation.

Comments: Due to missing permit and time delay, only one house was fully demonstrated with the developed system, but additional measurements were done at an existing house (Neogrid) installation with the PreHEAT system, and further measurements from a PV battery installation in a third house were collected and analysed. Results from this battery installation was applied for the controller test at the test rig at DTI.

Figure 2 Test house in Kalundborg with existing PV system and heat pump.

WP2 – Development of control strategies for providing services for stabilizing a power grid with a large share of RES and for optimization of self-consumption of local PV electricity

1. Literature study, modelling, and construction of a simulation model for use in control design.
2. Design and testing of model predictive control in combination with WP1, task 5.
3. Design and testing of portfolio control concept – tests in the OPSYS test rig and in EnergyFlexHouse at Danish Technological Institute.

4. Managing parameter variations in the system, e.g., by closed loop system identification.
5. Reporting and PhD dissertation.

Comments: This WP was mainly effectuated by Aalborg University with assistance from Neogrid and other partners. For practical reasons, planned tests in the EnergyFlexHouse at Danish Technological Institute were replaced by extra tests on the test rig.

WP3 – The OPSYS test rig

1. Retrofitting of the OPSYS test rig to allow for WP1 and WP2 tests.
2. Test of control strategies developed in WP1, task 3.
3. Test of control strategies developed in WP1, task 4.
4. Test of control strategies developed in WP1, task 5, and WP2, task 2.
5. Test of control strategies developed in WP 2, tasks 3 and 4.

Comments: This work package was delayed and faced several technical challenges due to software issues and trivial repetitive problems with the cooling system. The test rig is now functional with new features such as PV and battery in the energy balance calculation. The most important updates are the addition of automatic hot water tapping, reconstructed ground source loop with a buffer tank, new temperature sensors, and revision of user interface and software.

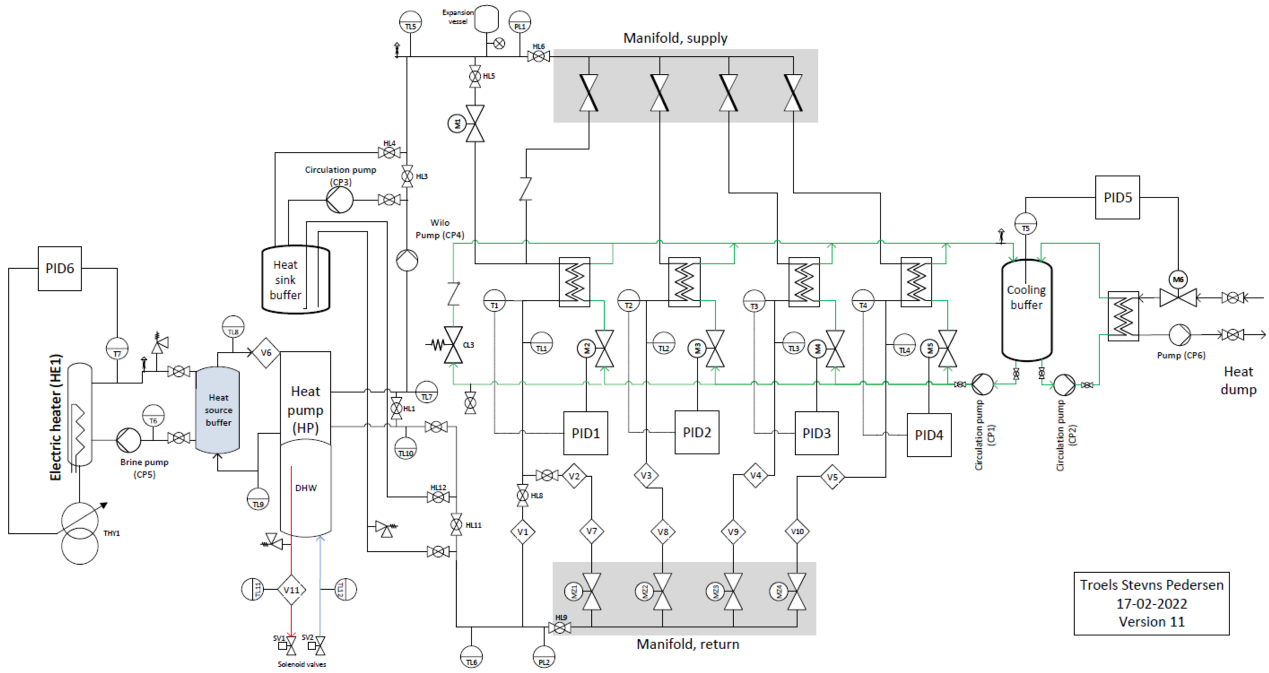


Figure 3: Test rig diagram after retrofit. The main physical change is the new brine buffer installed in parallel between the simulated ground heat and the heat pump Compress 7001 LWM 12. This has made the heat regulation much more stable.

Risks

It is a known commercial risk that the competition from other providers of smart home systems can become hard, and that the cost-benefit is critical in case of single-family houses with a limited cost saving potential. Neogrid has developed a simpler and less expensive version of their box (called "Predator") to mitigate this risk. The simpler box has reused many of the hardware modules developed within this project which has shortened the development time significantly.

Thermal discomfort: It has been a project specific risk that the test house could be exposed to unacceptable temperature fluctuations if something went wrong with the controller, but fortunately that did not happen.

Implementation and milestones

Milestones/Milepæle	**Status**
M1 Demosites found	Fulfilled. Two houses identified and checked (Kalundborg and Roskilde) In addition, Henrik Stærmose's house (Neogrid) was selected.
M2 Flow control implemented in PreHEAT	Fulfilled
M3 Controller for energy flexibility developed	Fulfilled
M4 Report on test of PreHEAT in demosites	Partly fulfilled as only the house in Kalundborg could be instrumented and measured due to lack of installation permit in Roskilde. In addition, Henrik Stærmose's house (Neogrid) was used for initial tests, analyses and development.
M4 Report on literature review	Fulfilled (Annex2)
M5 Report on MPC	Fulfilled (Annex2)
M7 Report on portfolio control	Fulfilled (Annex2)
M8 OPSYS test rig retrofitted	Fulfilled. Modifications are documented in Annex 3.
M9 Test of WP1.3-1.4 completed	Fulfilled. The controller was installed in PreHEAT and tested internally and in the Kalundborg house.
M10 Test of WP1.5 - WP2.2-3 completed	Fulfilled. Controller for energy flexibility tested in the Kalundborg house.
M11 PhD thesis	In final stage
M11 Final project report	Fulfilled
Commercial milestones/Kommerc. milepæle	
CM1 Market research made	Fulfilled, internal document
CM2 Evaluation of prototype installation made	Fulfilled, internal document
CM3 Market plan created	Fulfilled, internal document
CM4 Commercial sales started	Fulfilled, pilot series produced and sold (300 sold of basic version).

Unexpected challenges

A project involving practical installations and measurements will always deviate from the planned route. In this case, the biggest obstacles have been:

- Time delay due to long negotiations between the house owner and Roskilde municipality regarding installation of a heat pump with borehole. The project group hoped that the installation could be used for the project, but at the end of the day we decided to give up and instead intensify measurements and analysis of the Kalundborg house. As a supplement, the house in Roskilde delivered valuable data from a battery storage system that was installed during the project period, and these data were used to set up a battery model for the OPSYS test rig controller.

- In Kalundborg, the solar PV inverter’s data interface could not be directly connected to and controlled via the PreHEAT box. Apparently, this was a firm specific issue that could not be solved. Instead, an extra electricity meter was installed after the PV inverter in order to provide a reliable PV production signal to the PreHEAT box.
- Problems with instrumentation of the house in Kalundborg, especially communication between sensors and control box. In the end, the PreHEAT controller was switched to a completely new one which seems to work.
- COVID-19 also made it hard to visit the house to debug the installation.
- Compared to the original schedule, there was too little time to measure an entire heating season, so an extension of the deadline was necessary.
- Difficulties when upgrading software on the DTI test rig. The company that originally configured the BMS system ended up recommending an upgrade of our old measuring PC to a windows 10 machine, so they could update their software. This took a very long time.
- Problems with the cooling system for the DTI test rig. The work on the test rig was hampered by multiple cases of malfunction in the external cooling system. Finally, the test rig was connected to an alternative cooler that is part of the laboratory infrastructure, and it is now working well.

Finally, one of the project's key persons, PhD student Simon Thorsteinsson, has been on maternity leave which was not foreseen at the start of the project.

5. Project results

As previously described, the project has faced several obstacles, but nevertheless most of the objectives have been met. The most severe deviation from the planned results is that the final demonstration of the OPSYS 2.0 concept could only be fully realized in one single house. To compensate for this, the measurement campaign on the house in Kalundborg was intensified, and a lot of effort was invested in the installation of monitoring and control equipment. The project's main results are summarized below, and details can be found in Annex 1:

- During the project, several iterations and improvements based on the early model of the Neogrid PreHEAT box have been carried out. The early box (Allike) was mainly developed for district heating installations, but during the project, use cases and requirements were collected to address the connectivity towards heat pumps and heat emitter systems in private houses, leading to an upgraded version of the box (Avenger). One iteration of this box has been carried out, and efforts to develop and stabilize the software have been done during the project. The final version is now available in a professionally looking version that is versatile and robust.

Figure 4 "Avenger" – the last version of the control box from Neogrid.

- During the project, different interfaces to control the heat pump have been tested and demonstrated. Due to lack of a dedicated override control interface, the ambient temperature signal was manipulated to make the heat pump increase or decrease the power uptake. The results from these tests have shed light on the possibilities and pitfalls which need to be addressed when controlling the heat pump. Furthermore, this has led to new requirements for the PreHEAT box which have partly been implemented in the latest version and in the low-cost version (the Predator box, which were done in another project).
- During this study, an implementation-oriented and price-responsive MPC controller has been tested on a heat pump and made smart grid ready over the course of four months in the winter 2022-2023. The results show that by only using the concrete floor slabs, load shifting can be utilized to reduce heating costs by an estimated 11% at a test period of 97 days in the specific house without reducing the average indoor temperature. Even if almost no energy savings were achieved, the production patterns have been changed – increased consumption at night and a complete lack in the cooking peak – to support the grid (DSM demonstrated).
- Price savings are one benefit from the system, but a good and stable indoor climate is also a main benefit and driver for these solutions. Having a control system that can integrate and control the heat pump, the PV and the heat emitter system (floor heating), maximising self-consumption and minimizing import from the grid in high price / peak load scenarios, introduces savings / benefits in other places of the value chain (such as services to distribution system operators (DSOs) and operators of Heat-as-a-Service).

- Furthermore, it has been found that the evening peak is expensive under the current Danish price scheme, and about 76% of the savings provided by the MPC during the full study can be obtained just by blocking the heat pump in the evening peak (in the hours from 17 - 21). The overall conclusion is that the controller presented here can efficiently provide load shifting services with current technologies. This said, the incentives need to be stronger for this method to be broadly accepted and installed.
- Savings due to lower forward temperature/higher flow was investigated experimentally, and the COP of the specific heat pump was calculated. The effect of lowering the forward temperature is highest when the ambient temperature is relatively high. The study only saw a saving rate of 2.3 % but one should keep in mind that the heat curve was well adjusted from the beginning in this case.

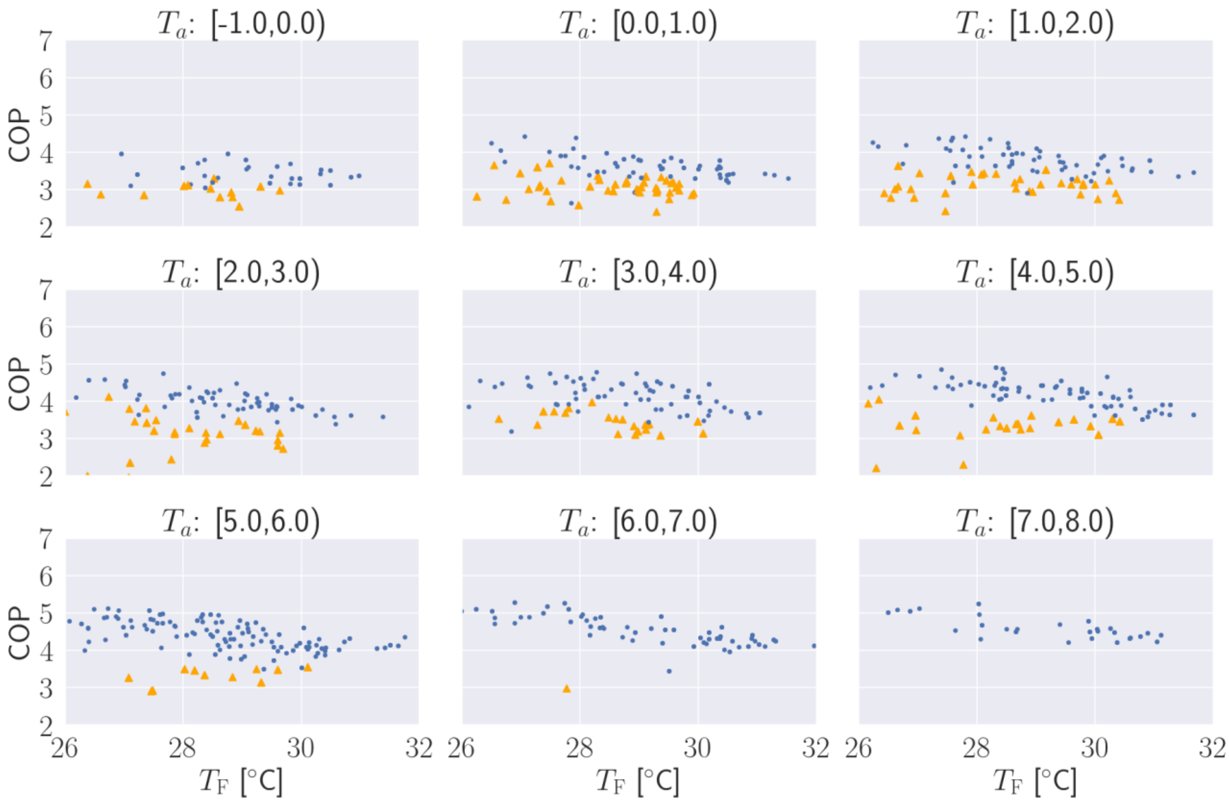


Figure 5 The relationship between forward temperature T_F and COP at different outdoor temperature intervals T_a. Each blue dot represents a COP estimate observed over a full hour. The orange triangles show the COP of an hour where the heat pump performed defrosting.

- It must be noticed that the rather modest savings obtained by using the MPC controller in the house in Kalundborg are not representative for an average dwelling. Firstly, the owner is very dedicated and technically competent regarding installation and adjustment of the heating system, thermostats etc., so the heat pump was running efficiently at a low temperature from the beginning. Secondly, the house is a low energy house, so the reference consumption was already low. 10-12% cost savings seem possible based on experience from other installations made by Neogrid.
- Battery data from a single-family house in Roskilde have been collected and analyzed. The data show that the battery is fully cycled on sunny days, and that the average round trip efficiency is approximately 85%. The losses are mostly related to the bidirectional DC/AC converter. These data have been used to adjust the battery model in the controller of the DTI test rig. Here it has been shown that a simple charge/discharge controller which is mainly used today in most of the battery inverters on the market can be improved by up to 20% by applying a more advanced Mixed-Integer Linear Problem (MILP) to

take into considerations of when to charge and when to discharge from an economical and energy wise perspective.

- The test rig at DTI was modified during the project, so that it is now able to run repetitive test sequences in order to compare different control strategies and parameter settings in households with heat pump, PV system, and/or battery storage. The reconstruction of the test rig included several major steps:
    - Change of the old heat pump to a new model from Bosch.
    - Addition of a large buffer tank for brine to stabilize the temperature control of the simulated ground source loop.
    - Connection to a new cooling circuit in the building.
    - Improvements in software and electronics.
    - After these changes, the system was used to test the control strategy with different scenarios for load and production profiles.

For a test during 5-day simulated winter period was the results below were achived with a simple battery control representing how most of the battery inverters are controlling today. 1st graph is the electricity consumption by heat pump and household appliances. 2nd balance between grid and PV production. 3rd battery charge/discharge balance and state of charge. 4th electricity prices divided into spot price, tariff, and tax. 5th accumulated operational cost during test period. 6th accumulated total grid balance during test period. From the 3rd graph can it be seen that the battery is only utilised to a minor extend, and some days the battery is not used at all:

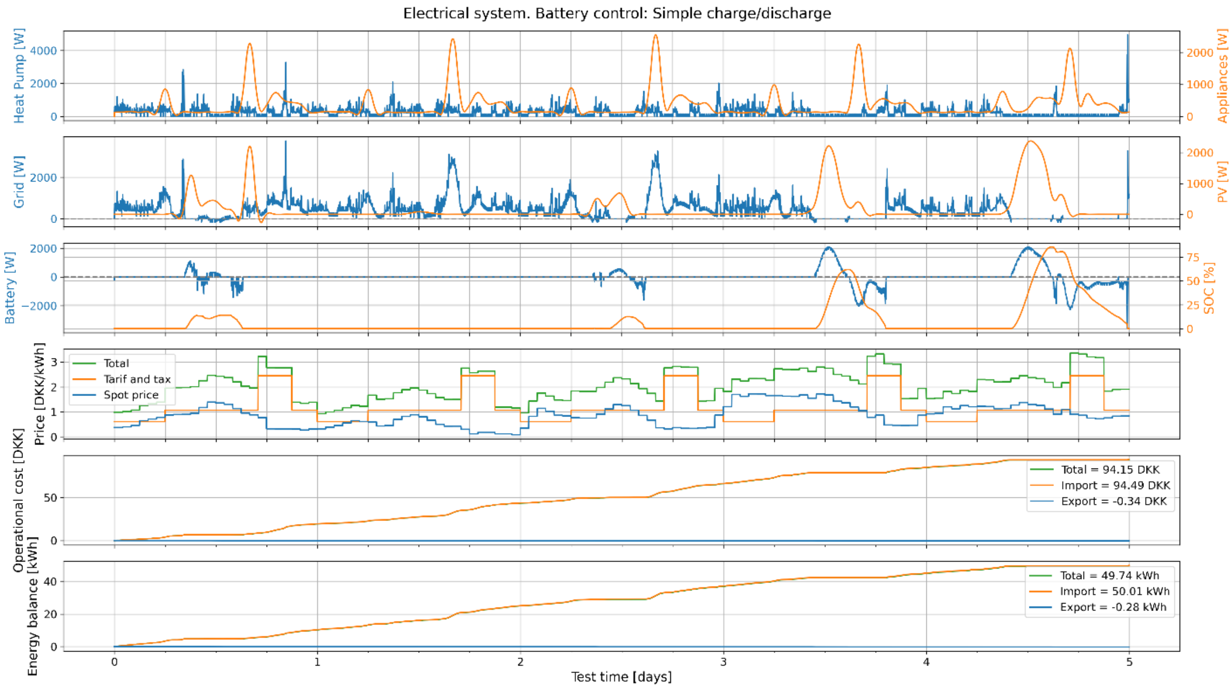


Figure 6: Meassured data from the Opsys testrig at TI, batteri control is simple charge/discharge.

By applying the more advanced MILP control algorithm the result is now far more interesting when looking at how the battery are included, the results are presented in the figure below:

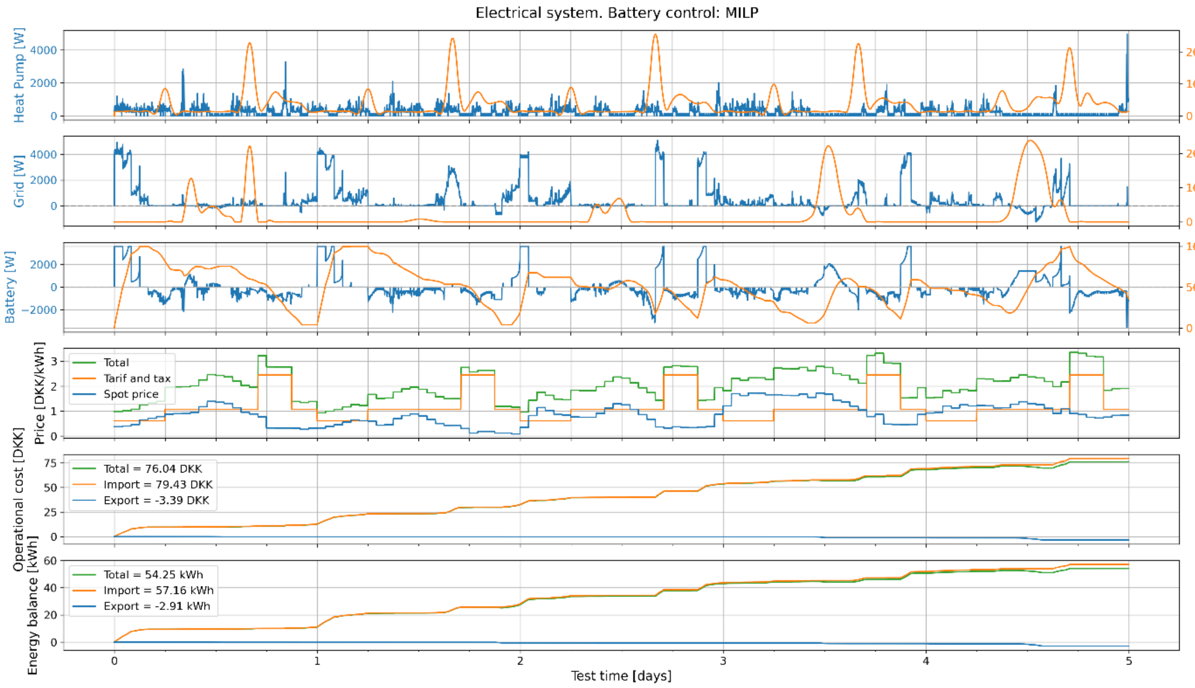


Figure 7: Meassured data from the Opsys testrig at TI, batteri control is advanced MILP.

Now the battery is used more frequently and more charged/discharged compared to the same period with simple control. The operation cost with simple control is in total 94kr compared to 76kr for the same period just with a smarter control, this leads to a total saving potential of up to 20%.

Dissemination of results

Target groups for the project results and dissemination material are partly academics working with building physics and simulation models, in particular MPC controllers, and partly a more practically oriented audience. The technical report (in Danish) is intended for installers, electricians, and product providers within heat pumps, hydronic heating systems, PV systems, and home automation. Some of the content has been used in DTI´s courses.

5.1 Publications

5.1.1 Conference papers

Paper 1

Conference: Cold climate HVAC and energy 2021; **Title:** Model predictive control of heat pump based on a regression model fitted to data measured in accordance to EHPA regulation; **Authors:** Simon Thorsteinsson, Søren Østergaard Jensen, and Jan Dimon Bendtsen; **Status:** Published; **DOI**: https://doi.org/10.1051/e3sconf/202124611008

Paper 2

Conference: CLIMA 2022: the 14th REHVA HVAC World Congres; **Title:** Transient analysis of individual return temperatures in hydronic floor heating systems; **Authors:** Simon Thorsteinsson, Henrik Lund Stærmose, and Jan Dimon Bendtsen; **Status:** Published; **DOI**:

5.1.2 Presentations

Presentation 1

Conference: 8th international conference on smart energy systems; **Title:** Flexible heating experiment of BK2020 house. **Authors:** Simon Thorsteinsson.

5.1.3 Journals

Article 1

Journal: MAGASIN FOR KLIMA- & ENERGITEKNIK, MILJØ, BYGNINGSINSTALLATIONER & - NETVÆRK / HVAC no. 1, January 2023; **Title:** Intelligent energistyring i husstande; **Authors:** Simon Thorsteinsson, Ivan Katic, Henrik Lund Stærmose, Brian Nielsen, Søren Dueholm; **Status:** Published.

5.1.4 Paper archives without review

Article 1

Archive: arXiv; **Title:** Long-term experimental study of price responsive predictive control in a real occupied single-family house with heat pump; **Authors:** Simon Thorsteinsson, Alex Arash Sand Kalaee, Pierre Vogler-Finck, Henrik Lund Stærmose, Ivan Katic, Jan Dimon Bendtsen; **Status:** Published, DOI: https://doi.org/10.48550/arXiv.2303.16289

5.2 Unpublished dissemination, in review or abstract accepted

In order to collect as many results as possible, the control demonstration ran until the 7th of march resulting in some publications being delayed to after project deadline. Other dissemination has been given during internal meetings with public agencies. A list of the above mentioned is given here.

Presentation 1

Status: Presented; **Outlet:** Danish Energy Agency; **Title:** Price responsive control of commercial heat pump.

Journal article 1

Status: In review; **Outlet:** Applied Energy; **Title:** Long-term experimental study of price responsive predictive control in a real occupied single-family house with heat pump; **Authors:** Simon Thorsteinsson, Alex Arash Sand Kalaee, Pierre Vogler-Finck, Henrik Lund Stærmose, Ivan Katic, Jan Dimon Bendtsen.

Conference article 1

Status: Abstract accepted; **Outlet:** CISBAT 2023; **Working title:** Making a domestic air-source heat pump smart-grid ready by overwriting the ambient temperature signal; **Authors:** Simon Thorsteinsson, Hanmin Cai, Jan Dimon Bendtsen, Philipp Heer, Jacopo Vivian.

6. Utilisation of project results

A judgement of the commercial results of the project is difficult, but since the beginning of the project, Neogrid has sold about 300 control units which at least to some extent is a result of the project. They expect their turnover to increase by 9 mill DKK over a time horizon of 5 years and as well as to hire 4 full-time employees.

For the other partners, the main benefit is the acquired knowledge on DSM and advanced control.

Market competition

The market for smart energy management systems for households is rapidly growing due to new and cheap internet connectivity of many devices such as heat pumps, inverters, thermostats, and EV chargers. The following products from the Danish smart home market have been identified as potential competitors:

SGX-01

Smartgrid X is a box that can disconnect the heat pump during periods of high electricity price. It activates via a potential-free switch / SG interface.

Figure 8: Simple box for appliance control.

The SGX-01 control box receives data every 10 minutes from the SGX Cloud where the forecast is continuously updated. This forecast takes into account the electricity price (and not just the current electricity price), the hourly differentiated tariff, wind, and temperature. A further description of the subscription types can be found at http://www.smartgrid-x.com

Assessment: With a price of just under DKK 800 and DKK 29/month in subscription, it will probably appeal to some homeowners. However, it is unclear how much better the product is than a simple contact watch that disconnects during the most expensive hours.

Tado

Figure 9: Control via IR interface to air/air heat pump (Tado)

This control box replaces IR remote control of air/air heat pumps and does not appear to be directly compatible with heat pumps for central heating. However, it can turn thermostats from the same company up and down so that one can increase or decrease the central heating.

Ngenic Tune

The smart thermostat Ngenic Tune is a self-learning system for control of heating systems. It is compatible with several heat pump brands.

Ngenic Tune controls the heating by adjusting the outdoor temperature that your heating system is measuring, so that it sees a different temperature than the actual one. On some heating systems, this value will be shown on the display.

With multiple indoor sensors, Ngenic Tune can control the heat in the house even better. You just need to select which sensors that should be used, and Ngenic Tune will then control the heat of the house using the average value of the selected sensors. You also get a complete overview of the historic data in the mobile app which can be useful for balancing the heat between different parts of the house with the help of thermostats or underfloor heating controls.

Figure 10: Control kit from NGenic.

The system consists of a weather sensor, an indoor climate monitor, and a gateway. According to the homepage, it costs 5.500 SEK, excl. installation. https://ngenic.se/en/tune/.

DIY via PreHEAT platform

Neogrid has suggested a very simple solution that may compete with their own PreHEAT box in certain cases. However, the DIY solutions could appeal to house owners that just want to have a simple cheap setup blocking the heat pump in expensive hours.

Neogrid provides a description of compatible wifi relays which can either be purchased at Neogrid or elsewhere and a guide to connect this to the Neogrid Backend.

After setting up an account at Neogrid and connecting the Wi-Fi relay, Neogrid provides control schedules for the specific heat pump installation based on prices, tariffs, outdoor temperature, wind, and sun dynamically trying to avoid high price hours and maintaining the required indoor climate.

Via an app, the user can see prices, and when the heat pump is blocked.

Wi-Fi relays can be purchased for prices below 200 DKK, and the monthly subscription will be in the range of 30 DKK.

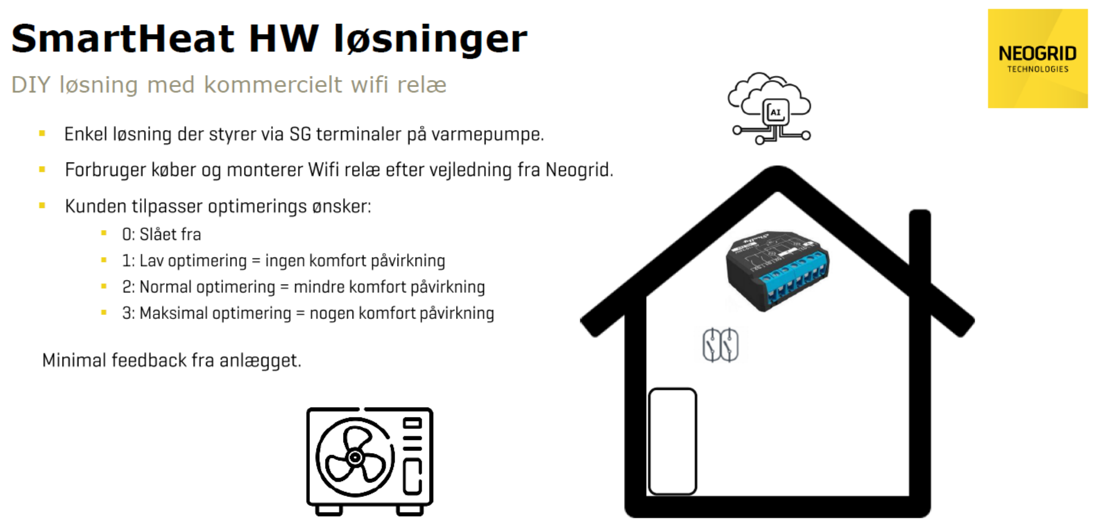


Figure 11: Simple relay control via Neogrid´s own user portal.

Smart home systems (SMA, Fronius), including all appliances

Many manufacturers of PV inverters and/or grid connected batteries have developed smart home controllers with many of the functionalities developed in OPSYS 2.0. However, they do not regulate floor system heating directly (so far).

Figure 12: Integration of battery storage, PV system, EV charger etc. Available from SMA inverters.

Furthermore, these systems are mostly simple rule-based systems only reacting on the present situation. i.e., if there is an excess production from PV, the battery is charged, and if there is a consumption in the house, the battery is discharged prior to consuming from the grid. These solutions are not able to determine if it had been a better business case to consume from the grid due to low prices and then consume from the battery during high prices. The latter is what we achieve with the OPSYS solution.

As these systems are mostly designed for local operation, it can be difficult to interface to them and manipulate the predefined rules – there are no interfaces allowing third parties to connect and control.

Some known brands with such functions from the Danish solar PV market are:

- SMA (AC Battery, PV inverters and user dashboard for system control)
- GROWATT (integrated PV and battery solutions with hybrid inverter).
- FRONIUS (PV solutions with use of excess electricity for heating or EV charging).

Remarks to the market situation

When the project started, the incentives regarding grid flexibility (load management) for private electricity consumers were very limited due to relatively low tariffs and stable electricity costs. The only incentive was that PV system owners could benefit from self-consumption instead of selling their surplus at spot market price.

Today, the situation is completely different:

- The war in Ukraine has caused the market price of electricity to increase, as it is closely connected with the gas price.
- Introduction of Tarif model 3.0 has led to huge daily variations of (transport) tariffs with a very high peak in the hours from 17 - 21.
- The temporary cancelling of electricity tax combined with low night tariffs has made night electricity much cheaper.

For households with PV, battery and heat pump it is a very complex optimization problem to find the mode of operation that minimizes the total cost, but this is exactly what the PreHEAT box with MPC algorithm does. The increased price dynamics is therefore a benefit for sales potential.

Energy policy objectives

In the light of the recent geopolitical situation and gas crisis, it is even more welcome now than at project start to replace gas fired heating systems in our buildings with heat pumps and solar energy. EU's energy plan Fit for 55 and the suggested solar PV obligation on new buildings are perfectly aligned with the project idea and results. So, the Danish and European markets seem open to embrace the developed solution among (less advanced) competitive products.

Sales barriers

The main barrier for the developed system is first of all cost. The advanced PreHEAT box (Avenger) is probably too expensive for small households with a low-cost saving potential, but its "little brother" (Predator) would be suitable. The installation requires skilled labour and time for adjustment and control of functions. Especially the interface with the heat pump and floor heating system is critical, so a further development in direction "plug-and-play" is important. In practice, heat pump manufacturers will need to give access to at least some part of their control system. Today, some manufacturers offer a Smart Grid interface (SG) based on German guidelines, but this only offers limited control options. The idea of SG interface is good, but despite its simplicity there still seem to be problems and different approaches on how each manufacturer has implemented it.

Based on the experience from the project, the following solutions would be suitable depending on the existing or planned technical installations in a given house:

Recommended solution:	Heat pump	Floor heating (thermal storage)	PV system	Battery (electrical storage)
Simple SG control	x			
Predator	x	x	X	(x)*)
Avenger	x	x	X	x

*) Depends on the interfaces provided by the hybrid inverter.

Updated business case

In the project application, a reference case was elaborated for a single-family house with PV and heat pump installation which showed that the major incentive was the opportunity to increase PV self-consumption. With the current change of electricity prices and tariffs, this case has been recalculated:

If assuming a typical electrically heated house with a total annual consumption of 12,000 kWh and a PV production of 6,000 kWh (6 kWp system), the following numbers are found by simulation with DTI's own tool developed in a recent project [ELFORSK project no. 349-063: Udnyttelse af solcelle-el i énfamiliehus med batteri og varmepumpe]:

- 3,320 kWh sold to the grid
- 8,972 kWh purchased from the grid
- PV self-consumption 48% (the rest is sold)
- Net cost = 2.7 * 8,972 - 0.75 * 3,320 = 24,224 - 2,490 = 21,734 DKK.

In this simplified calculation, average tariffs of 2.7 DKK/kWh purchased electricity and 0.75 DKK/kWh for sale to the grid are assumed (extremes due to the war in Ukraine have been excluded).

With the integration of a 5 kWh battery storage, the numbers found by simulation become:

- 2,087 kWh sold to the grid

- 7,733 kWh purchased from the grid
- PV self-consumption 67%
- Net cost = 2.7 * 7,733 - 0.75 * 2,087 = 20,879 - 1,565 = 19,314 DKK
- Increased income = 21,734 - 19,314 = 2,420 DKK/year.

A 5 kWh electrical storage is comparable with 15 kWh thermal energy delivered by the heat pump assuming: COP = 5 kWh / 15 kWh = 3. A 10 cm thick concrete floor of 100 m² and cycling with 3 K has a thermal capacity of about 45 kWh. Therefore, a traditional underfloor heating system can very well be used as a dump load for excess solar PV power (as long as there is a heating demand).

The best solution in practice will likely be to use a relatively small battery in combination with a larger thermal storage. Batteries are still very costly per kWh, but they make sense as short-term storage in combination with a heat pump and a thermal storage. By using a battery, the heat pump can run on solar PV for longer periods – even if there are drifting clouds. Batteries can further help prevent curtailment of PV electricity at peak production.

Business case with differentiated tariffs:

This is an example of storage of cheap electricity as thermal energy during periods with expensive electricity. The current tariffs from Radius are:

Aktuelle priser 1. marts 2023

Med moms / Uden moms

C | B-lav | B-høj | A-lav | A-høj

Aktuelle priser (øre/kWh)	Lavlast	Højlast	Spidslast
Vintertarif (oktober – marts)	18,86	56,60	169,80
Sommertarif (april – september)	18,86	28,30	73,59

Figure 13 Website from Radius.

Maximum difference in winter = 1.70 – 0.19 = 1.51 DKK/kWh.

If the heat pump can be disconnected between the hours from 17 - 21, from October to March, the savings can be estimated to:

- Annual consumption 8,000 kWh (out of 12,000 total electricity)
- ¾ of load estimated to be in winter season = 6,000 kWh
- 4/24 of the time running in high load period: 4 hours * 6,000 kWh / 24 hours = 1,000 kWh that can potentially be shifted to low price periods.
- Savings = 1,000 kWh * 1.51 DKK/kWh = 1,510 DKK/year.

This is at least 4 times higher than the estimate at project beginning and indicates that many heat pump owners can benefit from the Neogrid controller. If this load shifting becomes a requested service by the DSO, the value for the owner of the heat pump may become higher.

Related activities

Ph.D. student Simon Thorsteinsson from Aalborg University (AAU) has been affiliated with the project, and results from the project have been used in several teaching and other dissemination activities. The following projects at AAU have been running at AAU as spin-off from OPSYS 2.0:

- 7th semester project (5 students):
  "Rule Based Electricity Price Responsive Control for HVAC System Using Thermal Energy Storage".
- 7th semester project (5 students):
  "Identification of Dynamics and Modelling for a Multivariable HVAC System".
- MSc project (2 students):
  "Control of heating in a low energy single-family house".
- 8th semester project (5 students):
  "MPC based electricity cost optimization of thermal energy storage powered by heat pumps".
- MSc project (2 students):
  "Model Predictive Control of Residential Central Heating using Economic and Weather-based Data".

7. Project conclusion and perspective

The work with the OPSYS 2.0 project has paved the way for taking new and important steps towards grid flexibility and optimization of hydronic heating systems with heat pumps as well as for energy storage in grid connected PV systems. The original objectives were achieved with respect to development of hardware and software that can provide cost optimized model predictive control (MPC) of a family house using electricity at time variable cost as primary energy source.

The results obtained during four months in the winter 2022-2023 show that load shifting can reduce heating costs by 11% in the Kalundborg House only by activating the heat capacity of the building structure and without reducing the temperature comfort. The production patterns have been shifted to support the grid through increased consumption at night and by shutting the heat pump down in the evening peak.

Furthermore, it has been found that under the current Danish electricity price scheme of 1. January 2023, the evening peak is the decisive cost factor, and about 69% of the savings provided by the MPC can be obtained just by blocking the heat pump in the evening peak. Full or partial shutdown in the evening peak should immediately be broadly implemented. This rule creates correlated consumption patterns which might become problematic for the grid in the future. However, a simple shut down during these hours, does not necessarily keep the required indoor temperature, which is secured by the more advanced MPC controller.

In case the grid operators wish to use a more coordinated approach, controllers of the type presented here are needed. However, at the moment, the cost reduction obtained from price responsiveness cannot cover the costs of acquiring such capabilities, and therefore more financial incentives need to be provided. The ambient temperature override applied to control the heat flow of the heat pump has proven to be a functional but inefficient way to make it smart grid-ready. A dedicated input for reference control as a standard is desired if an advanced control of heat pumps should be the norm.

The expected energy savings due to direct control of the floor heating valves was limited because the heating curve was already well-adjusted to meet the actual demand in the test house. The measurements showed the largest potential for energy savings on relatively cold days with a high degree of sun because the controller would then predict the solar heating contribution in advance and restrict the heat pump from starting.

At DTI the test platform has been successfully modified (after several iterations) and a new controller installed that can activate hot water tapping and heat pump relays. It was demonstrated that different control strategies could be compared under the same boundary conditions and compared with respect to consumed electricity and total cost (hardware-in-the-loop platform). By including a model for PV generation and battery storage (besides the thermal storage), it is now possible to investigate many different sizes and system configurations.

Test results from the test rig at DTI show that the advanced control algorithm saves money compared to simpler strategies. The simple strategy was to charge/discharge at the exact moment from an energy calculation to even out export and import. The more advanced control consisted of forecasting 24 hours in the future to predict when it was most economical to use the stored energy in the battery. By implementing this one could save up to 20% on operational cost in power price.

Next steps and perspectives

Though the basic aim was fulfilled in the project there is clearly still room for improvement and simplification of the control system. The project has shown, in theory and practice, how weather-compensated heat pumps can provide energy flexibility through manipulation of the outdoor temperature sensor. This method was used, as there is currently no general method (standardized interface) by which the heat pumps can be controlled. Preferably, heat pumps should have an interface to allow external control of certain parameters such as the detected outdoor temperature. It is not a generic solution to use "home-made" bypass control like in the current project. It is important that simple retrofit solutions are developed, as the heat pumps sold today cannot otherwise achieve their full potential in terms of supporting the electricity grid.

We propose a simple solution where the heat pump can run in two modes: coexistence and cooperation. *Coexistence* is the mode of operation most often seen today where the heat pump solves its task relatively independently and ignorant of other systems in the building such as PV, battery packs, etc.

Cooperate is the state in which the heat pump is able to exchange information with other energy assets in the system to achieve a more optimal goal than those that can be formulated for individual components. Examples of this: The heat pump runs according to maximum efficiency (COP), the heat distribution system controls according to maximum temperature comfort and the pumps according to a third measure. We need to move away from a situation where every component only aims at its own goals to where the entire system is controlled according to optimal electricity and heat consumption defined by the available energy assets in question, so that the end customer achieves the desired comfort while minimizing the cost of heat.

Most heat pumps already have an app associated with it – i.e., the heat pump can communicate to a cloud platform from which others can theoretically get access. It just doesn't happen, as these solutions are most often proprietary. The reasons against making this option available are external control risks damaging the component and that companies see it as a competitive advantage to keep the API closed.

To address the first problem, it is proposed that control signals are references, i.e., a proposal for the control in which the component retains a "veto right". Example: the heat pump takes an external reference for heat production, but only follows the reference if it is mechanically sound.

To counter the second argument, one should consider whether closedness with respect to the API leads to a *"winner-takes-it-all"* mode where only those manufacturers who can provide total solutions – covering the value chain from sensors to controls designed for entire buildings or areas. In the long run, we should aim for standardization not only of communication protocols but also of the information to be exchanged between systems. In the short term, it would be a big step if a third party could have access to read internal meters and to adjust control signals for heat and hot-water production.

In the future construction materials should be more sustainable and there will be a growing fraction of wooden buildings with little thermal mass instead of current heavy concrete. The developed MPC should therefore be verified for such buildings too and for other climates than the Danish. Especially, the system would be interesting for colder and sunny climates where there is a high heating demand during winter but also significant PV production to power a heat pump.

8. Appendices

Appendix 1: Technical report (In Danish)

Appendix 2: List of publications

Appendix 3: Overview of the DTI testrig