Annex 55

Comfort & Climate Box – towards better integration of heat pumps and storage

Final Report – Part 5

Research Projects

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA
The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)
The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration, and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or "Annexes", in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

Disclaimer
The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organized under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The Heat Pump Centre
A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimize the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organizations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:

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Comfort & Climate Box – towards a better integration of heat pumps and storage

Final report of the combined ES Task 34 and HPT Annex 55

Part V – Research Projects

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Contents

READING GUIDE:
The variety in projects in this report might work somewhat confusing to find the information which should meet each individual interest. Therefore we have marked the reports which can be considered has containing specific knowledge of projects containing significant energy storage elements with an 'italic' and bold font title in this table of contents. The regular font marked projects contain more information from straight ahaead heat pump projects combined with misceleaneous storage options affiliated with heat pump technology.

1 Introduction

This document gives an overview of research projects that have been carried out within the Annex framework, supplemented by some earlier findings that relate to the work from this Annex. Many of the research projects are still ongoing (as of July 2021). For those projects, preliminary results have been shared here. Further results are to be expected during 2021 and 2022.

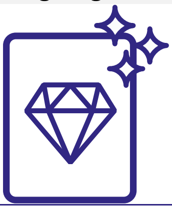
This project overview gives an impression of the breath of work that can be done on the CCB concept. While most of the projects have at least a minor focus on efficiency, affordability, flexibility and compactness are also gaining ground. This will help speed up the development of market-oriented CCB packages, that will provide efficient renewable heating and cooling to a broad range of customers.

The table below gives an overview of the available projects and their main strategic focus. For more information, contact information is provided in each project chapter.

Implementation strategy / **Project name**	Affordability	Compactness	Flexibility	Efficiency
(AT) Energy4Buildings				X
(AT) HybridHeat4San				X
(AT) HYBUILD		X		X
(CA) CCB prospects for Canada	X	X		
(DE) Smart-CASE-NZEB			X	X
(DE) Low charge HP circuit using propane		X		
(SE) CCB solutions for Sweden	X		X	
(UK) Smart Community Demonstration	X		X	
(UK) HP data from RHPP scheme				X
(UK) Freedom project			X	X
(UK) H2020 Chess-setup	X			X
(UK) Ulster University terrace st.	X		X	X
(US) Low cost PCM	X			
(US) HP with integrated thermal storage			X	X
(US) HP with underground PCM storage		X		X

Table 1 – Overview of projects with their associated implementation strategies.

2 (AT) Energy4Buildings

Country	Austria
Contact	Thomas Schoberer University of Applied Sciences Burgenland thomas.schoberer@forschung-burgenland.at
Status	Ongoing
Main CCB implementation strategies	 Energy Efficiency

The project energy4buildings is funded by the Austrian Ministry for Transport, Innovation and Technology BMVIT and the Austrian Ministry of Economy, Family and Youth BMWFJ within the funding scheme COIN.

2.1 Project goal

Within the project "energy4buildings" a test bench has been realized to create an interface between hardware, located in a laboratory, and a building simulation software. This integrated test bench with focus on electrical driven heat pumps and chillers can be used to simulate realistic conditions like part load behavior, stand-by-losses, on/off behavior or user-/weather conditions. To realize a so-called hardware-in-the-loop (HIL) method, simulation models of buildings, including different types of building technologies, have been designed. To validate the models, a mobile data acquisition system has been implemented to monitor the indoor environment like temperature, carbon dioxide, humidity as well as energy flows of the heat pump and storages. Measurements at a single-family house have been performed over a few weeks including both heating and cooling periods.

2.2 Project setup

For the measurement object a single-family house (heating energy demand ~25 kWh/m^2/a, gross floor area 300 m^2) with a capacity-controlled brine/water heat pump (6 kW thermal power output) in combination with a ground collector for space heating, as well as domestic water heating has been used. The heat pump is equipped with an external domestic hot water tank with a built-in heating element, which can optionally be coupled with solar thermal energy. In addition, a ventilation (MVHR) system and a PV system are used for the measurement object. The heat pump as well as the ventilation system can be controlled remotely via building automation. The heat pump is coupled to the PV system and modulated based on the PV power.

2.3 Status and time planning

Field measurements were carried out seasonally during the heating period in early 2020 and 2021 (ongoing) as well as in summer 2020. Data points were attached to balance the thermal output at the heat source and heat sink of the heat pump, as well as the domestic hot water storage tank. The power consumption of the heat pump, the yields from PV and consumption of the entire household and the technical room were determined electrically. To determine the boundary conditions, the outside temperature (2021) and partly global radiation (2020) were recorded. Performance figures for heating and DHW were calculated over the recorded period. High sampling rates provide information about user profiles. In order to assess and optimize the self-consumption rate, the house owner implemented a control system via the building management system, which uses excess power for hot water preparation or heating (up to the maximum value as required) in the event of excess electricity, depending on defined limit values. Key figures were calculated for heating and hot water operation. In addition, the PV excess electricity was determined. The field measurements were part of a work package from the project, which was completed in 2018. Measurements are still being carried out.

2.4 (Preliminary) results

The table below gives the first preliminary measurement results, based on the definitions below:

$$SPF_{sys} = \frac{\int (\dot{Q}_{SH} + \dot{Q}_{DHW})\, dt}{\int P_{el\ HP\ in}\, dt}$$

$$SCR = \frac{\int (P_{el\ PV} - P_{el\ \mathrm{feed\ in}})\, dt}{\int P_{el\ PV}\, dt}$$

Description	Variable	Value	Unit	System
Seasonal performance factor – system	SPF_{sys}	3,69	-	HP (SH+DHW)
Thermal Power system	$\dot{Q}_{sys}$	4,92	kW	HP (SH+DHW)
Self-consumption ratio of the PV system ($P_{el\ \mathrm{feed\ in}} < 0$)	SCR	0,70	-	PV

Table 2 – Exemplarily field measurement results in March 2021.

2.5 CCB implementation strategy

The current measurement setup in the project refers to the "Energy efficiency" CCB strategy. The integration of heat pump, storage and PV shows good efficiency figures, but has high investment costs and requires a lot of space in contrast to a compact device. An application for heating, cooling, hot water preparation as well as a coupling with PV and remote control is possible. The system used is applied to a low-energy house. The modulated heat pump is particularly suitable for systems with photovoltaic systems with a focus on the optimization of the internal consumption. Access via building automation and remote is possible. A ground collector is used as heat source.

3 (AT) HybridHeat4San

Country	Austria
Contact	Andreas Heinz Technical University Graz andreas.heinz@tugraz.atmailto:thomas.schoberer@forschung-burgenland.at
Status	Ongoing
Main CCB implementation strategies	Energy Efficiency

3.1 Project goal

The project HybridHeat4San ("Highly efficient combinations of photovoltaics and heat pumps for the refurbishment market") is focused on the development and analysis of a hybrid heating system for space heating and domestic hot water that is designed to enable an energy-efficient supply of renovated residential buildings with an existing radiator heating system, requiring high flow temperatures. A reduction of the overall electricity consumption is achieved by an efficient air-source heat pump using the natural refrigerant R290 (propane) and an optimized integration of a water combi storage tank (combi store). The heat pump is coupled to a PV system with the aim to reduce the electricity consumed from the grid by targeted operation of the compressor with PV electricity using intelligent control strategies. The described system is analyzed using detailed system simulations in TRNSYS and results are compared to a defined reference system using a set of performance indicators. Different control strategies are evaluated concerning the fulfilment of the project objective, which is to reach a reduction of electricity consumption from the grid of 25 % compared to the reference system. The influence of the PV size on performance figures and the operational (electricity) costs is analyzed.

3.2 Project setup

The described system is analyzed using detailed system simulations in TRNSYS. The main components of the proposed system were tested in the laboratory of IWT (heat pump) and SPF Institute for Solar Energy in Rapperswil (storage tank), whereby the results of these measurements were considered in the parametrization of the used simulation models. The complete heating system will be tested at SPF in a 6-day Hardware-in-the-Loop system test, the so-called Concise Cycle Test (SPF, 2021), which enables an extrapolation to annual results. The aim of this test is to confirm the results of the simulation work carried out within the project and the calculated performance figures.

3.3 Status and time planning

Modelling and system simulations are finished. All components of the system were built and assembled for the Hardware-in-the-Loop (CCT) test. The CCT was just finished, results are not yet available.

3.4 (Preliminary) results

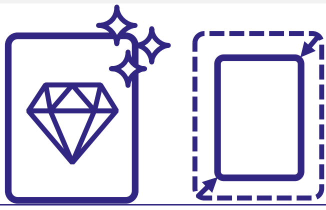
Results of simulations are shown in the table below and show that the electricity consumption from the grid can be reduced by 32% as compared to the reference system. The self-sufficiency ratio of the system

(SSR) can be improved from 0.19 to 0.35. Results from hardware-in-the-Loop test will be available in the future.

System		Reference system	System development
$W_{el,sys}$	kWh/a	6726	6242 (-7.2 %)
$W_{el,sys,grid}$	kWh/a	5807	3964 (-31.7 %)
$W_{el,grid}$	kWh/a	7902	6059 (-23.3 %)
$W_{el,feedin}$	kWh/a	6877	5518 (-19.8 %)
SPF_{HP}	-	2.71	2.90 (+7.2 %)
SPF_{sys}	-	2.27	2.43 (+6.8 %)
$SPF_{sys,PV}$	-	2.63	3.82 (+45.2 %)
SSR_{sys}	-	0.19	0.35 (+81.1 %)
SSR_{tot}	-	0.14	0.36 (+167 %)
SCR	-	0.21	0.37 (+72.2 %)

Table 3 – Water loop results.

4 (AT) HYBUILD

Country	Austria
Contact	Johann Emhofer AIT johann.emhofer@ait.ac.atmailto:thomas.schoberer@forschung-burgenland.at
Status	To be finished in 2021
Main CCB implementation strategies	 Energy Efficiency Compactness

4.1 Project goal

HYBUILD focuses on the development of two innovative compact hybrid electrical/thermal storage systems for stand-alone and district connected Buildings. The project aims at developing cost-effective and environmental-friendly solutions, while ensuring comfort conditions in residential buildings located in two different climates: Mediterranean climate where cooling is critical; and Continental climate where a stronger focus is put on heating demand. The project is led by the Spanish group COMSA Corporación and it associates 21 partners from 11 EU countries. It started in October 2017 and is running for 4 years. The project was selected as part of the Energy-efficient Buildings Public-Private partnership. AIT is responsible for the design of the Continental hybrid sub-system. The Continental hybrid sub-system uses a latent storage which is directly integrated into the heat pump cycle to utilize mainly sensible heat of the refrigerant after the compressor. With this novel desuperheater/storage, it is possible to generate domestic hot water (DHW) with a higher efficiency compared to state-of-the-art system.

4.2 Project setup

Within HYBUILD AIT and its Partners have:

- demonstrated the feasibility of the Continental system by implementing the entire system including the auxiliaries for three artificial apartments in the lab at controlled environmental conditions.

assessed the performance of the Continental system and compared it to a conventional heat-pump-system without the novel desuperheater/storage.
identified the critical points of the system and discussed them based on simulations, results from experiments and experiences during the implementation phase.

4.3 Status and time planning

Experiments in the lab and simulations are finished. Monitoring of the HYBUILD Continental System has started in March 2021 at the demo-site in Langenwang, Austria at the facilities of PINK GmbH.

4.4 (Preliminary) results[1]

The lowest payback time of 12.4 years, the highest energy savings per year of 622 kWh_{el}, and the highest profits after 20 years of 1083 EUR were found for an operating scenario with a passive house located in Helsinki with 7.75 standard apartments. The results of this work indicate that, although there is significant potential for energy savings in a refurbishment building in hot climate, from the economic point of view, the proposed system is better suited for a low energy building in average- and a passive house in cold-climates considering an average European electricity price of 0.22 EUR/kWh at the time of installation and a discount rate of 2%.

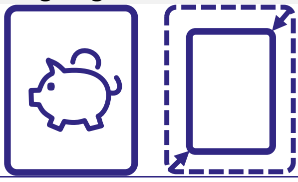
4.5 Experiments in the lab[2]

Technical feasibility and operation with rule-based control strategies have been successfully demonstrated for realistic use cases. Besides individual tests, the heat pump was operated over 48 hours with and without RPW-HEX at an ambient temperature of -2 °C, a feed water temperature for the heating system of 40 °C and an artificial tap water usage of 5.845 kWh per storage and day. Both systems, achieved the same average COP, but the RPW-HEX system was able to provide a 10 K higher average feed water temperature for DHW generation compared to the system without RPW-HEX. For the same feed water temperatures for DHW generation, an enhancement of about 3.1% of the average COP can be expected with the current system. This is about 60% of the theoretically possible value. Furthermore, for a low feed water temperature for heating of about 32 °C at -2 °C, an enhancement of the average COP up to 9.4% can be expected for the analyzed heating and DHW scenario with an improved design.

[1] J. Emhofer, K. Marx, T. Barz, F. Hochwallner, L.F. Cabeza, G. Zsembinszki, A. Strehlow, B. Nitsch, M. Wiesflecker, W. Pink: ***Techno-Economic Analysis of a Heat Pump Cycle Including a Three-Media Refrigerant/Phase Change Material/Water Heat Exchanger in the Hot Superheated Section for Efficient Domestic Hot Water Generation***; Applied Sciences, **10** (2020), 21; S. 7873.

[2] J. Emhofer, K. Marx, A. Sporr, T. Barz, B. Nitsch, M. Wiesflecker, W. Pink: ***Experimental demonstration of an air-source heat pump with a short term PCM storage operating as a desuperheater for energy efficient DHW generation in residential buildings***; Manuscript in preparation (not published)

5 (CA) CCB implementation prospects for Canada

Country	Canada
Contact	Justin Tamasauskas NRCan justin.tamasauskas@canada.camailto:thomas.schoberer@forschung-burgenland.at
Status	Ongoing
Main CCB implementation strategies	 Affordability Compactness

5.1 Introduction

Through the recently tabled *Canadian Net-Zero Emissions Accountability Act,*[3] Canada has outlined its desire to reach carbon neutrality by 2050. Achieving this target requires appropriate space conditioning systems capable of supporting a reduction of emissions associated with the built environment. Canada's *Market Transformation Roadmap*[4] presents a framework for the increased adoption of these systems, outlining key aspirational goals regarding system performance (seasonal heating efficiency >100%) and the integration of renewable energy. Heat pumps are a key element of this *Roadmap*, leveraging renewable energy sources to support an efficient space conditioning.

While heat pumps are an essential tool in reducing emissions associated with the built environment, their widespread implementation in Canada can pose a significant challenge for electrical grids. Heat pump use coincident to other electrical end uses (e.g., lighting, equipment, hot water) can result in a significant increase in house-level electrical demand. This situation may be further exacerbated when considering supplementary electric resistance heating commonly used to supplement air-source heat pump operations during cold winter days, which tends to occur with a high degree of simultaneity across systems in a given reign.[5] For areas with a current predominance of natural gas heating (as is the case in many Canadian regions), this means that utilities may be required to invest in additional infrastructure to appropriately meet this added demand. In areas with a current predominance of electrical baseboard heating, this presents a more challenging business case for utilities, as heat pumps will reduce overall electricity use, but may still account for similar peak demand to electric resistance systems.

It is clear that new solutions are required to facilitate a more widespread adoption of heat pump systems in Canada. Integrating heat pumps with thermal storage can provide a more flexible link between the thermal and electrical networks of the building, allowing the heat pump to better adapt its operations according to the needs of the grid. In doing so, heat pumps can be positioned as a key tool to *support* future smart grids,

[3] Government of Canada (GOC), 2020. Canadian Net Zero Emissions Accountability Act. Available at: https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050/canadian-net-zero-emissions-accountability-act.html [Accessed Sept. 2020]
[4] Natural Resources Canada, 2017. Paving the Road to 2030 and Beyond: Market transformation road map for energy efficient equipment in the building sector. Govt. of Canada, Ottawa, CA.
[5] Protopapadaki C., Saelens D., 2017. Heat pump and PV impact on residential low-voltage distribution girds as a function of building and district properties. Applied Energy 192, p. 268-281.

rather than an additional electric load that must be met. This chapter explores heat pump and storage systems from a Canadian perspective.

5.2 Exploring Design Criteria: Canadian Perspectives

As outlined in the introductory Annex documents, IEA HPT Annex 55 uses a series of quality criteria and archetypical implementation strategies to better classify and examine system development. Figure 1 summarizes key Canadian implementing approaches and quality criteria of interest. At its most basic form, Canadian work presented in this WP report focuses on an affordable and compact CCB system, while still maintaining suitability in integration and performance for the Canadian market.

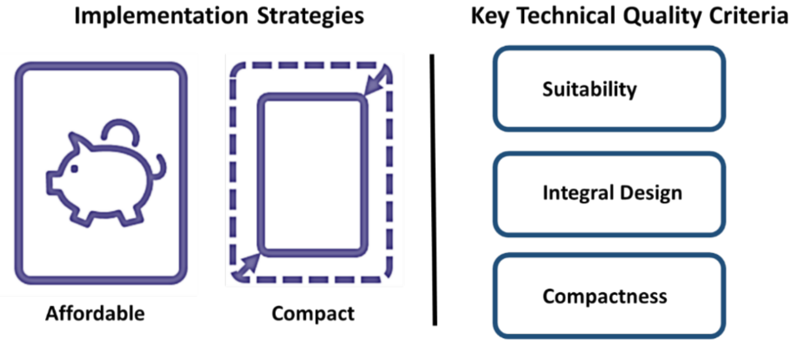


Figure 1 – Sumary of implementing strategies and key quality criteria.

5.2.a Implementing Strategy

Canadian work focuses on a hybrid of two archetype implementing strategies outlined in Annex 55: Affordability, and Compactness. As is the case with any new technology entering the market, first costs are critical. Heat pump systems (without storage) are already challenged by their higher first costs in comparison to more conventional furnace and electric baseboard systems.[6] While adding storage will naturally increase the cost of the system, this increase should be minimized through effective design to support more widespread uptake. Canadian homes also often have limited space in which to integrate thermal storage systems. Larger systems may reduce usable space in the building and pose installation and integration challenges, particularly in the large retrofit market in Canada. As such, development focus in this report is on compact systems that still provide a measure of flexibility (i.e., load shifting potential) to the electrical grid.

5.2.b Quality Criteria

Three main technical criteria are targeted, in support of design objectives:
Suitability: All products must be suitable for Canadian homes and buildings. Specifically, this means addressing three main requirements:

- Air-Based Distribution: CCB development work must target air-to-air heat pump integrations, in line with the air-based distribution systems common in Canadian homes.[7]

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[6] Tamasauskas J., Breton S., Kegel M., 2020. A Techno-Economic Assessment of Air-Source Heat Pumping Technologies in the Canadian Residential Sector. Accepted for Publication, Proceedings of 13th IEA Heat Pump Technologies Conference, paper 252.

[7] Natural Resources Canada, 2015. Survey of Household Energy Use. Ottawa, CA: Govt. of Canada. Available at: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/sheu/2015/tables.cfm [Accessed Jan 2020]

- Heating and Cooling Functionality: Developed CCB systems should provide both heating and cooling, as is typically provided by space conditioning systems in Canada. This also maintains an important avenue for CCB deployment as a replacement for convention air-conditioner systems.
- Cold Climate Performance: Systems should maintain a significant degree of capacity and efficiency at colder ambient temperatures in order to limit reliance on auxiliary electric resistance heating.

Integral Design: Any CCB system must be delivered as an integrated set of physical components and controls, in a similar manner to current generation heat pump systems. This supports ease of installation and commissioning, and better ensures consistent performance.
Compactness: As outlined above, storage size must be kept to a minimum to address space constraint issues.

5.3 Storage Requirements and Selection

Storage requirements and material selection have important implications for the flexibility, affordability, and compactness of any CCB system. This section explores how, and how much, energy should be stored by a CCB in Canada, given the design objectives outlined previously.

5.3.a Storage Requirements

Any CCB should have sufficient storage to reduce heat pump electricity use during a peak event of a given duration. The length of this peak event has important implications for the degree of flexibility offered to the grid, as well as the size of the storage.
In Canada, peak events typically during the morning (6 AM to 9 AM), or evening hours (4 PM to 8 PM) when lighting, equipment and (in some cases) hot water use is highest.[8] Figure 2 shows a sample heating load profile for a cold winter day, noting hours of peak demand.

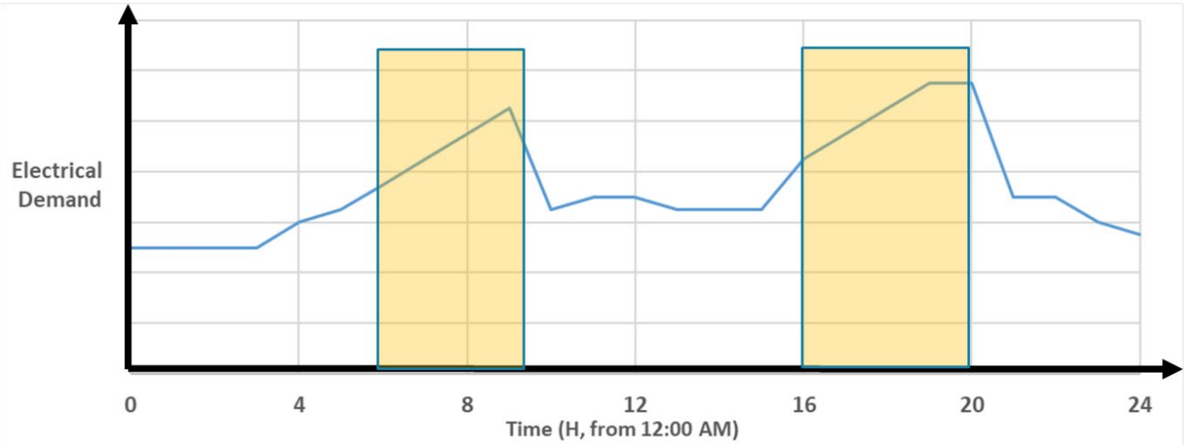

Figure 2 – Typical heating load profile, noting peak hours.

As a balance between flexibility (i.e., load shifting ability), compactness, and system cost, storage capacity in this report is based on covering the maximum thermal demands of the building for two hours during the two defined peak periods. While this provides a consistent methodology for storage sizing, it is important to note that actual storage capacities are likely to vary significantly depending on the location and vintage of the house in which the CCB system is to be integrated. For mass-production units, this likely necessitates a flexible approach to system design, using (as an example) reduced, standard, and enhanced storage options which would be selected by either the homeowner, utility, or installer.

[8] Hydro-Quebec, 2020. Dynamic Pricing: Rate Flex D. Available at: https://www.hydroquebec.com/residential/customer-space/rates/rate-flex-d.html [Accessed Aug. 2020]

Figure 3 summarises required storage capacities for (i) a new, code compliant home (**NC**), and (ii) a home built in the 1950s (**1950s**) in four Canadian cities:[9]

- Montreal: A cold & humid climate, 4200 HDD, T_{Design} -23°C
- Toronto: A cold & humid climate, 3520 HDD, T_{Design} -18°C
- Edmonton: A cold & dry climate, 5120 HDD, T_{Design} -30°C
- Vancouver: A maritime climate, 2825 HDD, T_{Design} -7°C

Results are calculated using detailed TRANSYS simulation models of a typical Canadian home (Two above ground floors, basements, total heated floor area 280 m^2), with further information available in Appendix 5.A. It is clear that there exists a strong correlation between the heating degree-days, envelope performance, and required storage capacities: Storage needs are highest in colder climates, and in homes with poorer levels of insulation. None of these findings are surprising – However, they do highlight the need for flexible storage design, as no single capacity is sufficient for all Canadian regions and construction vintages. It is also important to note that these results are based on a single housing geometry, with results likely to vary for smaller houses.

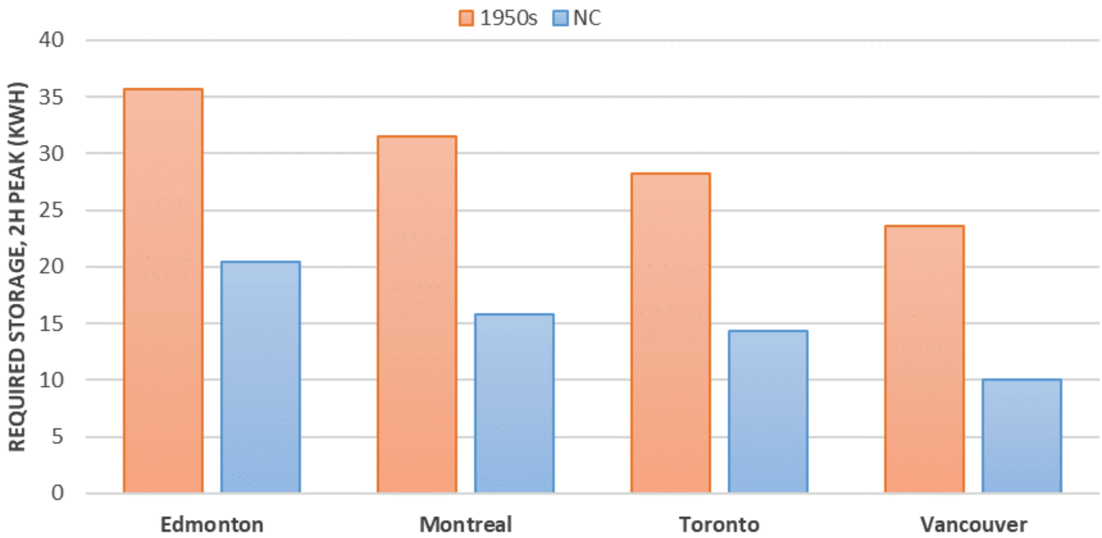

Figure 3 – Sample storage requirements according to region and construction vintage.

5.3.b Storage Material Selection

Storage material selection has important implications for the compactness, cost, and performance (energy transfer rates to and from the storage) of the CCB. In general, approaches in the literature examine the use of either sensible[10] or latent storage (via the use of Phase Change Materials, PCMs).[11]

To examine the impact of storage material selection, three common materials are examined:

- Water-based sensible storage: Temperature rise 15°C

[9] National Research Council of Canada. National Building Code of Canada. 13th ed. Ottawa: NRC; 2010.
[10] Arteconi A., Hewitt N.J., Polonara F., 2013. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. Applied Thermal Engineering 51 (1–2) p. 155-165.
[11] PCM Products, 2021. Phase Change Material Solutions. Available at: https://www.pcmproducts.net/Phase-Change-Material-Solutions.htm [Accessed Jan. 2021]

- Paraffin-based PCM: Phase change at 42°C, storage capacity 123 kJ/L and Salt-hydrate PCM: Phase change at 44°C, storage capacity 298 kJ/L[12]

Figure 4 compares the volume of storage associated with each of the three materials above, based on the required storage capacities for the new construction homes outlined previously. It is clear that use of PCMs, especially the salt hydrate, significantly reduce volumes associated with a given target capacity.

Given the Canadian emphasis on compactness, the remainder of this report will focus on CCB systems using PCM materials. However, it is important to note that final design and material selection are dependent on more than just the energy storage density of the materials. Additional factors, including the conductivity, cost, corrosiveness, and chemical stability, will all be evaluated when making final design decisions. It is also important to note that Canadian activities in this Annex focus on the integration of *existing* storage materials with heat pumps, rather than development of new storage mediums.

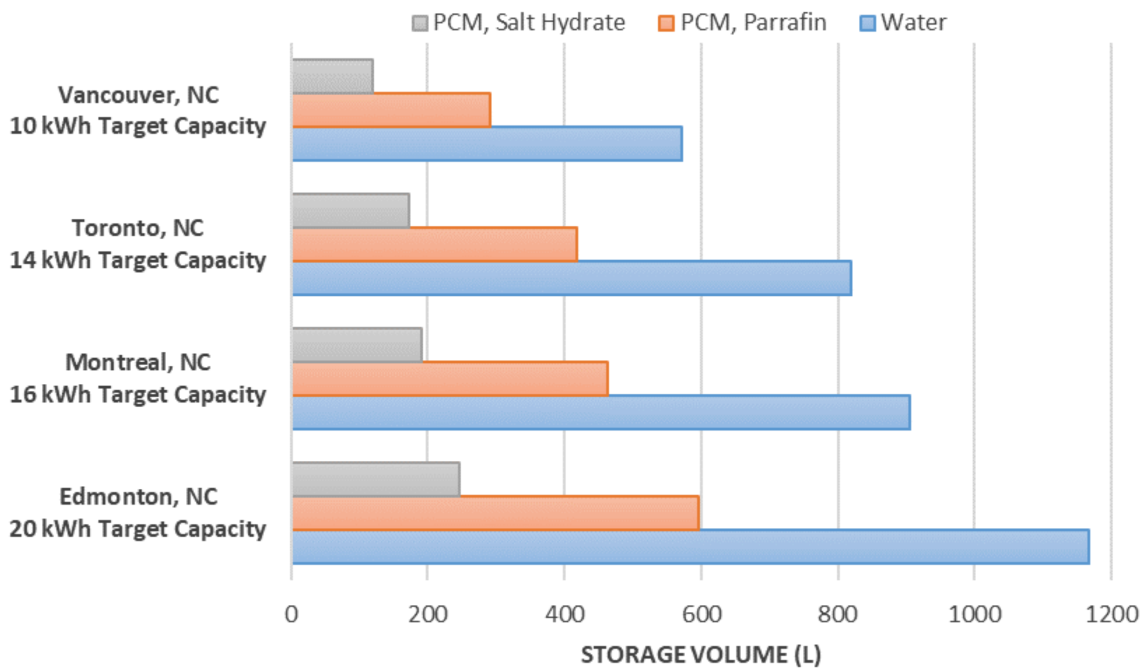

Figure 4 – Comparison of associated volumes for three potential storage materials.

5.4 System Integration: A Heat Pump Level Examination of HP & Storage

The way in which thermal storage is integrated with the heat pump has important implications for the performance, energy flexibility potential, and suitability of the system. In general, CCB systems examined as part of Canadian activities consist of three main components:

- Outdoor unit (Refrigerant-Outdoor Air HX and Compressor),
- Indoor unit (Refrigerant- Indoor Air HX and fan), and
- Thermal storage unit (Refrigerant-PCM heat exchanger and fan).

[12] Emhofer J., Barz T., Marx K., Hochwallner F., Cabeza L., Zsembinszki G., Strehlow A., Nitsch B., Weiss M., 2019. Integration of a compact two fluid PCM heat exchanger into the hot superheated section of an air source heat pump cycle for optimized DHW generation. Proceedings of 25th IIR International Congress of Refrigeration, p. 4415-4423

Despite the relatively simplicity of the component list, system performance and associated energy flexibility is closely tied to the way in which these components are configured. Two potential system configurations, suitable for ducted and ductless configurations, are shown in Figure 5, derived from available information in the literature.[13] Both configurations aim to minimize operation of the heat pump compressor during peak hours by using the thermal storage unit to directly heat the occupied space. However, they differ in the manner in which the storage and indoor units are arranged.

Energy is added to the thermal storage unit (i.e., charged) by using it as an additional condenser. Refrigerant exiting the compressor passes through a series of tubes surrounded by a PCM, allowing for a direct refrigerant-storage heat exchange without the need for secondary heat transfer fluids. During off-peak hours, air is blown over the PCM in order to release stored thermal energy for space heating. It should be noted that this requires a PCM with a phase change temperature near 45°C in order to provide sufficient capacity to heat the occupied space.

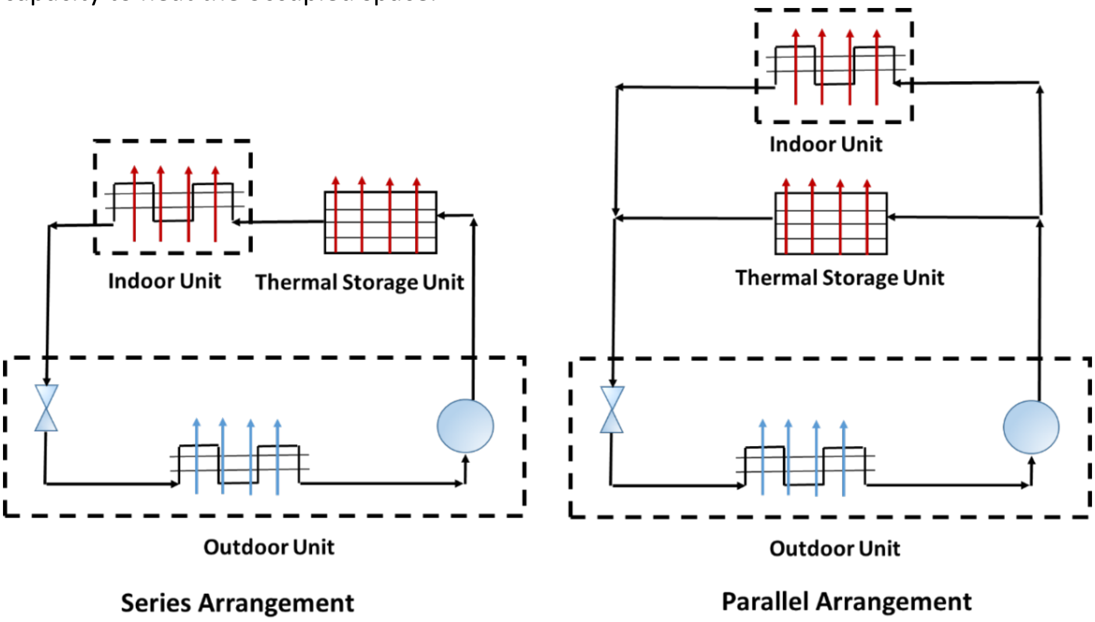

Figure 5 – Two potential CCB configurations.

Each configuration offers specific benefits:

- **Series Arrangement:** Offers the ability to use the storage unit as a desuperheater. This can result in a larger temperature difference between the PCM and refrigerant, but at the expense of lower energy content and refrigerant heat transfer coefficients.
- **Parallel Arrangement**: Allows the storage unit to be charged at full or part load by dividing flow between the storage and indoor units. This configuration takes advantage of the higher two-phase refrigerant heat transfer coefficients and energy content available during full (vapor and two-phase), condensation.

The two above configurations are heating focused, in line with primary objective of development work presented under this Annex. However, the parallel arrangement could potentially be adapted to provide additional energy flexibility in cooling by integrating a cool thermal storage material into the thermal storage unit. Energy could be removed from the cool storage during off-peak hours and used to cool the

[13] Maaraoui S., 2013. Etude et Conception d'une Pompe a Chaleur Residentielle Integrant un Stockage par Chaleur Latente. PhD Thesis, MINES Paris, Paris, FRA.

space during peak periods. However, an additional PCM material (with a far lower phase change temperature) would be required vs. the current heating configuration.

5.4.a Cycle Level Analysis of Configurations

One of the main challenges in designing heat pump and storage systems is ensuring sufficient charging times. Heat pump and storage systems may be required to respond to multiple peak periods during the same day (e.g., morning and evening events), necessitating sufficiently fast charging during off-peak hours. Charging times are closely related to the quantity of energy transferred from the refrigerant to the storage material, which in turn depends on:

- Capacity for Charging: Whether the full, or partial capacity of the heat pump is used to charge
- Refrigerant Phases Used: What portion of the condensation process (vapor, two-phase, liquid) is used for charging. Typical configurations in the literature include use of a desuperheater or using the full condensation process to charge.

To examine these issues, a simple thermodynamic model of a 2-ton air-source (air-air) heat pump model was developed. Figure 6 shows estimated charging times derived from this model, assuming a perfect heat exchange between the refrigerant and PCM. Using only a portion of the condensation process (i.e., superheated vapor) slows the charging process by limiting the energy content available. Similarly, charging at partial load significantly increases the time required to achieve a full charge. Results clearly show that, in order to sufficiently charge between morning and evening peak periods, systems would need to charge above 70% part load, while using the energy available from the full condensation process.

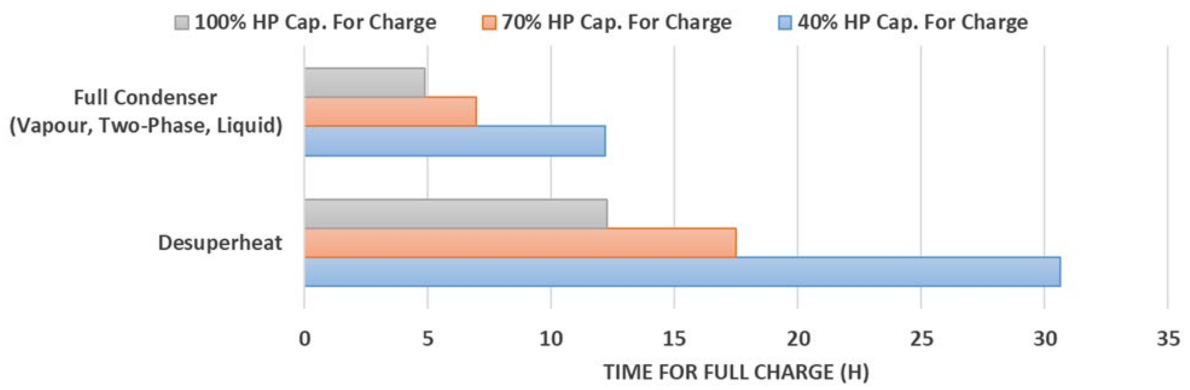

Figure 6 – Estimated charging times at full and part load conditions.

5.5 Enhancing Energy Flexibility: A Building Level Analysis

The performance of CCB systems depends not only on the integration of the heat pump and thermal storage, but also on how the CCB system integrates and interacts with the building. To better under this perspective, a simulation-based analysis is used to examine the energy flexibility (i.e., load shifting) potential of the CCB configuration defined in section 5.4 in typical Canadian single-family housing. All modelling work is performed in TRANSYS v. 18, using a combination of custom and standard component models.

5.5.a Building

Analysis is focused on typical single-family Canadian housing in Montreal, QC. Building geometry is based on the Canadian Centre for Housing Technology test homes,[14] and consists of two above ground floors and a finished basement with a total heated floor area of approximately 280 m^2. Envelope performance is based on current building code requirements in Canada [7] for the Montreal region. All building modelling is performed in TRANSYS using the Type 56 multi-zone building component. To provide a base of comparison for the CCB systems examined later, a base case mechanical system is also defined, with key characteristics summarized in Table 4. It is important to note that the Montreal home does not have a central ducting system, in line with typical practice for homes heated using electric baseboards. As such, the air-conditioner (and, later, heat pump) is integrated as a ductless split system, with the indoor unit mounted in the stairwell between the first and second floors of the home.

Characteristic	Montreal
Central Air Distribution	No
Primary Heat Fuel & System	Electric Baseboard Heaters
Heating Efficiency	100%
Space Cooling System	Split AC Unit COP = 3.3*
DHW Fuel	Electric
Heat Recovery Ventilator (HRV)	Yes

*At AHRI rating conditions

Table 4 – Key Characteristics for base case mechanical system.

5.5.b Heat Pump

Analysis focuses on cold climate air-source (air-air) heat pump systems. Cold climate heat pumps combine variable capacity compressors with larger outdoor heat exchangers and other cycle improvements to increase heating capacity at colder outdoor temperatures, while still efficiently modulating at milder conditions.[15] These improvements result in units that are better adapted to the operating conditions of air-source heat pumps in the cold Canadian climate.

Heat pump systems in this initial analysis are integrated in a ductless, single split configuration: One outdoor unit and one indoor unit located in the stairwell between the first and second floors of the home. The heat pump is sized to meet the heating load of two the above ground floors at an outdoor temperature of 17°F (-8.3 °C), in line with Natural Resources Canada's *Air-Source Heat Pump Sizing and Selection Guide* Sizing Option C.[16] In this configuration, it is assumed that the heat pump only serves the first two floors of the building, with the basement heating using electric baseboards, as in the initial base case. Heat pump operations are supplemented as required when space temperatures fall 1°C below the desired setpoint of 21°C. A summary of relevant heat pump parameters used in the analysis is provided in Table 5.

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[14] Swinton, M.C., Entchev, E., Szadkowski, F., Marchand, R. Benchmarking twin houses and assessment of the energy performance of two gas combo heating systems. Ottawa, CA: Canadian Centre for Housing Technology.

[15] Sager, J., Mackintosh, T., St-Onge, G., McDonald, E. and Kegel, M., 2018. Detailed performance assessment of variable capacity inverter-driven cold climate air source heat pumps, 9th International Cold Climate Conference. Kiruna, Sweden.

[16] Natural Resources Canada, 2021. Air-Source Heat Pump Sizing & Selection Guide. Govt. of Canada, Ottawa, CA.

Characteristic	Montreal
HP Size	1.5 Ton
HP Configuration	Ductless
Heating COP*	4.1
Cooling COP*	4.2
Min. Operating Temperature, Heating Mode (°C)	-25
% Capacity at Cut-Off Temperature (Max Speed)	66%
Average Min: Max Capacity Ratio	0.33

*At AHRI Rating Conditions

Table 5 – HP parameters for sample analysis.

An appropriate heat pump model is critical to appropriately assess the impact of the targeted technologies. This study uses a custom data driven TRANSYS component model, Type 3256, for all heat pump simulations. Type 3256 is based on extensive test experience with ductless variable capacity heat pumps and includes a number of new features such as performance variation with compressor speed, and short-term characteristics including defrost and compressor behavior during start-up.[17] Cycling is also accounted for via the implementation of a time constant to model capacity degradations from steady state values during start-up. In this analysis, heat pump data is derived from extensive experimental testing of a ductless, cold climate unit in a single split configuration.

5.5.c CCB Integration

Thermal storage is integrated with the heat pump model above via the parallel configuration presented in Figure 5. It is assumed that both the indoor unit and thermal storage unit are located in the stairwell between the first and second floors, thus providing heating to both levels of the home.
Control Strategies: The heat pump is charged during off-peak hours by using the thermal storage unit as an additional thermal sink for the system. Specifically, charging occurs when:

I. It is a defined charging period (off-peak hours, ambient temperature below -5°C)
II. The storage has available capacity, and
III. Heat pump is operating at less than full capacity for space heating

If the above three criteria are met, the heat pump is operated at its maximum compressor speed, and additional thermal capacity not required at the indoor unit is instead directed to the thermal storage unit. This configuration allows the storage to be charged over a wide range of full and part load conditions, while still providing space heating as required during off-peak periods.

The thermal storage is discharged during peak periods by turning off the heat pump compressor, and activating a fan integrated in the thermal storage unit. For initial simulations, discharge lasts for the full peak period, at the defined discharge rate in the storage model. Should space temperatures fall below 19.5°C, storage operations are supplemented by the heat pump or auxiliary system (if $T_{Outdoor}$ < -25°C). Future work will use more detailed models to assess the variation in heat transfer rates during the discharge process.

[17] Breton, S., Tamasauskas, J., Kegel, M., 2019. An Evaluation of Cold Climate Variable Capacity Air-Source Heat Pumps in Canadian Residential Buildings Using an Enhanced Component Model. Building Simulation 2019. Rome, IT, paper #211116.

Additional Notes on Peak vs. Off-Peak Hours: Peak events in the Montreal region tend to occur during the coldest winter days, when a coincidence of lighting, equipment, hot water and electrically driven space heating drive large aggregated loads. In this initial analysis, storage use is limited to periods when:

- Ambient temperatures < -15°C
- Hours: Morning (6 AM – 8AM), Evening (5 PM – 7 PM)

Actual peak periods in Montreal are generally longer than the 2H used above. However, as noted earlier, storage is sized to cover loads for 2H in an effort to balance flexibility, compactness, and system cost.

Storage Design: The thermal storage is sized to cover a 2H peak event for the target building, as outlined earlier. A salt hydrate storage material is used in order to minimize storage volumes, in line Canadian design objectives (estimated size 1m x 1.2m x 0.3m). Key storage parameters are provided below in Table 6. Future work planned as part of Canadian activities will use detailed modelling to better estimate actual heat exchanger efficiencies and charging/discharging rates from the storage.

Storage Capacity	15 kWh
Discharge Rate	3 kW

Table 6 – Storage parameters for sample analysis.

5.5.d Results

The simulated performance of three mechanical systems is compared over the first 60 days of the year (from Jan. 1). A one-week warm-up period is also included in order to minimize the impact of initial conditions. The electrical demand of the building during peak periods is compared for three systems:

- Electrical baseboards (**Elec. BB**)
- A cold climate variable capacity heat pump without storage (**CCHP**)
- A cold climate variable capacity heat pump with storage (**CCHP + Storage**)

Figure 7 compares the distribution of electrical demand (median, 99th percentile, maximum) for all three systems in Montreal. During the coldest winter periods ($T_{Outdoor}$<-25°C), the CCHP is unable to operate and must rely on auxiliary resistance heating, increasing demand. This operation clearly poses a challenging business case for grid operators, who may sell less electricity but still be required to maintain infrastructure for the worst-case peak. On the other hand, the CCHP + storage case appears to offer meaningful demand reductions vs. both systems throughout the operational window, primarily because auxiliary resistance heating can be offset through the storage.

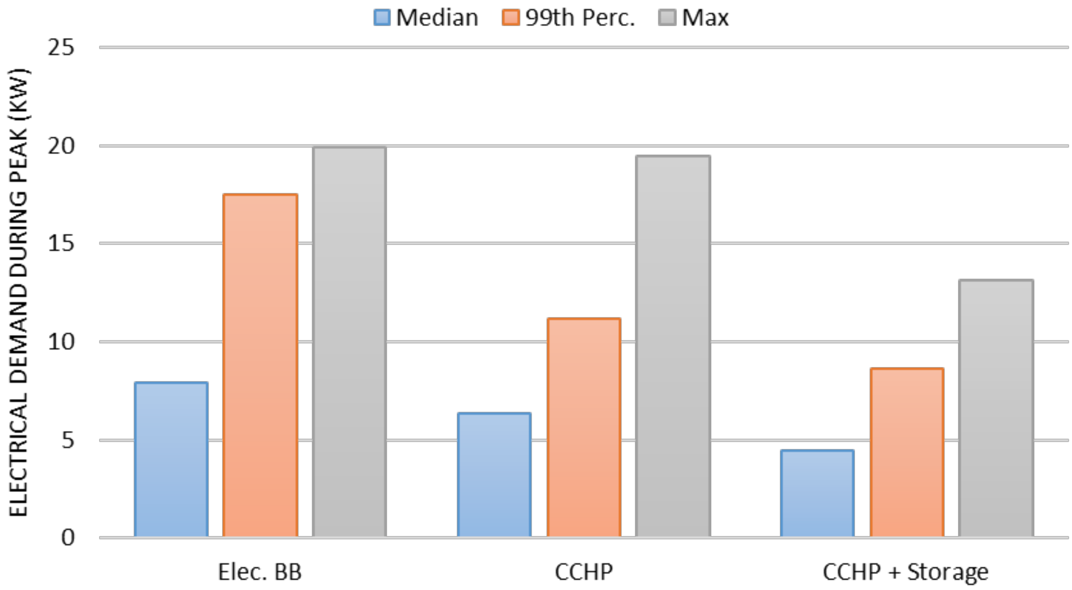


Figure 7 – Impact of heat pump and storage on electrical demand in a single-family Canadian home.

It is important to note that these results are highly specific to the case examined. A detailed analysis shows the ability to shift electrical demand is closely tied to the ability of the heat pump to charge the storage during off-peak hours. Should the building thermal load remain high during off-peak hours, the heat pump may have limited ability to charge the storage, reducing the magnitude of demand reductions obtained. This impact could potentially be mitigated by taking advantage of thermal storage inherent in the building mass by, for example, allowing space temperatures to fluctuate in a predefined comfort range.

5.6 Conclusions

This chapter has examined the development of Climate and Comfort Box (CCBs) systems from a Canadian perspective. Key takeaways include:

System Design Priorities: Work described in this report focuses on compact and affordable CCB systems suitable for the Canadian market. Specifically, this means a focus on air-source (air-air) heat pump systems, providing both heating and cooling, with strong cold climate performance.

Storage Requirements and Selection: Defining storage requirements for the CCB system requires a careful balance between energy flexibility (i.e., load shifting) potential, compactness, and affordability. Storage was sized to cover the heating loads of the building for a 2H peak event. However, given the strong dependency on building size, climate, and construction, flexible approaches (i.e., several storage capacities options) are likely required for market-available CCB systems. High-energy storage density materials (e.g., phase change materials) are also of importance in Canada to ensure system compactness.

Integration of Storage within Heat Pump Cycle: A potential integration of thermal storage within the heat pump cycle was presented. Energy is added to the storage during off-peak hours by using the thermal storage unit as an additional heat sink. During on-peak hours, the storage is then used to directly heat the space, avoiding use of the heat pump compressor. Cycle level analysis showed the importance of dedicating a suitable portion of capacity to charging to ensure the system can be used during multiple daily peak events.

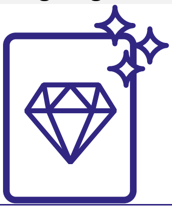
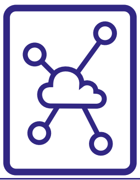
Assessing Energy Flexibility Potential: A simulation-based approach was used to examine the demand reduction potential of the above outlined CCB system, in comparison with heat pump only and electric baseboard cases. Results showed that the proposed CCB system was able to reduce both median and maximum electrical demand during peak periods by offsetting use of auxiliary heating systems during the coldest winter periods. The contents of this report represent an initial step in the assessment of CCB systems from the Canadian perspective. Ongoing and future activities target a more in-depth examination of the subjects introduced above. This will include a more complete assessment of storage material selection, and its method of integration within the heat pump cycle. Additionally, further work will explore system performance in different regions and building types and expand on the role of system sizing on peak demand reductions.

5.A Housing Model Summary

Housing models used in the analysis were selected to be representative of typical single-family housing, with building geometry based on the Canadian Centre for Housing Technology (CCHT) test homes located in Ottawa, Canada.[18] The modelled home included two above ground floors and a finished basement, with a total heated floor area of 284 m^2. The building envelope was modified to represent new construction housing in each region using National Building Code of Canada (NBC) minimum requirements for the appropriate climate zone[19]. Further information on model development is available in Kegel *et al.*[20]

[18] Swinton, M.C., Entchev, E., Szadkowski, F., Marchand, R. Benchmarking twin houses and assessment of the energy performance of two gas combo heating systems. Ottawa, CA: Canadian Centre for Housing Technology.
[19] National Research Council of Canada. National Building Code of Canada. 13th ed. Ottawa: NRC; 2010.
[20] Kegel, M., Sunye, R., Tamasauskas, J., 2012. Life Cycle Cost Comparison and Optimisation of Different Heat Pump Systems in the Canadian Climate. eSim 2012: 7th Conference of IBPSA-Canada. Halifax, Canada, paper # 1110.

6 (DE) Smart-CASE-NZEB

Country	Germany
Contact	Christian Scheigler Hochschule München christian.schweigler@hm.edu
Status	Ongoing
Main CCB implementation strategies	  Energy Efficiency Flexibility

Smart-CASE-NZEB is supported by the German Federal Ministry of Economic Affairs and Energy.

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6.1 Key project data

6.1.a Project goal

Development of a novel integration of a latent heat storage into a domestic heat pump, providing enhanced efficiency in comparison to conventional storage concepts. The system is intended for grid serving purposes such as peak reduction, load shifting and grid integration of renewable energies. The project provides a proof of concept, including results for the energetic performance of the system.

6.1.b Project setup

The concept is based on direct heat exchange between the evaporating or condensing refrigerant and the phase-change-material (PCM) inside the storage, and integration of the heat storage in a serial configuration between two condenser heat exchangers. This cascade replaces the original condenser. Thus, an intermediate heat carrier loop for heat transfer between the PCM and the refrigerant is not required, allowing for minimum temperature loss and best adaptation to the temperature profile of the heating circuit.

6.1.c Status and time planning

After conceptual design and simulation, a first demonstrator has been constructed in the laboratory. The next step is a field test in a building under real conditions.

6.1.d CCB Implementation Strategy

Referring to the Basic implementation strategies for CCBs, the focus of the project and the new system is on flexibility and energy efficiency.

6.2 Overview: Heat pump with cascaded integration of latent heat storage (HP-LHS-system)

By directly integrating a latent heat storage (LHS) in conjunction with a second condenser heat exchanger into the internal cycle of a heat pump (HP) and applying a special operating concept, an increase of the temperature and pressure lift for charging the heat storage is avoided and the efficiency of the overall system is increased in comparison to conventional concepts. This is accomplished by direct heat exchange between the evaporating or condensing refrigerant and the phase-changematerial (PCM) inside the storage and by integrating the heat storage in a serial configuration between two condenser heat exchangers. Thus, an intermediate heat carrier loop for heat transfer between the PCM and the refrigerant is not required, allowing for minimum temperature loss and best adaptation to the temperature profile of the heating circuit. (Figure 8)

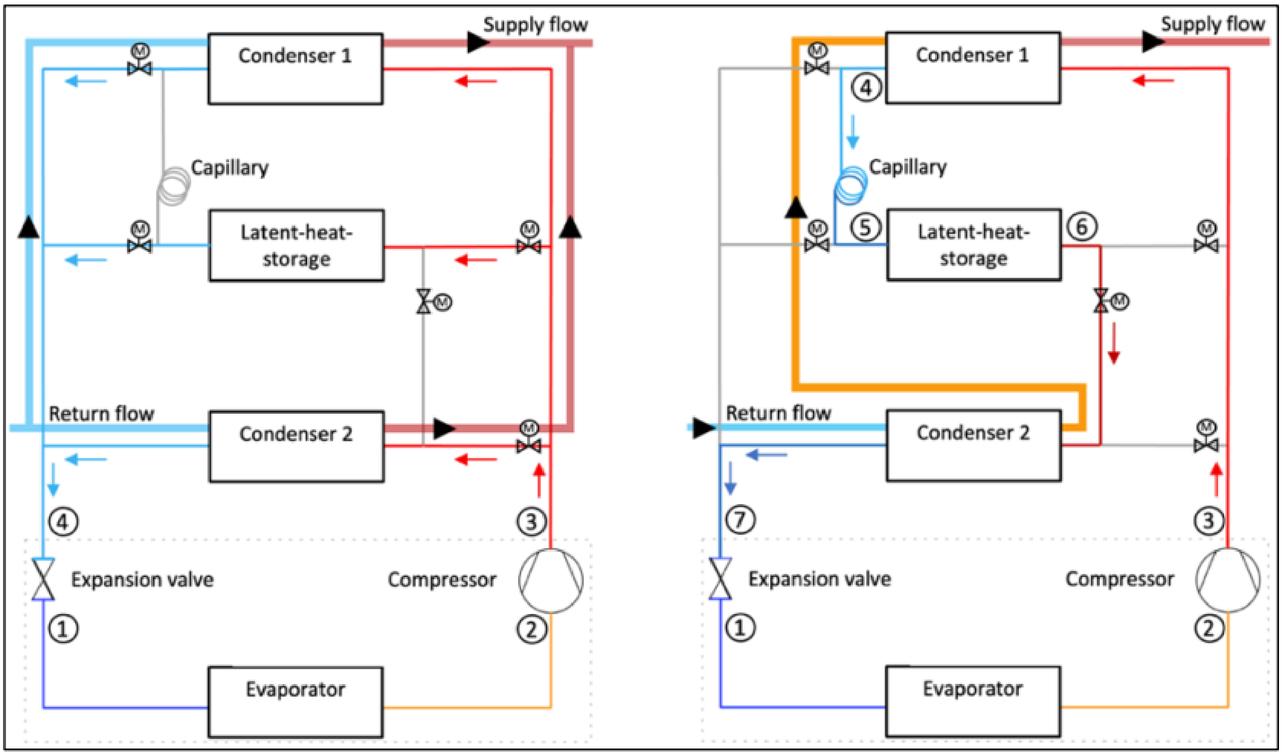


Figure 8 – Charging and discharging of the circuit.

The latent heat storage is charged by melting the PCM inside the latent heat storage due to condensation of the refrigerant, described by state points 3 and 4 in Figure 9. The figure shows the complete refrigerant cycle with the relative pressure and temperature levels, which is equivalent to a commercially available heat pump. The charging of the storage takes place at the design condensation temperature level of the regular cycle, as it would be operated without a storage. Therefore, a phase change material (PCM) is chosen with phase change slightly below this condensation temperature (Figure 9). The storage can be charged in parallel operation with the two condenser heat exchangers, like shown in Figure 11, on the left. The refrigerant cycle can also be directed only through the two or one of the two condensers, for providing heating power without charging the storage, or only through the LHS, for charging the storage only.

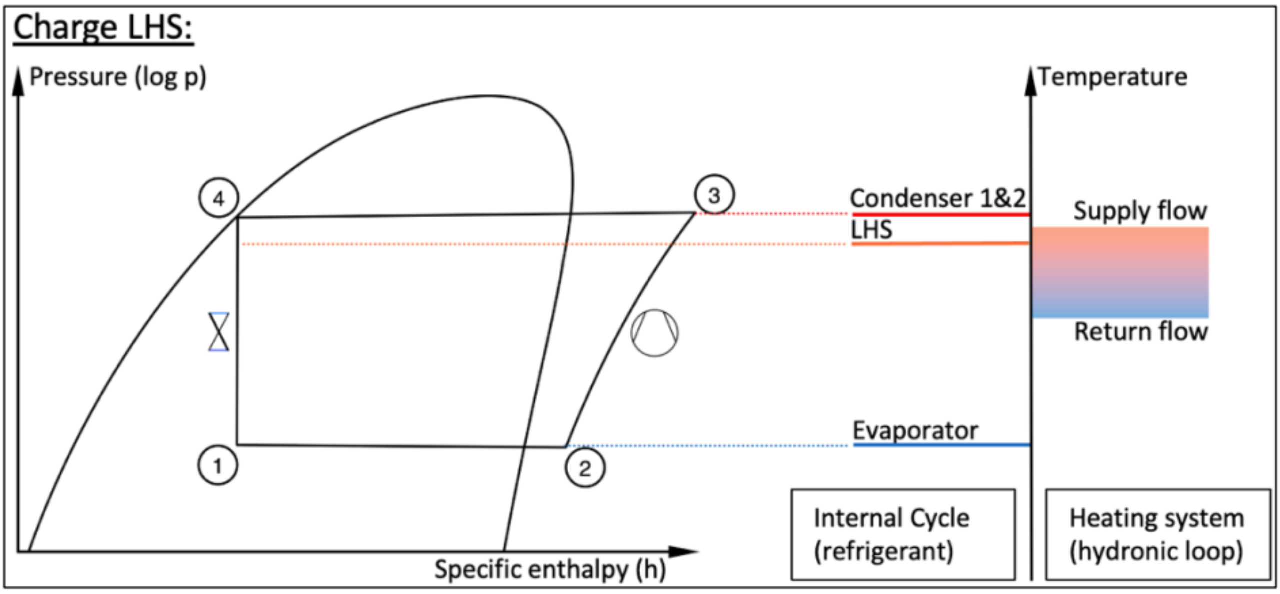


Figure 9 – Temperature levels and refrigerant cycle while chargin the LHS.

When discharging the storage by solidification of the PCM due to evaporation of the refrigerant, the latent heat storage is cascaded in series with the regular condenser and the second, additional condenser (Figure 8, right). The refrigerant cycle of discharging the LHS in cascade operation with the relative pressure and temperature levels is shown in Figure 10. The refrigerant is liquefied in the first condenser (state points 3 to 4), then, after passing a capillary (state points 4 to 5), evaporated again in the LHS (state points 5 to 6) and liquefied again in the second condenser (state points 6 to 7). The evaporation in the LHS happens at slightly lower pressure and correspondingly lower temperature compared to the first condenser. During charging of the LHS at the regular temperature level of the first condenser, heat is stored at slightly lower phase change temperature of the PCM. In order to provide sufficient temperature difference, the processes of evaporation driven by the LHS and final condensation of the refrigerant in the second condenser take place at lower pressure and lower temperature compared to the first condenser. On this lower temperature level, the return heating flow is preheated in the second condenser by liquifying the refrigerant again and then brought to the desired supply heating flow temperature in the first condenser. For the three heat transfer processes on the refrigerant side in condenser 1 and 2 as well as in the LHS the temperature range between the return heating flow and the supply heating flow is available as the total driving temperature difference.

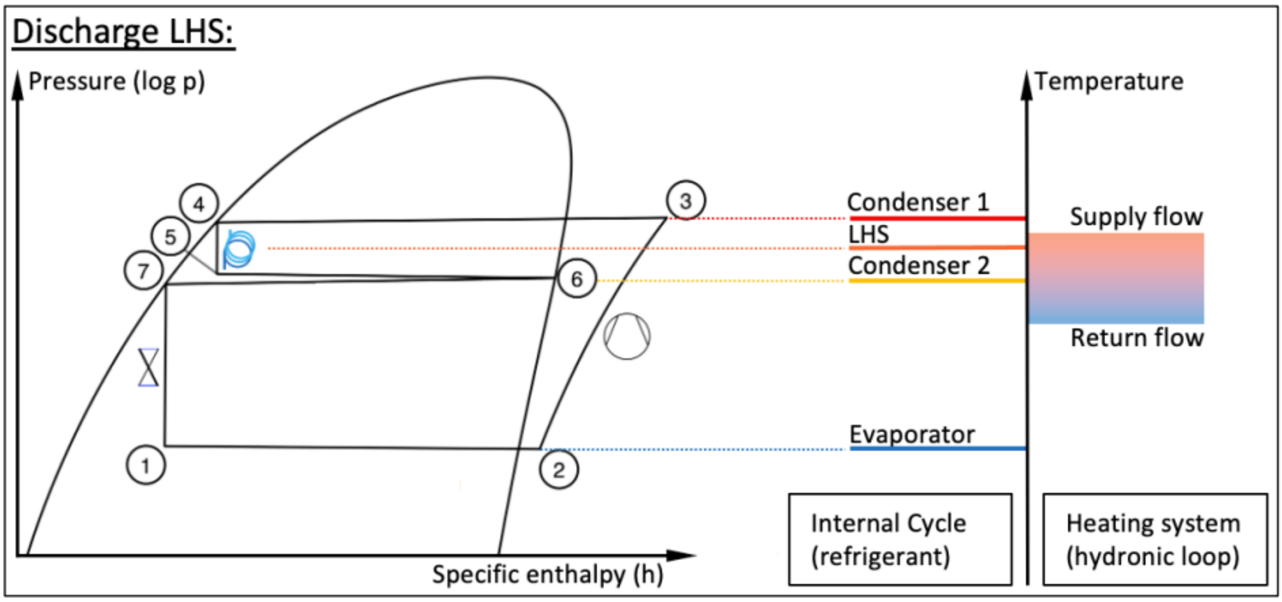


Figure 10 – Temperature levels and refrigerant cycle while discharging the LHS.

6.3 Design of the latent heat storage

A model was developed for the development of the HP-LHS-system using the software EES. The heat transfer processes in the latent heat storage were included in a two-dimensional calculation model. The calculations are based on two discretization, in length and radius direction regarding the tubes of the heat exchanger in the latent heat storage. The calculation model was successfully validated with the already existing test stands in the lab of Munich University of Applied Sciences (MUAS). The graphs in Figure 11 show calculation results of the dynamic behavior of the HP-LHS-system while discharging the LHS regarding heat duties and temperatures in the overall system. The calculations are based on a 35/45°C heating loop system, a phase change temperature range of the PCM between 43°C and 40°C and a heat demand of 8 kW. The focus is on the contribution of the two condensers, following the time-variant heat output from the latent heat storage. The analysis of the dynamic operating characteristics formed the basis for dimensioning the latent heat storage-heat exchanger-cascade. In the upper diagram of Figure 11 the variable phase change temperature of the PCM as well as the temperatures of the heating water loop are displayed. As shown in the lower diagram, maximum heat duty of the LHS is available for a period of about one hour. Afterwards, the power decreases continuously until the capacity of the storage is exhausted.

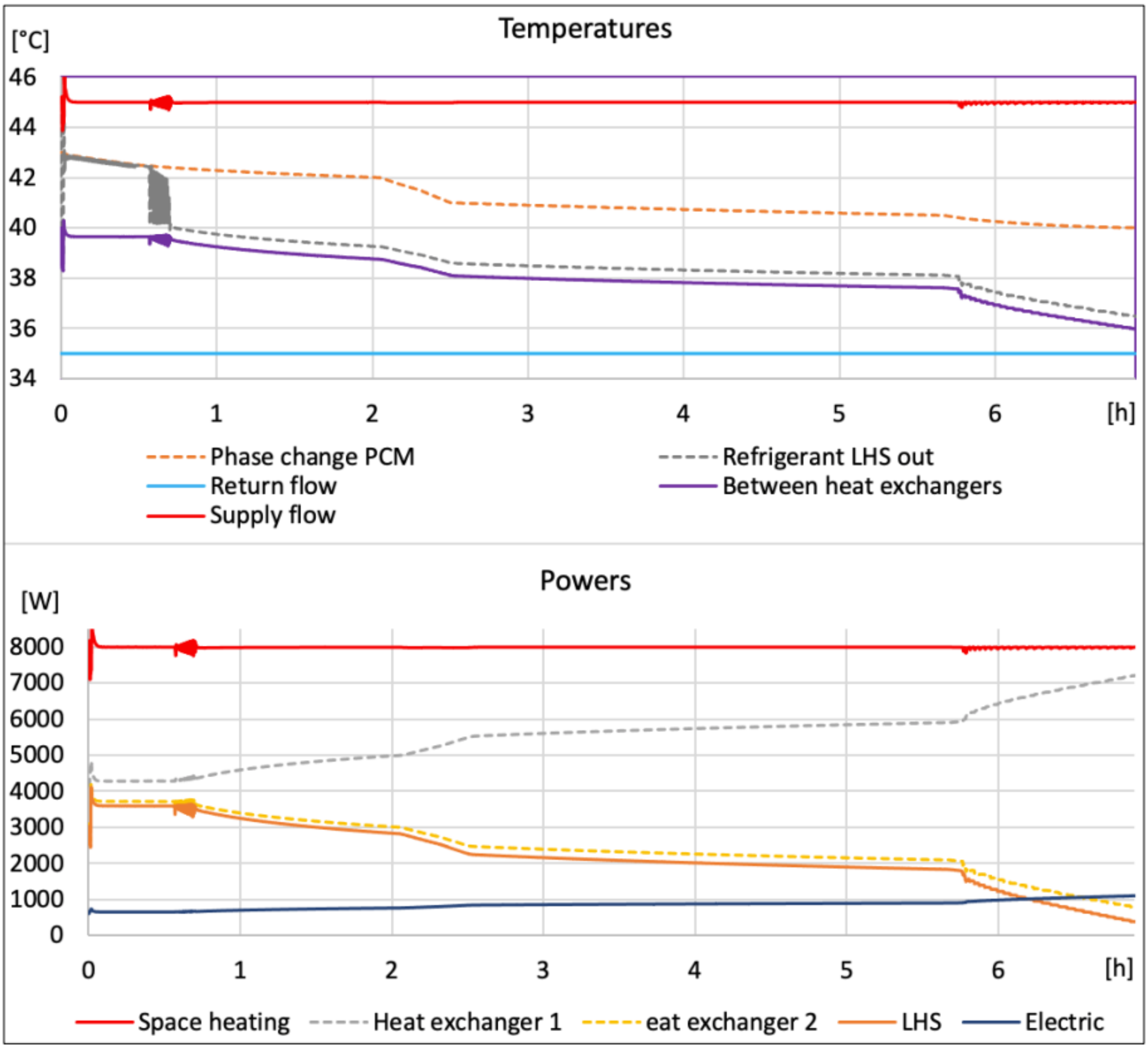


Figure 11 – Simulation results with the 2D EES model for developing the latent heat storage.

6.4 Conception and construction of a demonstrator

A demonstrator of the heat pump with integrated latent heat storage has been constructed, starting from a commercial heat pump model. The internal refrigerant cycle is regulated by 8 solenoid valves. Depending on the operating mode, including whether the LHS is being charged or discharged, combinations of closed and open valves are set. In the heating water cycle, four ball valves are used for the change between the different operating modes. Concluding the theoretical planning, a 3D-model has been developed that takes into account all relevant aspects and requirements (Figure 12). The light grey shapes represent elementary components. The largest cuboid is the LHS, in the upper third are the two condensers, in the lower third is the evaporator (smaller cuboids). The compressor (cylinder) is placed next to the evaporator, opposite is the box for the electrical components and the control system. Under the LHS is a refrigerant collector. The pink pipes form the refrigerant cycle, the turquoise pipes the brine flow and the blue pipes the heating water circuit. Grey and orange balls show valves, green balls and cubes represent measuring equipment. The frame to which all components are attached is displayed in dark grey. Figure 13 shows the status of the construction after the first test runs. The implementation was carried out closely identical to the structure of the 3D model.

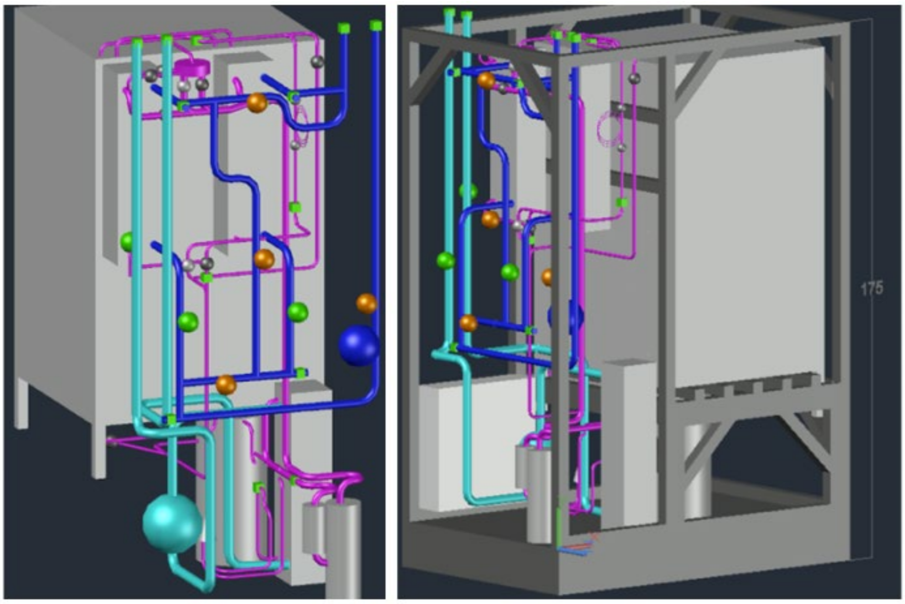


Figure 12 – 3D model of the HP-LHS-system with measurement and regulation components.

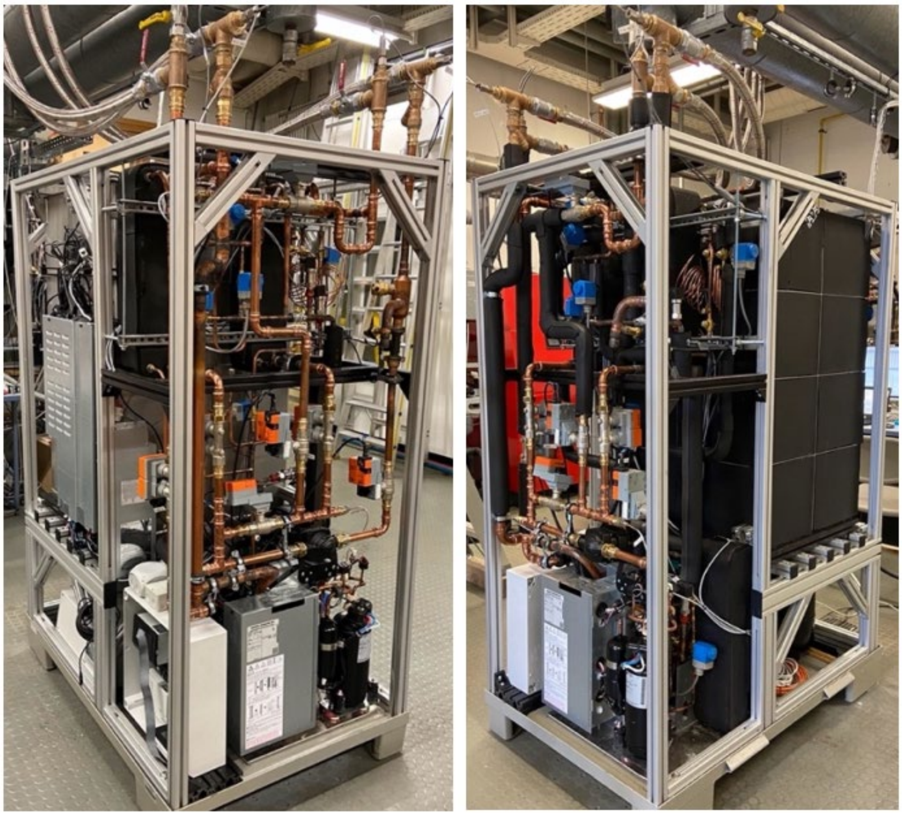


Figure 13 – Pictures of HP-LHS-system after first test runs.

6.5 Proof of function by experimental investigation

The functioning of the novel heat pump system with integrated heat storage is demonstrated by a test run with constant operating temperatures during charging and discharging of the LHS. According to the general concept, this criterion is decisive for the energetic performance of the system. A negative influence of the use of the heat storage on the efficiency of the heat pump system shall be avoided. In the left part of Figure 14, the temperature profiles of the heating water and the latent heat storage during charging of the storage are shown. The two heat exchangers that supply heat to the heating loop show the same heating water inlet and outlet temperatures, as the components are supplied with refrigerant and heating water in parallel. During loading, the LHS stays at the melting temperature of the PCM. The right part of the graph shows measurement data of the discharging process, with the heating water passing through the two heat exchangers in serial flow. The cold return flow of the heating circuit enters condenser heat exchanger 2. After preheating in condenser 2, the heating water is brought to the supply flow temperature by heat transfer in condenser 1. The temperature of the storage (LHS) always stays between the temperatures of return and supply flow of the heating circuit. At the beginning of the discharging process, when the LHS can provide maximum contribution, the preheating in condenser 2 provides roughly half of the total heat output of the heat pump. As the state of charge of the LHS and thus its thermal maximum power decreases, the temperature increases in condenser 2 drops and the heating water outlet temperature of condenser 2 approaches the return flow temperature of the heating system. When the capacity of the LHS is exhausted, the intermediate temperature between condenser 2 and 1 and the temperature of the return flow coincide.

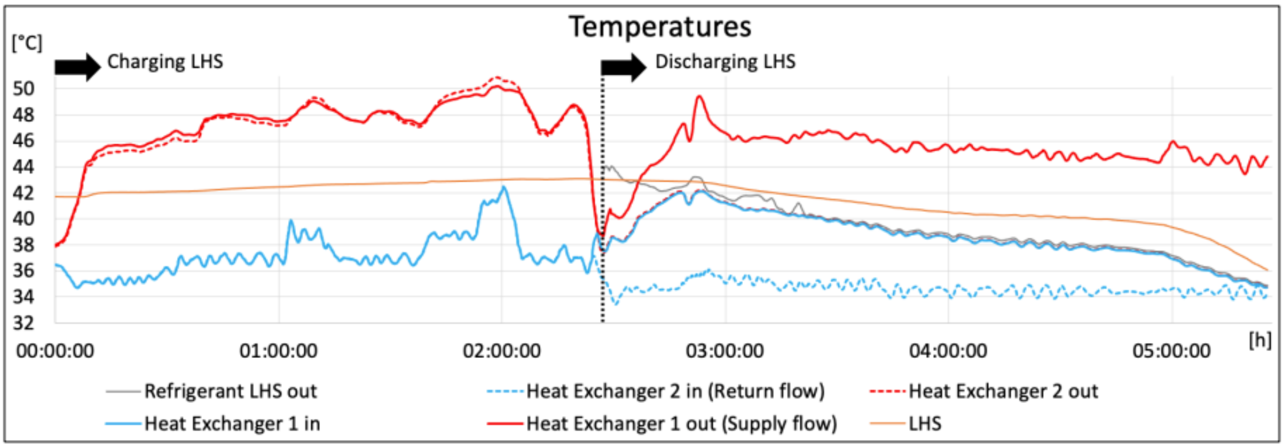


Figure 14 – Temperatures in the HP-LHS-system while charging (left) and discharging (right) the storage.

Figure 15 shows the heat duty of the LHS, the absorbed electrical power and the heating power delivered to the heating loop. During the charging process, the system delivers heat to both the heating loop and the LHS. During the discharging process, the heat output from the heat pump cycle is supplemented by heat extraction from the LHS. Due to this reversal, a substantial decrease of the electrical power consumption is achieved when operation is switched from charging to discharging, even with slightly increasing heat output to the heating loop.

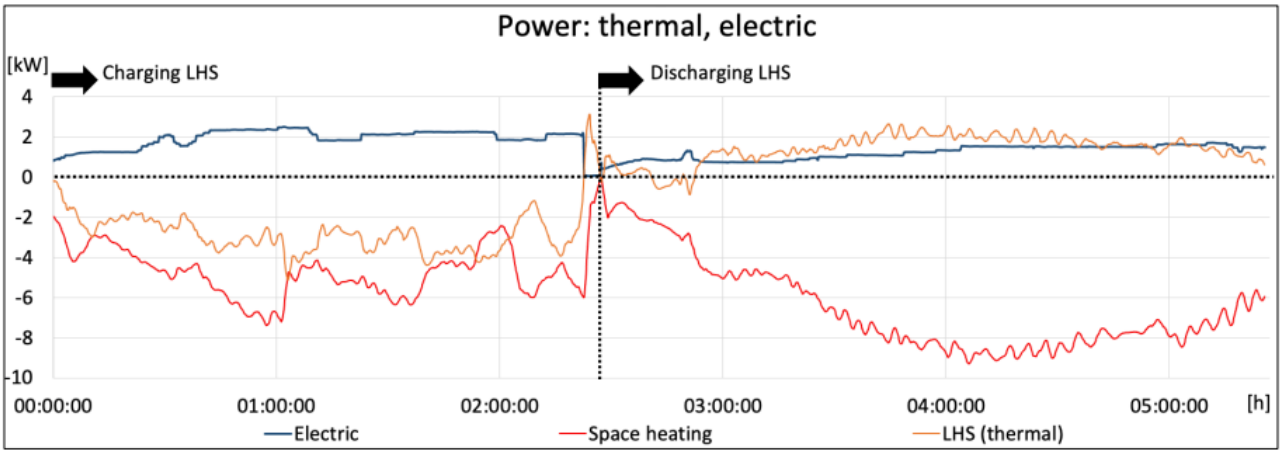


Figure 15 – Power in the HP-LHS-system while charging (left) and discharding (right) the storage.

This effect is also reflected by the values of the COP, which are shown in Figure 19. In order to characterize the function of the heat pump system with integrated heat storage two definitions are used. Following the conventional approach, the supply of useful heat is expressed by the system COP (COP_{system}), taking into account the heat supply to the heating system ($\dot{Q}_{heating}$<0) and the electric consumption ($P_{electric}$>0) of the heat pump:

$$COP_{system} = \frac{\left|\dot{Q}_{heating}\right|}{P_{electric}}$$

When the LHS is charged, the refrigerant flow increases in relation to the normal operation of the heat pump, resulting in a rise of the electric consumption of the compressor. Consequently, COP_{system} drops below the nominal COP value for operation without heat storage. During unloading of the thermal storage, circulation of refrigerant is reduced due to repeated evaporation and condensation of refrigerant in the LHS and the second condenser, respectively. Thus, heat output of the heat pump system can be maintained, while the compressor is operated at reduced load, resulting in an increase of COP_{system}. The efficiency of the heat pump cycle with integrated LHS is described by COP_{cycle}, based on a balance of the internal heat pump cycle. In analogy to the conventional formulation, this figure of merit takes into account the net heat flow of the cycle and the respective work of compression i.e. heat transfer to the LHS is counted negatively, heat gain provided by the storage is counted positively.

$$COP_{cycle} = \frac{\left|\dot{Q}_{heating} + \dot{Q}_{LHS}\right|}{P_{electric}}$$

During charging of the storage, the cycle supplies heat to the heating system ($\dot{Q}_{heating} < 0$) and to the LHS ($\dot{Q}_{LHS} < 0$), accompanied by operation of the compressor at high load. When the storage is discharged, heat output of the cycle is supplemented by heat extraction from the LHS ($\dot{Q}_{LHS} > 0$), allowing for reduced operation of the compressor. When compared to operation without thermal storage, COP_{cycle} identifies the influence of changed operating conditions of the internal cycle, like evaporation or condensation pressure or refrigerant mass flow.

During the test run with a changeover from charging to discharging (see Figure 16) the cycle COP (COP_{cycle}) remains in an almost constant range, independently of the current mode of operation. In contrast, COP_{system} shows the potential of the heat pump system with integrated LHS for flexible operation and load shifting. While a rather low system COP (COP_{system}) is found during charging of the LHS due to the heat input to the LHS, the COP_{system} rises above the value of the cycle COP (COP_{cycle}) when discharging the LHS. This behaviour results from the fact that the additional effort previously expended to charge the LHS is recovered when discharging the LHS.

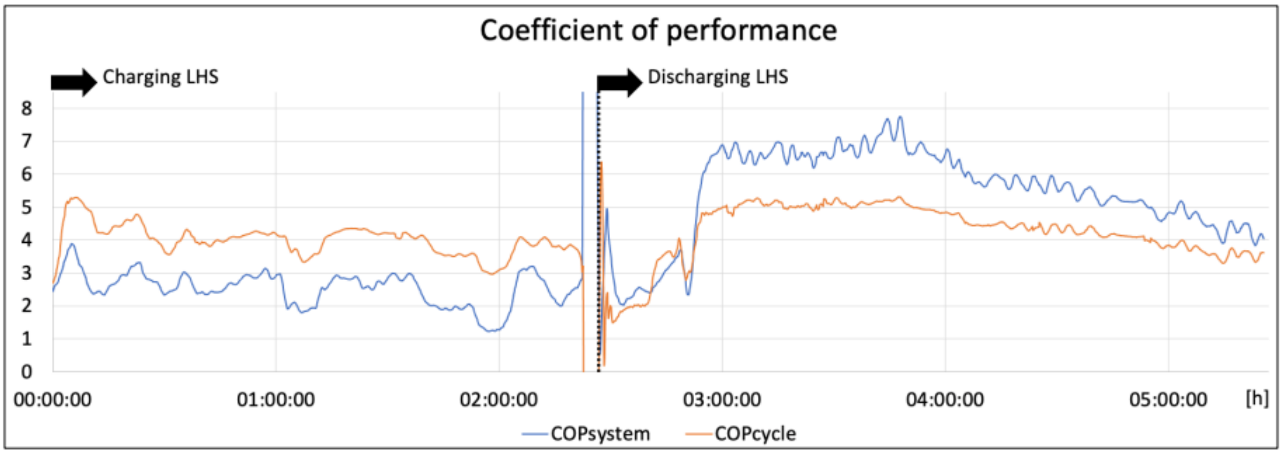


Figure 16 – COP in the HP-LHS-system while charging (left) and discharging (right) the storage.

6.6 Pilot Installation

Experimental verification of the technical concept of the heat pump system with cascaded integration of the latent heat storage will be followed by a pilot installation of the system in a realistic environment. The heat pump will be applied in a building of a partner university in Tampere, Finland. The flexibility of the heat pump system with thermal storage will be used to reduce peaks of electric consumption, with positive effects for the stability of the grid supply and for the cost of supply for the consumer. The optimization aims at maximum self-consumption of PV electricity generated onsite and reduced electric demand for space heating, providing compensation for other dominant consumers, e.g. the electric sauna heater of the university sports facility.

7 (DE) Evaluation of a low charge heat pump circuit using propane

Country	Germany
Contact	Marek Miara Fraunhofer ISE marek.miara@ise.fraunhofer.de
Status	Ongoing
Main CCB implementation strategies	Compactness

7.1 Project Goal

The installation and usage of heat pumps is increasing worldwide. Especially in Europe, the heat pump has become the dominant heating solution in new buildings. Due to F-gas regulations, new solutions concerning the refrigerant itself are needed. The regulations encourage and force the shift towards refrigerants with very low GWP values, such as natural refrigerants.
Propane is a refrigerant with a minimal impact on the environment with a very low GWP value of 3 and excellent thermodynamic properties. To reduce the risk of its flammability, a refrigerant circuit using propane needs to be designed that it uses a minimal amount of refrigerant and does not exceed 150g. Such a heat pump must deliver 5-10 kW and make use of market available components.

7.2 Project Setup

For the design of the water to water heat pump, the components with high refrigerant content i.e. parts with a liquid phase were focused upon. For the heat exchangers, asymmetric plate heat exchangers with a smaller inner volume on the refrigerant side were utilised. For the pipework, the diameter and length of the pipes was reduced where possible, especially for the liquid and injection lines. The compressor was selected for low lubricating oil content and the future work will consider a system without a 4-way reversing valve.

7.3 Project Results

Simulations using IMST ART from the University of Valencia revealed the challenges of obtaining a correct viable charge of propane when utilising variable speed heat pumps with compressor speeds up to 120Hz. Maintaining the maximum charge of 150g, a heating capacity of 7.7 kW and COP of 3.6 at 60Hz was achieved. A summary of the modelled components is noted in Table 7.

	V 1.0	V 2.5	V 2.6	V 3.0	V 4.0
Compressor (all ~30cm^3 displacement)	Scroll Manufacturer 1	Rotary v1 Manufacturer 2	Rotary v1 Manufacturer 2	Rotary v1 Manufacturer 2	Rotary v2 Manufacturer 2
Condenser	Long Asymmetric 16 Plates	Long Asymmetric 16 Plates	Short Asymmetric 38 Plates	Short Asymmetric 46 Plates	Short Asymmetric 38 Plates
Evaporator	Long Asymmetric 16 Plates	Long Asymmetric 16 Plates	Long Symmetric 16 Plates	Long Symmetric 28 Plates	Long Symmetric 16 Plates
Piping	Pipes v1	Pipes v1	Pipes v1	Pipes v2	Pipes v1

Table 7 – Summary of modelled scenarios.

For Version 1.0, a scroll compressor and two asymmetric heat exchangers were modelled. In other versions, the scroll compressor was replaced by a twin rotary compressor. The heat exchanger and piping stayed the same. Version 2.5 to Version 2.6 saw changes in condenser from a long heat exchanger with small number of plates to a short heat exchanger with high number of plates. Version 3.0 used the same compressor, but totally different hex and tubing. For version 4.0, it used piping and heat exchangers of version 2.6 but built with a different twin rotary compressor with a smaller inner volume. This is illustrated in Figure 17.

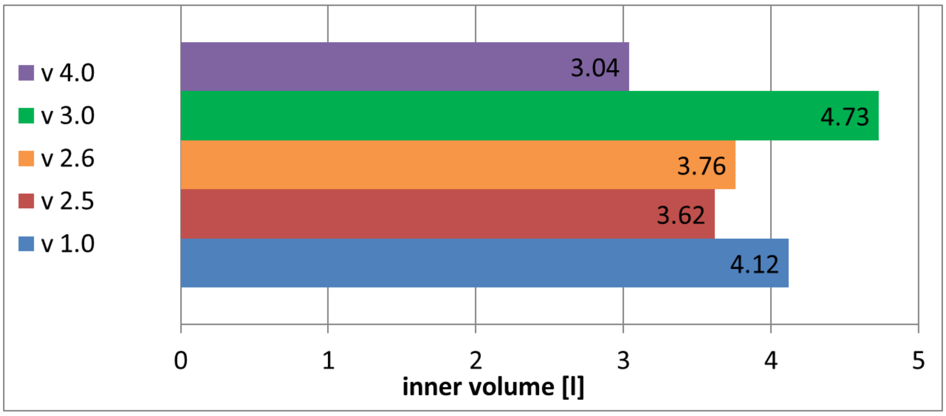


Figure 17 – Summary of equipment choices on refrigerent volumes.

Coefficient of Performance and heat capacity for various versions is noted in Figure 18 and Figure 19. The 150g limit in R290 charge is also noted at the performance test standard of evaporator Brine supply at 0°C and condenser water outlet of 35°C at 10K of superheat with a compressor speed of 50Hz.

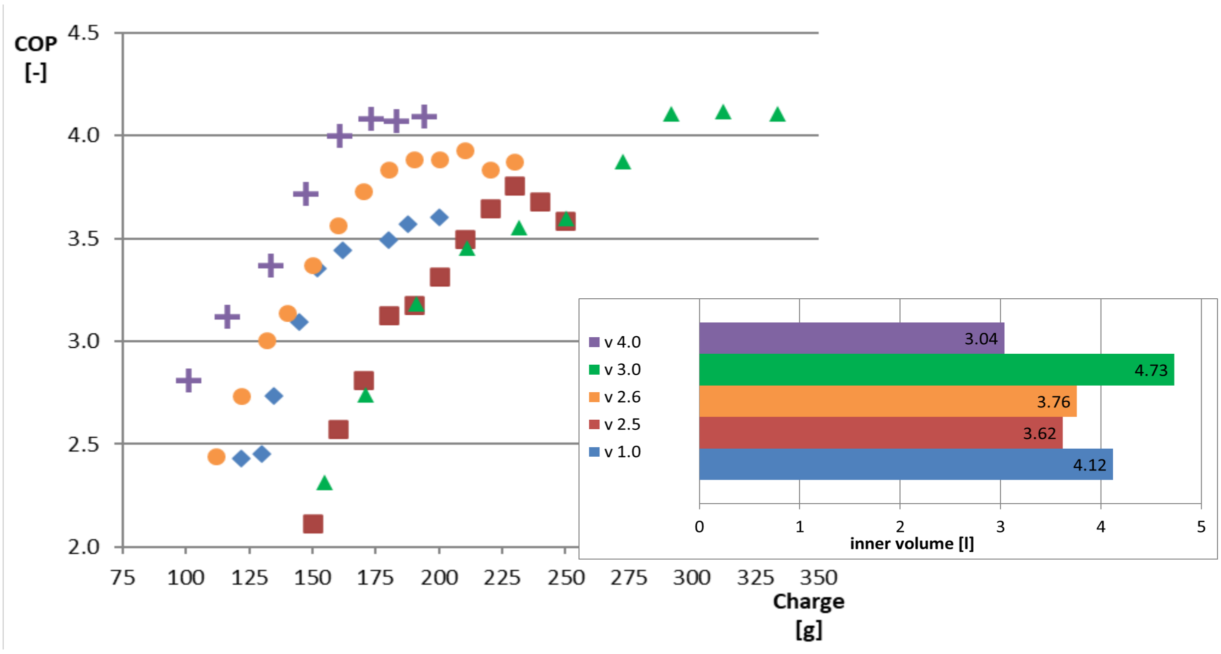


Figure 18 – COP for selected refrigerant volumes.

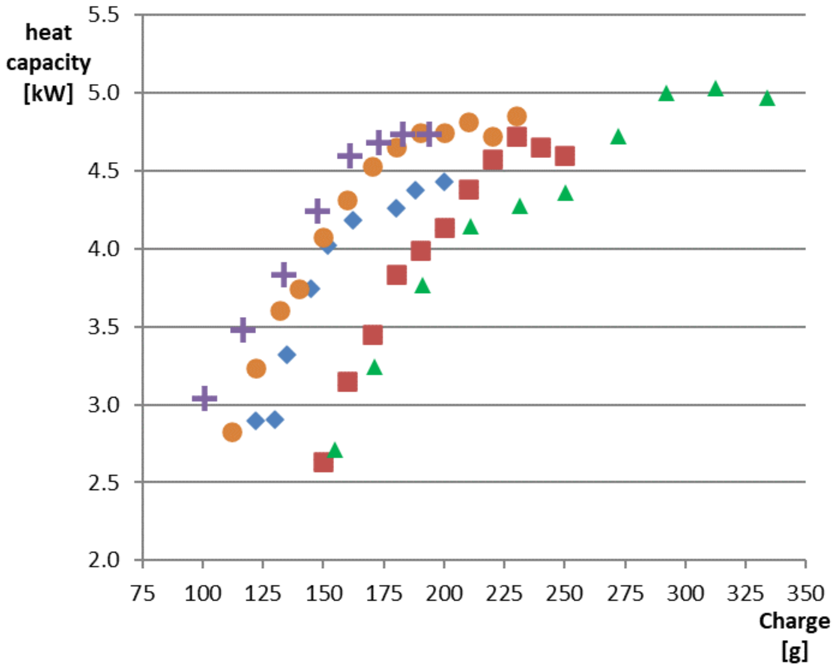
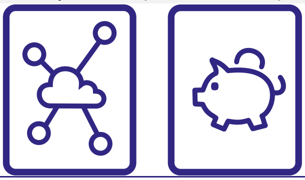


Figure 19 – Heat capacity for selected refrigerant volumes.

The project highlights that there is an optimum between refrigerant charge and performance of the unit. For control/stability reasons, it is an advantage to have a liquid collector between the condenser and the expansion device. Alternatively, high subcooling can be achieved through the deployment of an oversized condenser but this adds to the refrigerant charge and capital cost. In strongly charge reduced systems, there might be a higher chance of two-phase flow or steam bubbles in front of the expansion valve. Due to small leakages in the refrigerant circuit and for a higher reliability commonly produced heat pumps are slightly overfilled with refrigerant that they can operate for long periods even though they lose small amounts of refrigerant. In a charge reduced circuit this is not possible. Very compact brine to water circuits allow to reduce the refrigerant charge to a very low level.

8 (SE) CCB solutions for the Swedish market

Country	Sweden
Contact	Markus Lindahl RISE markus.lindahl@ri.se
Status	Completed (2019-2021)
Main CCB implementation strategies	 Flexibility Affordability

RISE Research Institutes of Sweden has together with two Swedish universities, KTH Royal Institute of Technology and Dalarna University and the two heat pump manufacturers Nibe and Thermia cooperated in the research project "Swedish contribution to Comfort and Climate Box Annex – a collaboration between IEA TCPs and Mission Innovation" founded by the Swedish Energy Agency. A project that ended in December 2021.

8.1 Project Goal

The project goal is to develop concept solutions for three types of Comfort and Climate Boxes with focus on integral design, simple installation, control and affordability. Based on the CCB archetypes described within the Annex the Swedish project focusses in first-hand on the archetype "Flexibility" with focus on smart control in combination with storage in order to lowering the running costs and increase self-consumption on PV-power. The three concepts include a heat pump in combination with storage and integrated smart control adapted for primarily single-family houses on the Swedish market.

The three concept solutions are:

- Ground source heat pump in combination with PV-panels, energy storage, passive cooling and integrated control of the CCB.
- Air source heat pump in combination with PV-panels, energy storage, cooling and integrated control of the CCB.
- Exhaust air heat pump in combination with PV-panels, energy storage and integrated control of the CCB.

For the most promising concept a prototype will be developed and tested.

8.2 Project Setup

Drafts of the three concepts solutions described above have been developed and simulated in TRNSYS to evaluate the performance of the concepts and to test new control algorithms. In addition, simulations in IDA Indoor Climate and Energy (ICE) have been made to evaluate different strategies for comfort cooling.

The TRNSYS simulations focus on evaluating the CCB concepts when used for space heating and production of domestic hot water (DHW) for a single-family building located in Norrköping, Sweden (located 160 km south of Stockholm on the Swedish east coast). A full year has been simulated based on climate data and power prices for 2019, with a simulation step of 1 to 3 minutes. DHW profile and domestic electricity demands have been derived using load generator with one minute resolution based on a stochastic

Markov-chain model according to Widen et al (2009)[21] and for the DHW demand, the model has been calibrated to comply with Bales et al (2015)[22]. The building simulated is not the same for all systems since different types of heat pumps are normally installed in different types of buildings.

The simulations are used to evaluate different alternatives for storage as well as different sizes and temperature levels of the storages. Not all alternatives have been simulated for all concept solutions. In addition to the alternatives for storage different algorithms for "smart control" have been developed and tested in the simulations. The control algorithms can be divided in two main groups; algorithms to increase self-consumption of PV-power and algorithms that decrease the running costs by producing more heat and use the storage when the electricity and/or power prices are low.

Heat Pump
GSHP
ASHP
EAHP
Storage alternatives
DHW tank (additional tank volume or higher temperature)
Pre-heating tank for DHW
Battery
Building envelope (changes in indoor temperature)
Control algorithms
Increased self-consumption of PV-power
Decreased running cost

Table 8 – Summary of CCB alternatives evaluated in TRNSYS simulations.
(Note that not all combinations have been evaluated)

The results have been evaluated based on different electricity price scenarios, both for today's and future electricity and power prices in combination with investment costs.

	S1	S2	S3	S4	S5	S6	S7	S8
Contract[1]	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly
Network[2]	Energy	Energy	Capacity	Capacity	Energy	Energy	Capacity	Capacity
Tax reduction[3]	No	No	No	No	Yes	Yes	Yes	Yes

[1] Refers to the type of contract a homeowner will have with the electricity supplier, hourly prices with a fixed fee or monthly prices with a larger fixed fee.
[2] Refers to the network owner's business model of charging based on volumetric energy usage (Energy) or peak loads (Capacity). Both have the same fixed fee.
[3] Refers to the presence of the 0.60 kr/kWh (0.06 Euro/kWh) micro producer tax credit applied on PV generation sold to the grid.
Table 9 – Overview of price scenarios for power

[21] A combined Markov-chain and bottom-up approach to modelling of domestic lighting demand, Energy and Buildings, October 2009, Joakim Widén, Annica M. Nilsson, Ewa Wäckelgård
[22] Database of energy, environmental and economic indicators of renovation packages for European residential buildings Energy and Buildings 8 September 2019, Chiara Dipasquale Roberto Fedrizzi Chris Bales

Simulations of comfort cooling has been done in IDA ICE in order to evaluate possibilities to improve the comfort related to cooling. The simulations have focused on passive cooling from the bore hole for a single-family building with an installed GSHP. The cooling is distributed to the indoor air using a fan coil. Both a Swedish villa with “normal” heating demand and a low energy building has been included in the simulations.

A prototype of a CCB based on a ground source heat pump with possibilities to passive cooling and energy storage has been developed within the project and evaluated in lab. Testing of control functions have been done as well as a system testing based on a 6-day method. Within the project new control algorithms for an exhaust air heat pump have been developed and implemented.

8.3 Results

8.3.a CCB based on GSHP, TRNSYS simulations

The first concept solution consists of a ground source heat pump in combination with PV-panels and thermal energy storage in the form of a domestic hot water tank.

System Design

The CCB configuration is based on a single-family house occupied by four people. The building has been modelled using Type56 in TRNSYS and has the characteristics of a Swedish building from 1960s. The main inputs used for the building model are presented in Table 10.

Floor area	U-value (walls)	U-value (roof and floor)	U-value (windows)	Ventilation	Infiltration
125 m^2	0.6 $W/m^2/K$	0.3 $W/m^2/K$	1.2 $W/m^2/K$	0.4 ACH[1]	Variable, simulates opening of windows

Table 10 – Main inputs for the building model
[1]air changes per hour

Space heating (SH) and domestic hot water (DHW) are both provided by a variable speed ground source heat pump. The heat pump has a peak compressor power of 5 kW, reached at a frequency of 88 Hz. At these conditions the GSHP can provide 13 kW of heating power with a COP of 2.6. The system has been modelled based on a performance map, with a compressor speed that ranges from 20 to 88 Hz.

The heat pump in its basic configuration is equipped with a 180l storage tank for DHW, while no tank is used for the SH. The temperature of the water used for SH is calculated based on the heating curve of the building, while the top node temperature of DHW has been set at 55°C with a dead band of ±3°C.

The electricity is supplied both by the power grid and a 5 kW roof mounted PV system. The panels are modelled using Type562 in TRNSYS, where an efficiency of 17% and a tilt of 25° has been set as inputs.

For the simulations, 1-minute weather data for Norrköping from the year 2019 is used from SMHI. The 1-minute data is averaged to match the 3-minute simulation time-step.

Table 11 summarizes the main boundary parameters of the simulated system.

Heat pump	PV-panels	Storage tank	Ground source	Building	Location
Brine to water	South orientation 25° tilt	1 for DHW with 180L capacity	Single borehole U-type	Single family house with 4 occupants	Norrköping
Variable speed (20-88 Hz)	5 kW	Optimization study on the size of the tank	Non-grouted	Building from the 60s with modern windows	Weather data from SMHI (2019)
Monovalent	Type 562 in TRNSYS		200 m depth		

Table 11 – Main boundary conditions of the system

The system has been simulated with two different control strategies:

- a "normal" strategy, where the heat pump is working independently from the PV system and is supplying thermal power only based on the occupants' demand.
- an "solar" strategy that activates every time there is overproduction from the PV system. In this condition the heat pump increases its compressor speed to match the available power. The DHW tank is used as a thermal storage since the extra power is used to heat the top node temperature of the DHW tank up to 67.5°C, with the aim of increasing the self-consumption of the CCB.

Figure 20 demonstrates how the strategies work showing PV production, electricity load and top node temperature in the DHW tank.

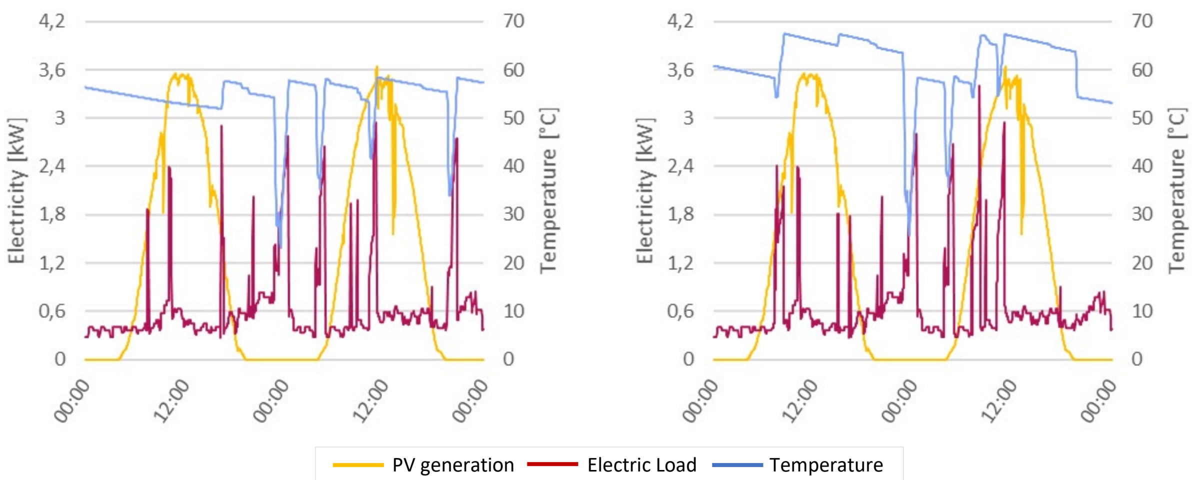


Figure 20 – Normal strategy (left) and solar control strategy (right)

The resulting annual heating demand is 11,766 kWh_{th}, which corresponds to 94 kWh_{th}/m^2 per year. The domestic hot water profile gives as annual demand of around 170 l/day, which amounts to 3427 kWh_{th}/y, while the electricity demand for lights and appliances amounts to 5214 kWh_{el}/y. On a 3-minute time step the peak heating demand corresponds to 9.92 kW_{th}, which is reached in February, and in that condition the heat pump compressor is operating at 3.04 kW_{el} with a COP of 3.26. Figure 21 shows the monthly energy demand of each energy need.

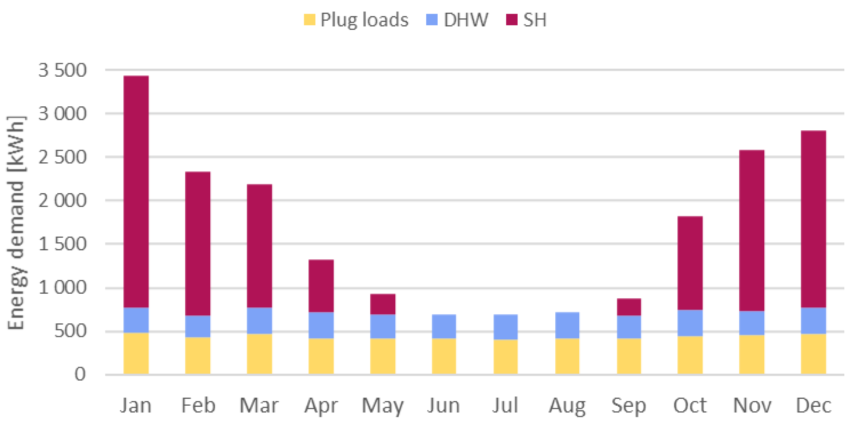


Figure 21 – Monthly energy demand of all types

Simulation results

In the normal operation conditions, the total annual electricity consumption amounts to 8646 kWh_{el} of which 77% is supplied by the power grid, giving a value of self-sufficiency of 22.9%. The annual PV production corresponds to 4851 kWh_{el}, resulting in a self-consumption of 40.9%.

Once the "solar" control strategy is applied, the annual electricity demand increases to 8796 kWh_{el}, but the share of self-consumed PV electricity is also increasing, lowering the grid purchases to 74% of the total electricity supply. The self-consumption and self-sufficiency of the new system increase respectively to 47.3% and 26.1%. Figure 22 shows the difference in the monthly electricity supplied by each technology.

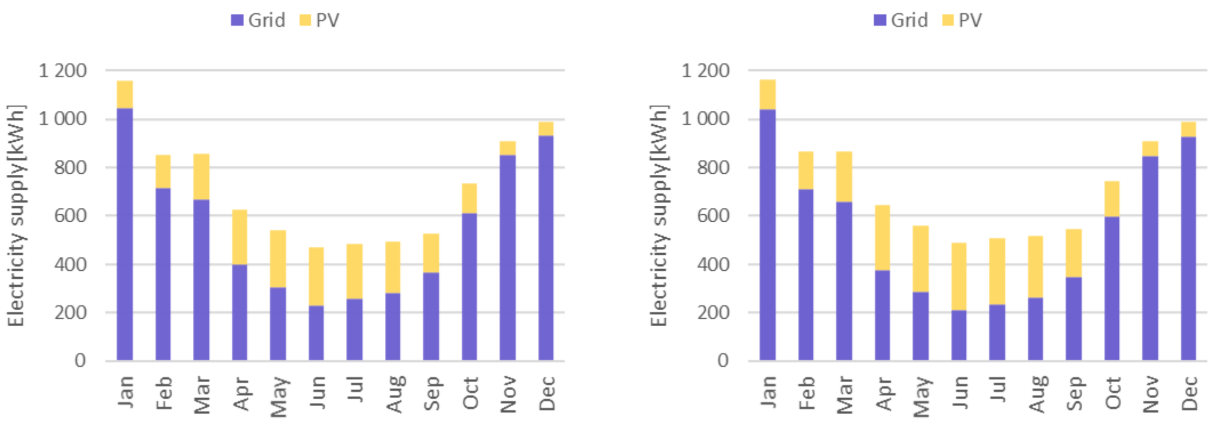


Figure 22 – Electricity supplied by grid and PV in the normal (left) and optimized (right) operation strategies

To evaluate the possibility to further improve the performances of the system under the new control strategy, a sensitivity analysis on the tank size has been performed. More specifically, the tank volume has been increased from 180l up to 1000l.

From Figure 23, showing the duration curve of the top node temperature, it can be noticed that the operating time of the new control strategy can be extended to more than 4000h per year already with the 300l tank, but it increases only of few hundred hours more with the 1000l tank.

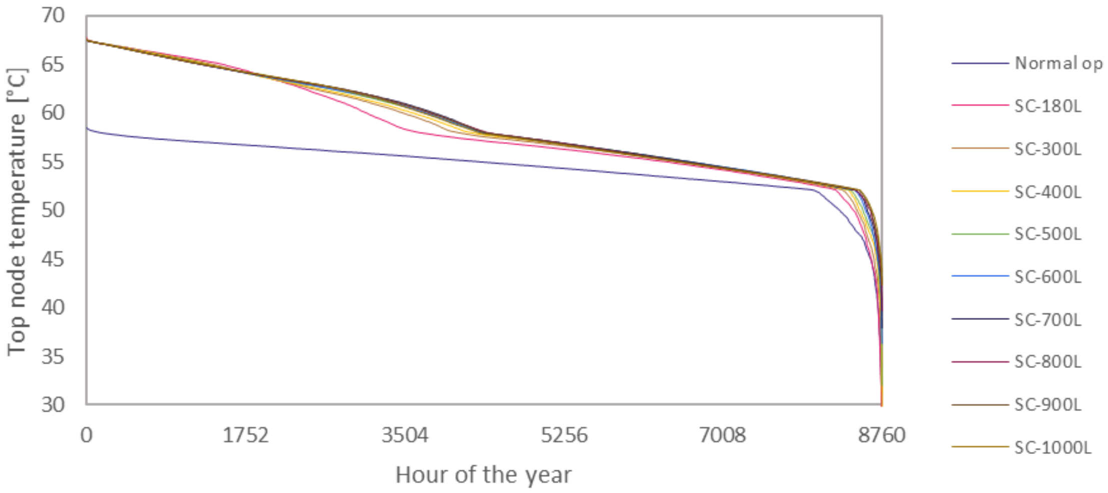


Figure 23 – Duration curve of top node temperature for normal operation and solar control (SC) strategy for different tank sizes

The increase of the tank size also creates a negative effect on the average COP, especially in the summer months, when the new control strategy is active the most. The heat pump has lower performances when operates at higher temperatures at the condenser, and as soon as the new control strategy is active the average COP drops. Then, by increasing the size of the tank the new control strategy stays active for more hours, resulting in a lower efficiency of the heat pump on a monthly basis. Figure 24 shows how the average COP changes for the different operation strategies.

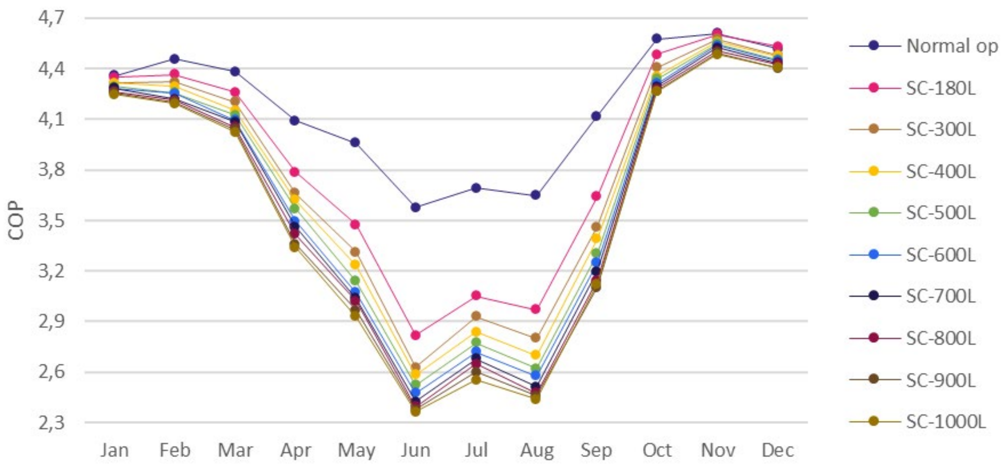


Figure 24 – Monthly average COP for normal operation and solar control (SC) strategy for varying tank sizes.

Regarding the electricity consumption, the more the volume of the DHW tank increases, the more the overall electricity demand increase. However, the self-consumed electricity generated by PV increases as well, lowering the grid purchases. This can be observed in Figure 25, which shows the absolute variation of electricity consumption and self-consumption of the systems.

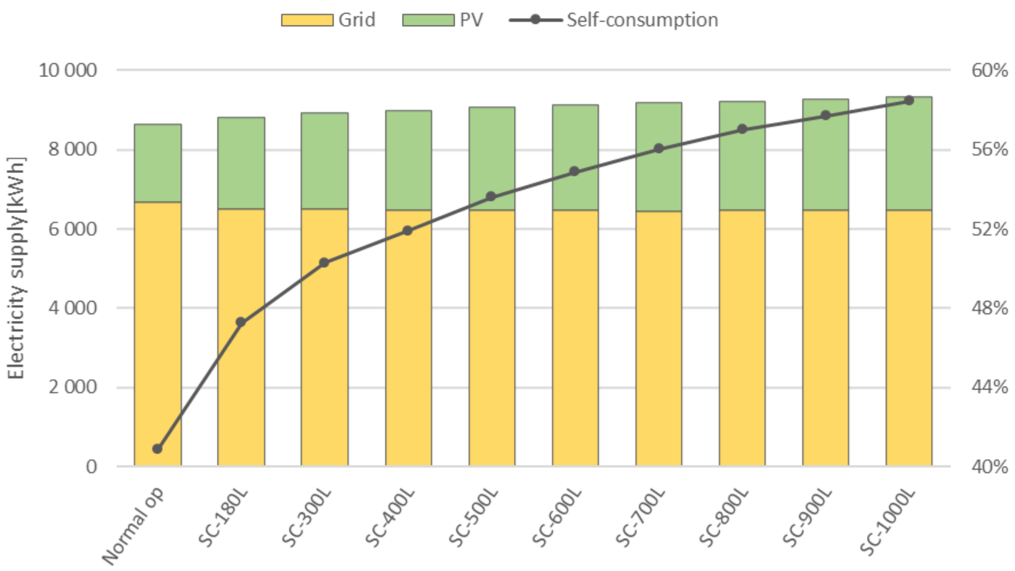


Figure 25 – Absolute variation of electricity supply and self-consumption for normal operation and solar (SC) strategy for different tank sizes

This effect is achieving its limit with a 600l tank, reaching an annual grid purchase reduction of 3% respect to the normal operation conditions. This can be observed in Figure 26, which shows the relative variation of self-consumption, self-sufficiency and grid purchases for all the modelled configurations.

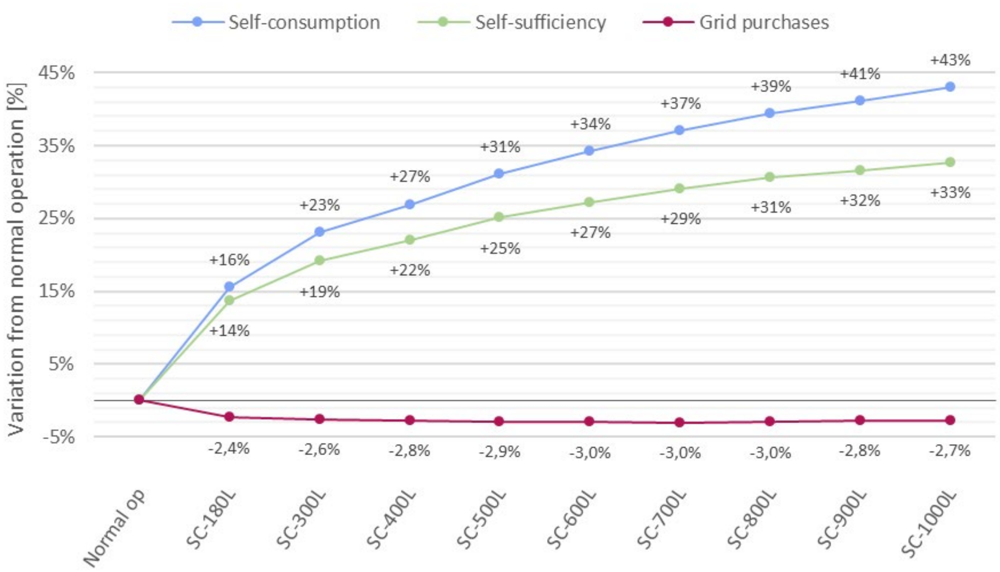


Figure 26 – Relative variation of KPIs for normal operation and solar control (SC) strategy for different tank sizes.

The extra amount of electricity needed for larger tanks is the result of increasing thermal losses due to larger surfaces of the tank. Thermal losses increase is relatively small when the operation mode switches from the normal one to the one that improves the self-consumption, but a rapidly increase is noticed as soon as the volume of the tank is increased.

At normal operations the losses amount to 360 kWh_{th}/year but they reach almost 1200 kWh_{th}/year with a 1000l tank. Figure 27 shows the absolute and relative variation of heat losses in the DHW tank.

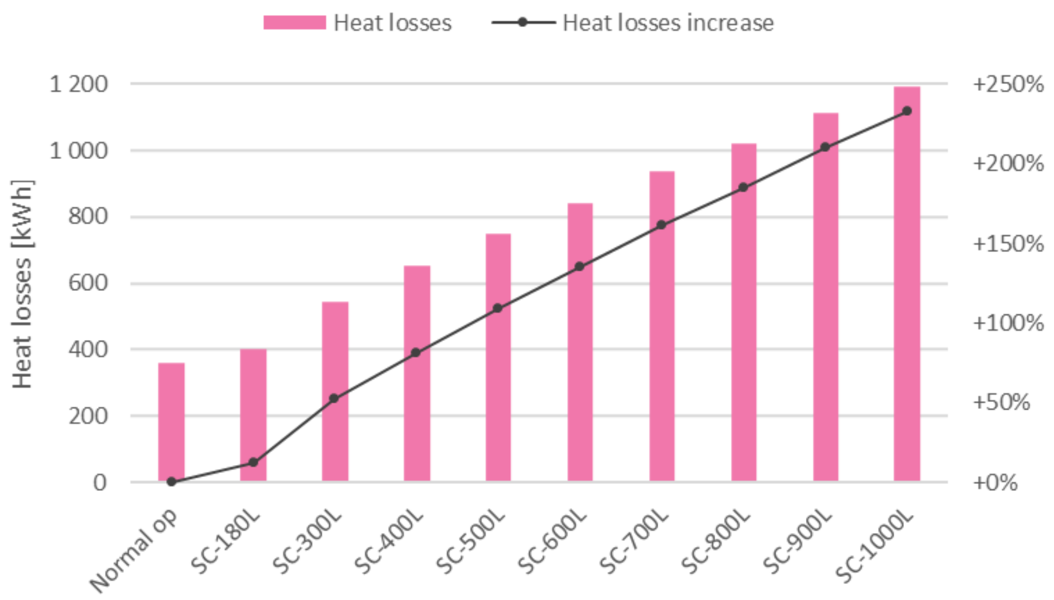


Figure 27 – Heat losses in DHW tank at normal operation and solar control (SC) strategy for different tank sizes

8.3.b CCB based on ASHP, TRNSYS simulations

The concept simulated consists of an air-to-water heat pump combined with PV-panels and energy storage, i.e., thermal storage or battery. As thermal storage a domestic hot water tank (DHW), an additional pre-heating tank for domestic hot water or the building envelope is used changing the setting s for indoor temperature. The system configuration is illustrated in Figure 28.

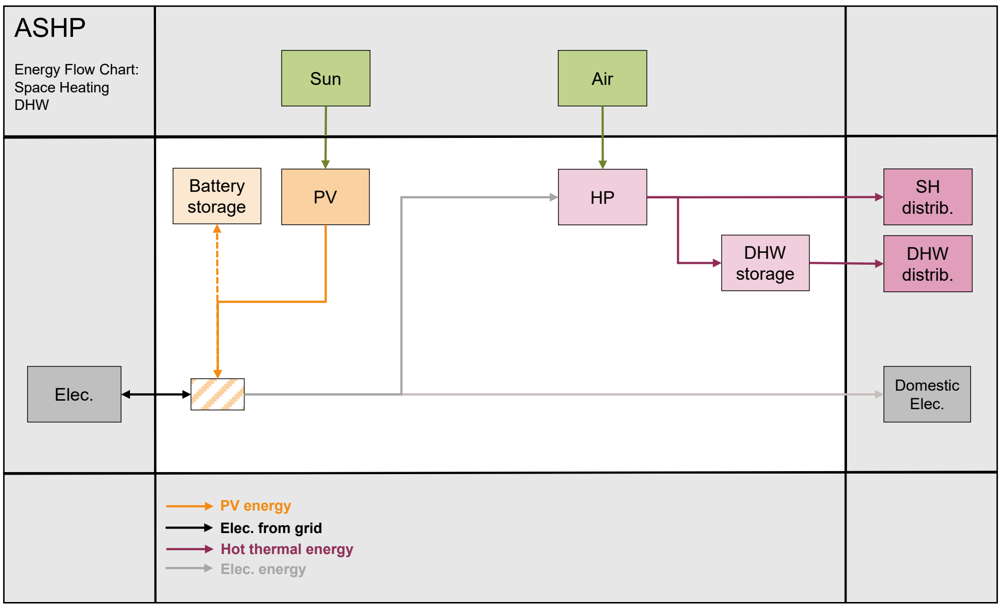


Figure 28 – Overview of CCB concept based on ASHP simulated in TRNSYS.

System Design

The CCB configuration is based on the same single-family building as used for the GSHP concept, A 125 m^2 building with radiators. The building is assumed to be occupied by 4 people and has been modelled using Type56 in TRNSYS. The summary of the main characteristics for building model are presented in Table 10 above. The indoor set temperature is 21°C, which gives an annual space heating demand of 12 000kWh$_{th}$/y, corresponding to 96 kWh/m^2 per year. The domestic hot water profile used gives as annual DHW demand of approximately 3 800 kWh$_{th}$/y, while the electricity demand for lights and appliances amounts to 5 200 kWh$_{el}$/y.

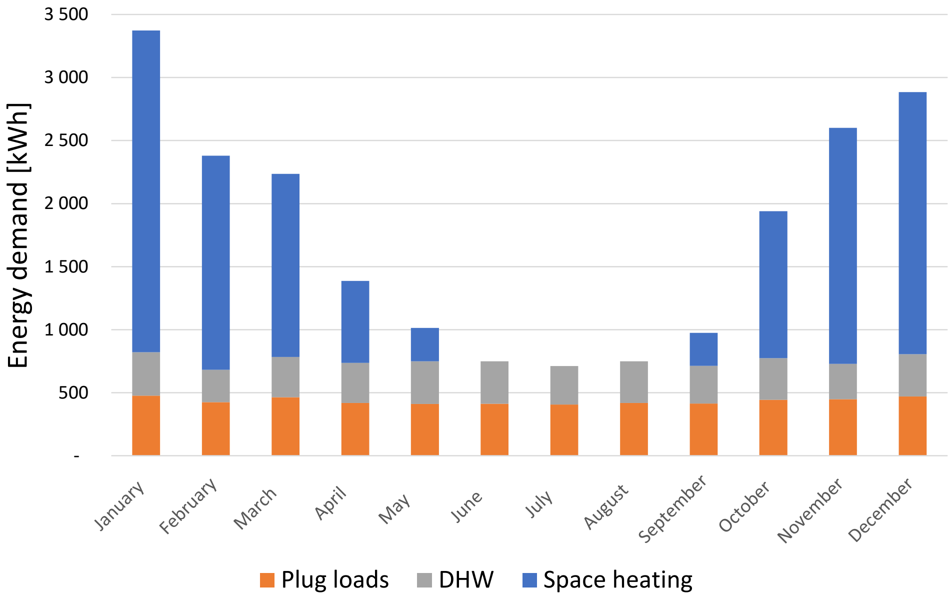


Figure 29 – Monthly energy demand for the simulated building.

Space heating (SH) and domestic hot water (DHW) are provided by a variable speed air-to-water heat pump with a capacity range of approximately 3-9 kW$_{heat}$ at +2°C outdoor temperature. The heat pump has been modelled based on a performance map in TRNSYS, where the heat pumps performance and heating capacity are dependent on compressor speed, supply- and outdoor temperature. The heat pump system is monovalent but if needed, an electric auxiliary heater is activated in order to provide additional heat to meet the thermal needs. The heat pump in its basic configuration is equipped with a 180l storage tank for DHW and no space heating buffer tank. The supply temperature of the water used for SH is based on the heating curve of the building, while the DHW production has been set to start at a top node tank temperature of 48 and stop at 52°C. The control algorithm of the model prioritizes production of DHW over the space heating demand.

The electricity is supplied both by the power grid and a 5kW roof mounted PV system, with a tilt of 25°. For the simulations, weather data for the year 2019 obtained from SMHI have been used and the Swedish city of Norrköping has been chosen as location. Norrköping is located 160 km south of Stockholm on the Swedish east coast. 1-min has been set as simulation time-step.

The PV panels are connected to a regulator and inverter, which is modelled with Type48 (mode 1) In TRNSYS. The model can be connected to a battery. Type48 firstly ensure comparisons of the electrical load of the building with the amount generated by the PV-panels. Excess electricity is either delivered to a 12Ah battery (if such is attached and not fully charged) or distributed to the electrical grid. Type48 also models the conversion from AC to DC. Table 12 summarizes the main boundary parameters of the simulated system.

Heat pump	PV-panels	Storage	Building	Location
Monovalent Air-to-water heat pump	South orientation, 25° tilt	DHW tank (180l)	Single family house with 4 occupants	Norrköping
Variable speed (3-9 kW_{heat})	5 kW			Weather data from SMHI (2019)

Table 12 – Main characteristics for the CCB concept based on an ASHP system i.e., the boundary conditions of the base case.

Apart from modelling the base case, described in Table 12, the model was developed further to simulate the impact of different control strategies in combination with different alternatives for storage. Control algorithms were developed with the aim of either increasing self-consumption of PV-electricity or decreasing the operation cost for a pricing scenario.

PV-algorithm

The algorithms to increase self-consumption activates every time there is overproduction from the PV system (the PV-power produced is larger than the electricity needs of the house). It then triggers a signal that either allows for the battery to be charged, the setpoint temperature of the DHW tank to increase or allow for the HP return flow to pre-heat the tap water in a pre-heating tank before going in to the ordinary DHW-tank. Additionally, if the HP return flow is zero and there is a surplus greater than 1 kW of electricity and the temperature in the pre-heating tank is below 54 °C a different signal is activated which activates the heat pump until the temperature in the preheating tank is above 54°C or the entire excess has been utilised.

Price-algorithm

The price algorithm is based on the spot market prices from Nord pool. The three hours with lowest spot market price during the day is defined a low-price hours and the three hours with the highest spot market price is defined as high-price hours. Based on if the hour is defined as a low- or a high-price hour the set values are changed:

- Elec. price T_{indoor}: For the case when the building envelop is used for energy storage the set value for the indoor temperature is change +0.5° for a low-price hour and -0.5° for a high-price hour.
- Elec. Price $T_{DHW\text{-}tank}$: When the DHW-tank is used for energy storage the set value for the tank is increased with 10° for low-price hours and decreased with 5°for high-price hours.
- Elec. price PH-tank: For the case with a pre-heating tank, a low-price hour activates the use of the pre-heating tank, and the return flow (space heating water) is used to pre-heat the tap water in a pre-heating tank of 75 l before the tap-waters enters the ordinary DHW-tank. For high-price hours no changes to the settings are made.

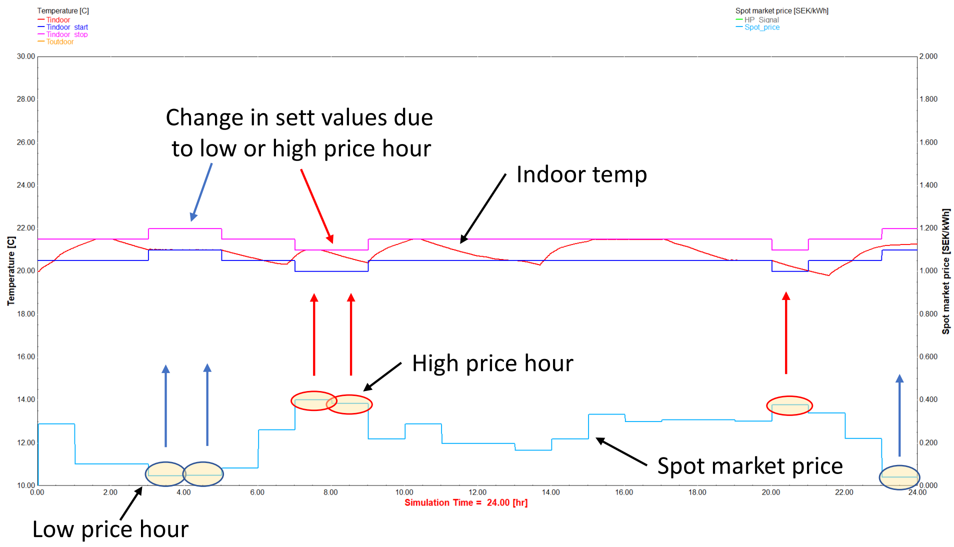


Figure 30 – Schematic overview of the price algorithm. A "low-price hour" increases the set value and a "high price hour" decreases the set value. In this example the set value for indoor temperature is changed.

Time-algorithm

The time algorithm is a simplified version of the price-algorithm. The algorithm is based on the assumption that the electricity price is generally lower during the night but increases in the morning. This makes it possible to use the control algorithm without any external input about electricity prices.

- Time T_{indoor}: For the case when the buildings thermal mass is used for energy storage the set value controlling the indoor temperature (heating curve) is changed with +0.5°C from 03:00-06:00 and -0.5°C from 06:00-09:00. The set values for when the heat pump starts and stops are changed with the same values.
- Time $T_{DHW\text{-}tank}$: When the DHW-tank is used for energy storage the set value for the tank is increased with 10°C from 03:00-06:00 and decreased with 5° from 06:00-09:00.
- Time PH-tank: For the case with a pre-heating tank, the pre-heating tank is activated from 03:00-06:00, and the return flow is used to pre-heat the tap water in a pre-heating tank of 75l before the tap-waters enters the ordinary DHW-tank.

Simulation results PV control algorithm

The simulation results presented below shows the variation in electricity demand from the grid for different storage solutions. The aim of the algorithms used is to increase PV self-consumption. The logic of the algorithm is such that if a surplus of electricity is generated from the PV panels the excess can be stored either as heat (in a tank which can be used to pre heat domestic hot water) or electricity (in a battery).

Figure 31 below shows the building's total electricity use over the simulated year compared to the bought electricity from the grid for the different alternatives. The difference between total electricity demand and bought electricity is covered by internally produced solar.

As can be seen in the graph below, the total electricity demand is relatively similar for all alternatives (black bars in Figure 31). Regarding the annual amount of bought electricity, the base case has the highest demand (blue bars in Figure 31). For the cases with a preheating tank the annual amount of bought electricity decreases slightly with increased size. The least amount of electricity from the grid is required for the case with a battery.

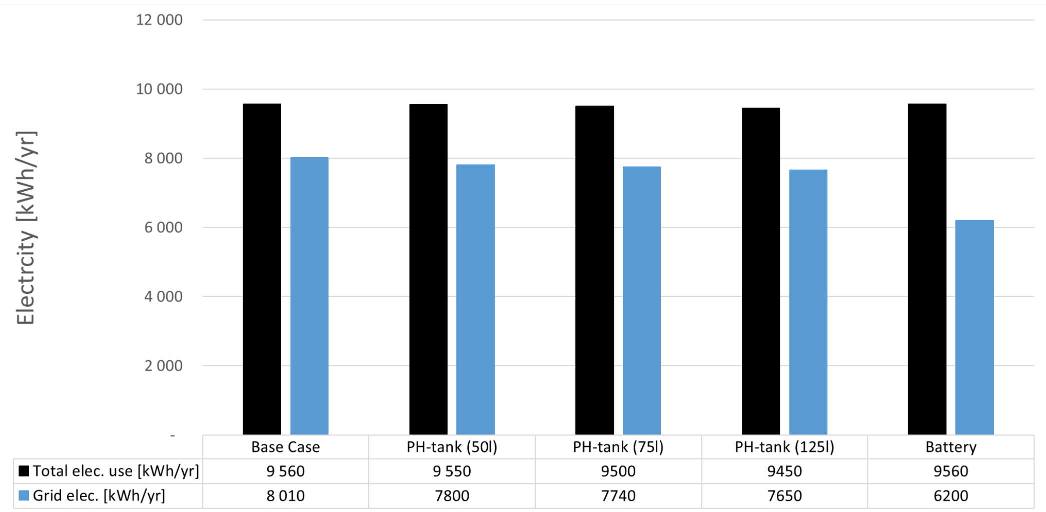


Figure 31. Total annual electricity demand for the building (in black) and annual amount of electricity bought from the grid (blue). Base case is compared to three different sizes of pre-heating tanks and a battery.

Similar to the result in Figure 31, Figure 32 illustrates the advantages of implementing storage solutions to the system. Rather than describing amount of bought electricity Figure 32 illustrates the result in terms of self-consumption. As the algorithm used is intended to increase the self-consumption using different types of storage solution it is not surprising that all cases performs better that the base case. It is not suitable to compare the results for the battery and the storage tanks with each other as they are not designed to be able to store the same amount of energy, they are also implemented in different parts of the system. The battery has the potential of reducing the total amount of bought electricity and the pre-heating tank can only decrease the amount of bought electricity for heating the domestic hot water.

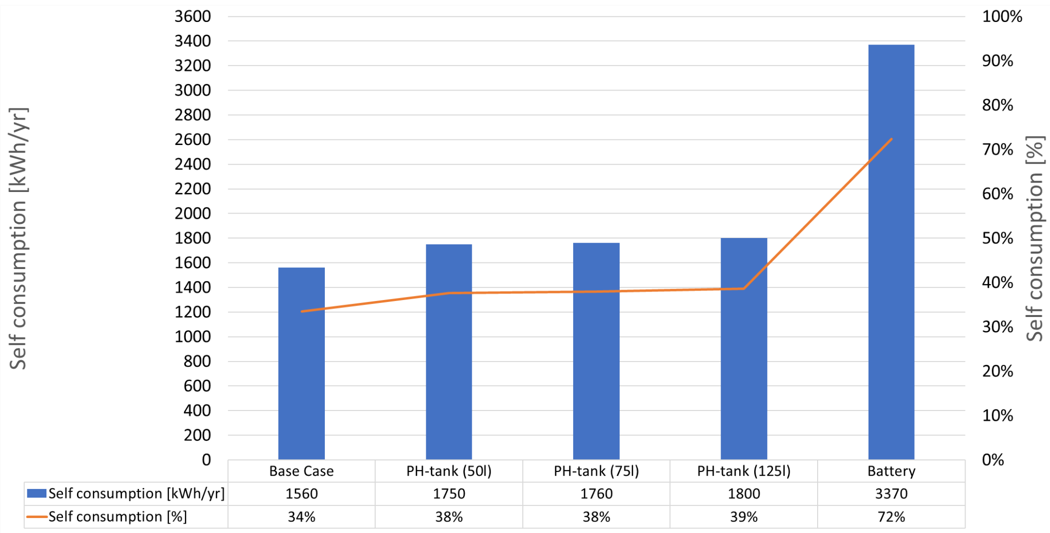


Figure 32. Self-consumption of electricity for base case, three cases with different sizes of pre-heating tanks and a case with battery.

The annual electricity cost is calculated for the building in total, including electricity use for space heating, DHW and plug loads. The cost includes purchased electricity, fixed fees and for some of the price scenarios a peak capacity cost. Revenues from sold excess PV electricity is also included in the net total cost. In Figure

33 the electricity cost for the base case is compared to two sizes of a pre-heating tank and an electric battery for each price scenario, see Table 9.

The black bar in Figure 33 shows the net cost for the different alternatives and price scenarios. As can be seen in Figure 33, the alternative with a battery in combination with the PV-algorithm is the best chose in order to reduce the running costs. For this case the annual running cost decreases with above 12% for price scenario 1 and 2 (with no tax reduction for sold solar and a network fee based on electricity consumption. On the other hand, the battery also comes with the highest investment cost.

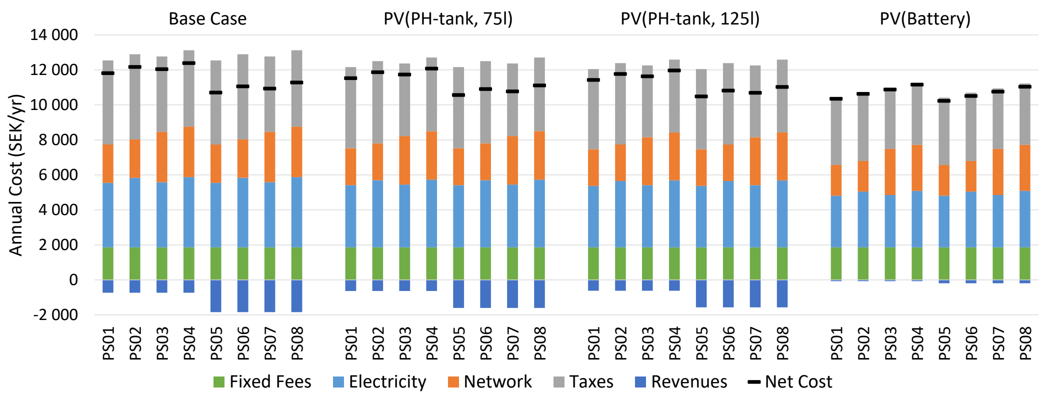


Figure 33. Breakdown of annual electricity cost and revenue (sold electricity) and the associated fees for the eight price and power scenarios summarized in Table 9. Base case is compared with the three different storage alternatives combined with an activated PV algorithm. The total annual electricity cost (net cost) for each case is shown with black lines.

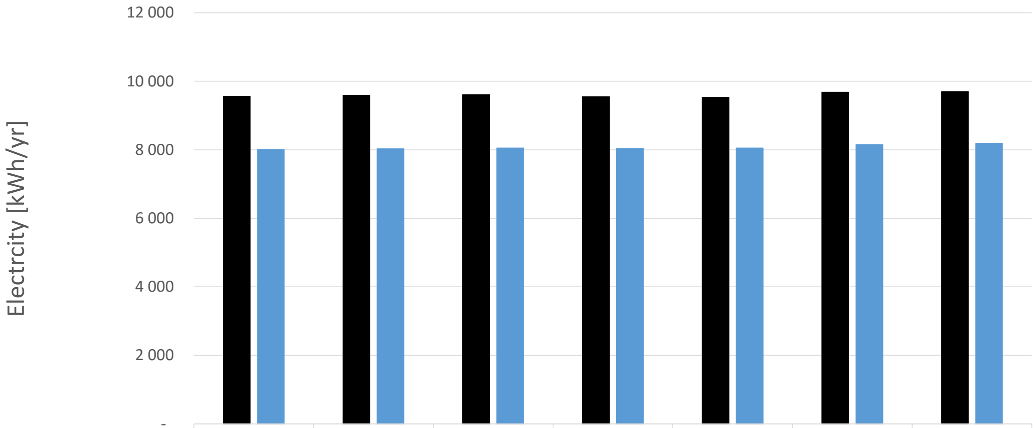
Price- and time control algorithm

The simulation results presented below shows the results with an activated price or time algorithm combined with three different alternatives for storage, The DHW-tank, an additional pre-heating tank for tap-water or the buildings thermal mass, thereby changing the set values for the indoor temperature. The results are compared with a base case with no smart control algorithms activated or any additional storage except for the ordinary DHW-tank. The total annual electricity use includes electricity use for space heating, DHW and plug loads (for lights, white goods, electronic equipment etc).

Figure 34 below shows the buildings total electricity use over the simulated year compared to the bought electricity from the grid for the different alternatives. The difference between total electricity demand and bought electricity is covered by internally produced solar.

As can be seen the total electricity demand is relatively similar for all alternatives., with a small increase in electricity demand for in first-hand the control algorithms using the DHW-tank as storage. Higher set temperature gives lower COP and thereby increases the electricity consumption, while a lower set temperature increases COP. Especially for the alternative with DHW-tank the lower set values during high-price hours cannot compensate for the lower COP during low-price hours. A higher tank temperature also increases the tank losses. Those losses are only partly assumed to reduce the heating demand of the building in the simulations.

A somewhat higher electricity demand is expected for this control algorithm. The question to be answered if could lead to overall lower cost for the electricity.



	Base Case	Price Tindoor 0.5°C	Time Tindoor 0.5°C	Price PH-tank (75l)	Time PH-tank (75l)	Price DHW-tank	Time DHW-tank
Total elec. use [kWh/yr]	9 560	9 590	9 610	9 550	9 530	9 680	9 700
Grid elec. [kWh/yr]	8 010	8 030	8 050	8 040	8 050	8 150	8 190

Figure 34. Total yearly electricity demand for the building compared to electricity bought from the grid. Base case is compared with the three different storage alternatives combined with an activated price- or time algorithm.

The annual electricity cost is calculated for the building in total, including electricity use for space heating, DHW and plug loads. The cost includes purchased electricity, fixed fees and for some of the price scenarios a peak capacity cost. Revenues from sold excess PV electricity is also included in the net total cost. In Figure 35 the electricity cost for the base case is compared to the three storage alternatives with an activated price algorithm.

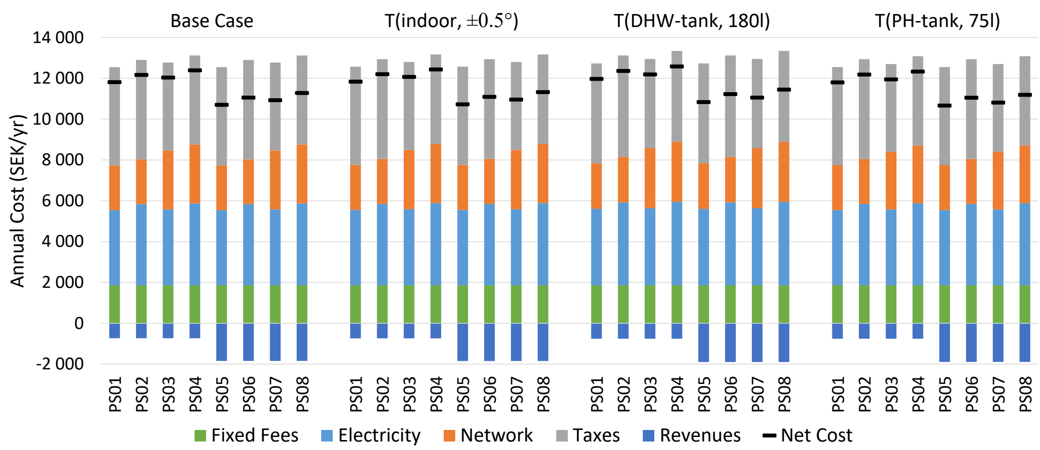


Figure 35. Breakdown of annual electricity cost and revenue (sold electricity) and the associated fees for the eight price and power scenarios summarized in Table 9. Base case is compared with the three different storage alternatives combined with an activated price algorithm. The total annual electricity cost (net cost) for each case is shown with black lines.

The potential savings between the different alternatives are small, close to negligible, but the alternative with a pre-heating (PH) tank is the most promising alternative for savings related to the running cost. A disadvantage with a PH-tank compared to the other alternatives are the need for an extra tank leading to both higher investments costs and a larger area needed for the unit.

8.3.c CCB based on EAHP, TRNSYS simulations

System Design

The reference building is a typical Swedish single-family house (SFH) of one floor with a gabled roof. The house has an overall U-value of 0.2 W m^{-2} K^{-1}, 143 m^2 heated floor area using a radiant concrete floor heating system or radiators on demand. A detailed model of the house with six zones shown in Figure 36, is developed in the simulation software TRNSYS 17. TRNSYS's type 56 is used for the house model. The two main zones (1 and 2, living room and kitchen respectively) have a set temperature of 21°C which can be adjusted individually upon demand. The utility room and bedrooms (zones 3, 5 and 6) have 20 °C while the bathroom has 22 °C. The ventilation rate is 0.5 air changes per hour, and infiltration is 0.033 m3/s. Internal window shading is applied with 80% shading factor if the room temperature goes above 23 °C, and the infiltration is increased above 24 °C to account for opening of windows.

A compact, variable speed, exhaust air heat pump is used and delivers heat either for SH or for DHW. The heat pump is modelled based on detailed measured data in steady state for the full range of operation and been used to make the performance used by the model. The 180l DHW tank is modelled with the non-standard type 340, as well as the additional 253l tank with the difference that has an internal heat exchanger which preheats the tap water so has the advantage to avoid legionella formation. The SH is supplied by the heat pump through a 25l buffer store modelled by type 60. In space heating mode, the heat pump is controlled according to a heating curve and compensatory control algorithm dependent on the SH supply temperature. Moreover, an electric auxiliary heater is activated in steps when the thermal power provided by the heat pump is insufficient to meet thermal power need.

The lithium-ion battery system has a capacity of 7.2 kWh of the type LIFEPO4 and the PV inverter is bi-directional. The modelling of the PV-battery system is done including detailed losses of the system. The battery management system is actually modelled as connected to the electrical junction box of the building and can control the import or export electricity to the grid, while controlling the charging and the discharging of the battery storage.

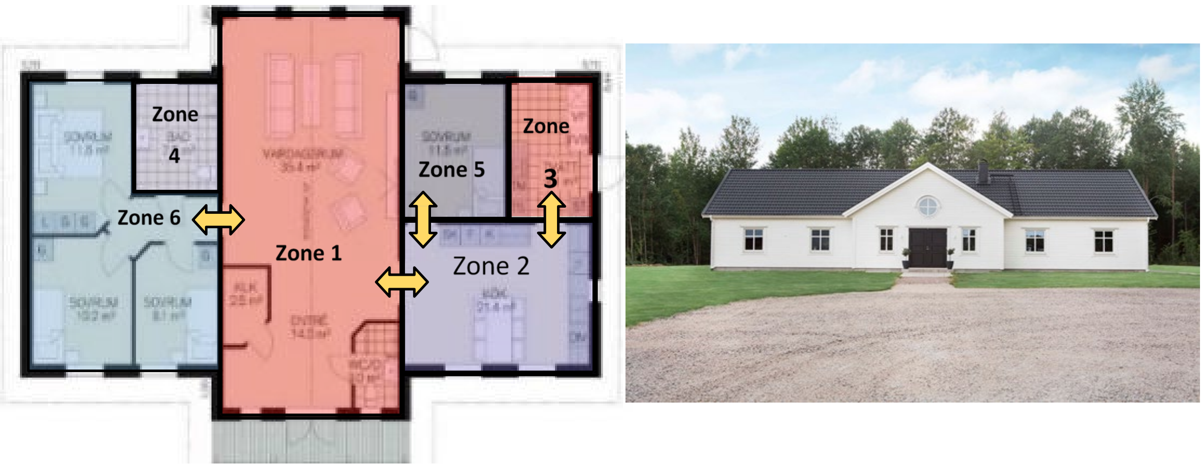


Figure 36 – Layout of the building that is modelled with 6 thermal zones (left side) and the actual front view of the house (right side).

Household DHW, appliances data and heating demand, base case	Energy [kWh/year]
DHW discharge energy	3487
SH demand	12146
PV electricity yield	5119
Electricity for appliances	3644

Table 13 – Energy demand of the household and PV annual yield in the base case.

The developed control algorithms[23] both electrical and thermal mode (variant 1) and (variant 2) listed in were implemented in the system to increase the self-consumption of PV-electricity by utilizing the electrochemical storage (batteries) and by storing thermal energy in the compact domestic hot water store (activate the heat pump to increase the set point in order to overheat beyond the reference setpoint). The extra hot water tank (variant 3) has an internal heat exchanger which preheats the tap water when there is PV excess energy.

For the case of the thermal mode during overheating of the compact and the additional tank the heat pump compressor speed and respectively the load demand is adjusted to the available excess PV electricity. The auxiliary heater is restricted during the predefined summer period or whether a threshold of ambient temperature is exceeded. This is done as there is a risk that any benefits of the algorithms are negated by unnecessary use of the normal control of the auxiliary heater. In the electrical mode (variant 1) all the excess available PV electricity is consumed by the battery system after all the household loads are covered.

The objective of the Price algorithm which is used in variants (3-6) is to control the HP in order to adjust the space heating demand or overheat the compact tank or even to preheat the extra tank according to the spot market price signal and the near future forecast. More details can be found from Psimopoulos, E., et al.[23] . The base case includes no control between the PV system and the HP operation and no extra storage type. In Table 14 an overview of simulations is shown

	Algorithms		Storage options			
Variants	**Price**	**PVxs**	**Battery[1]**	**DHW store temp**	**Extra DHW tank**	**Building[2]**
Base case						
1		X	X	X		
2		X		X	X	
3	X			X		X
4	X			X	X	X
5	X	X		X	X	X
6	X	X		X		X

[1] **Battery is only used with PVxs (excess electricity)**

[2] **Building uses floor heating in zones 1 and 3 by varying set temperature (fig 31)**

Table 14. Simulation variants for the EAHP system.

[23] Psimopoulos, E., et al. (2019). "Techno-economic analysis of control algorithms for an exhaust air heat pump system for detached houses coupled to a photovoltaic system." Applied Energy 249: 355-367.

Simulation results

The simulation results which include variants 1 and 2 and the base case are shown in and respectively as far as the energy use of the system and the key figure indicators self-consumption, solar fraction and final energy use which is the bought electricity of the grid. Table 15 lists the cost calculations in Euros for each of the two variants compared to the base case.

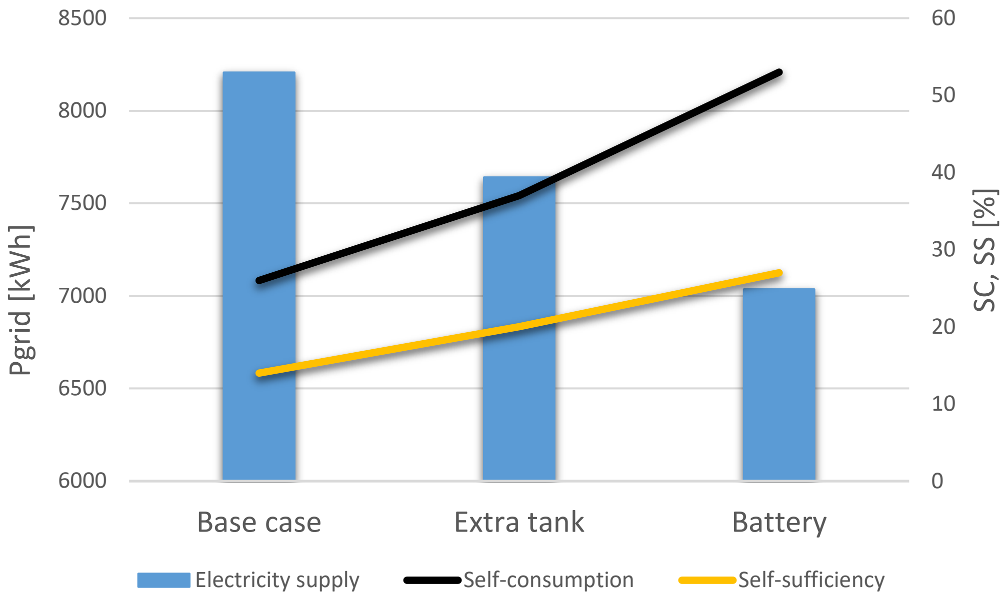


Figure 37. Key indicators (electricity supply from the grid, self-consumption and self-sufficiency) of the two additional storage types (variants 1 with a battery and variant 2 with additional PH-tank, both also including an increased DHW storage temperature) compared to the base case.

Table 15 - Breakdown of the final electricity cost (in SEK) based on price scenario 1, including annual fee.

	Income	Cost	Net cost
Base case	1499	13012	11512
Variant 1	854	11496	10642
Variant 2	1252	12276	11025

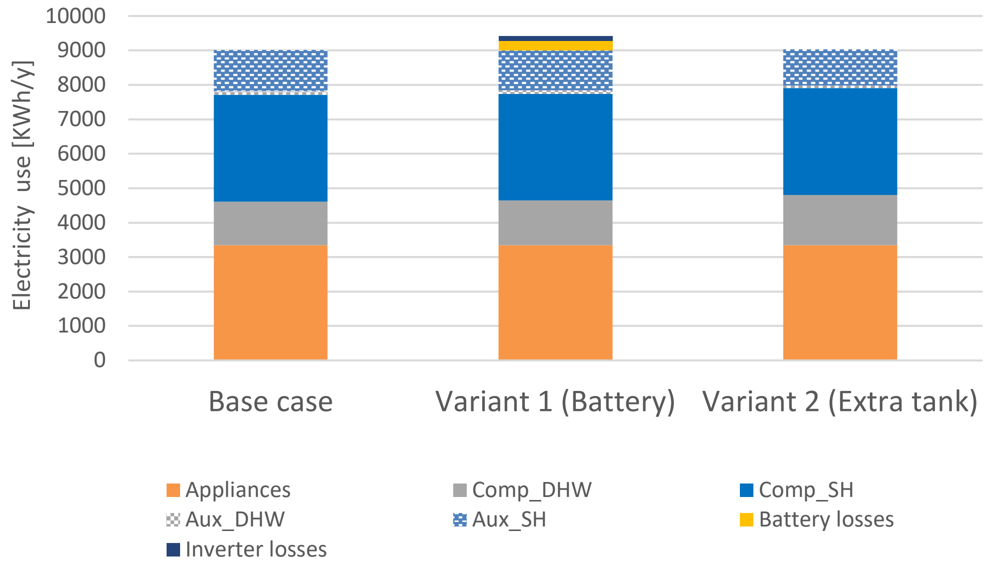


Figure 38. Breakdown of the electricity use of the heat pump components (compressor and aux heater for SH and DWH) for variant 1 and 2 as well as the related losses of the battery system (variant 1).

shows the economic results and specifically the total annual cost (net cost) of the addition of the two examined storage types compared to the base case for the eight respective contract scenarios for energy and power prices, which are listed in Table 9. For the case of the battery storage, it is noticed small increase in the total electricity use which is caused by the combined inverter and battery charge and discharge cycle losses.

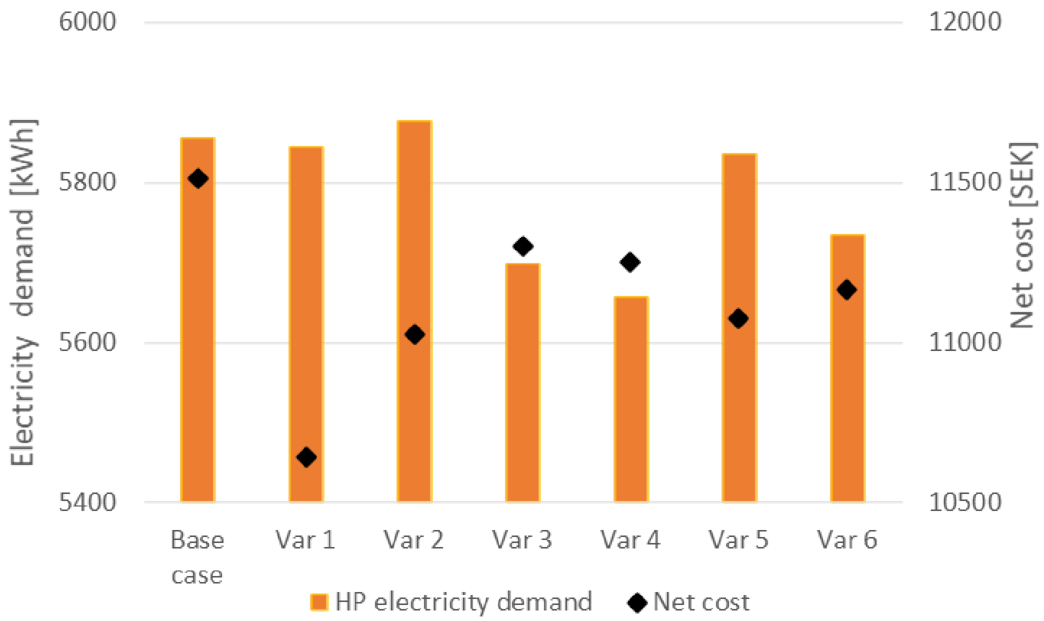


Figure 39. Annual net cost of electricity (based on price scenario 1) and total electricity use of the HP for all six variants compared to the base case

Figure 23 shows the economic results and specifically the breakdown of the annual net cost of the addition of the two examined storage types compared to the base case for the eight respective contract scenarios for energy and power prices, which are listed in Table 9.

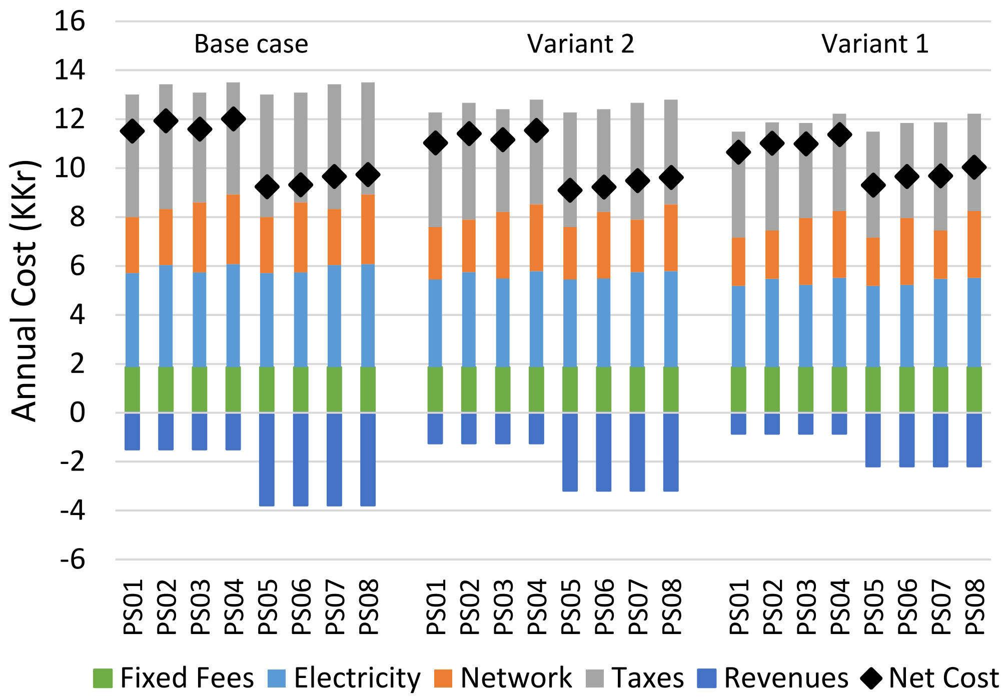


Figure 40. Breakdown of annual operational electricity cost components and revenue (sold electricity) and the associated fees for the eight price and power scenarios summarized in Table 9. Base case is compared with the two different storage alternatives and an activated PVxs algorithm. The total annual electricity cost (net cost) for each case is shown with diamonds.

It can be noticed from Figure 40 that scenario 4 (monthly prices and capacity cost) results in the highest net annual cost and this trend is similar for the two examined energy storage types. The battery storage (variant 1) has the highest impact on net cost savings for price scenario S1, including the combination of hourly energy prices, a network fee based on volumetric energy usage and no tax reduction. The result is a marginal decrease among the 4 optional scenarios with or without tax reduction.

Life Cycle Cost

In order to provide a holistic point of view beyond the energy use and economic evaluation, the economic sustainability of the two storage types is examined and determined by the life cycle cost (LCC).
The examined period is considered 15 years which is the average service life of the specific heat pump system. In the base case is included the PV system so no capital cost is considered just the cost to purchase each storage type. The thermal tank is considered that has no degradation during the life time which is also approximately 15 years and the annual degradation of the PV system and the battery system included in the calculations. It is found that two battery storage units are required for the lifetime of the HP system based on the annual degradation (service life up to 8 years). More details of equipment costs and assumptions for the determination of the LCC are listed on Table 16.

Table 16 Life cycle cost inventory

Equipment	Capacity/ volume	Cost			Life span
		Purchase	Installation	Maintenance	
		Euros/kWh or Euros/L	Euros/kWh	Euros/year	years
EAHP		Base case	Base case	Base case	15
Energy storage					
Battery lithium ion/LIFEP04	7.2 kWh	600€/kWh	50% of investment cost, 300/kWh	1% of investment cost	2 units for 15 years
Water tank	273 L	6/L	1 000€	40€	1 unit 15 years
Replacement					
Battery lithium ion/LIFEP04	7.2 kWh	350€/kWh	175€/kWh	1% of investment cost	
SPV (7 years)[1]					

[1] Present value factor for replacement is considered 0.58

In Figure 41 the results of the life-cycle cost calculations are shown. The results for life cycle cost calculations for the two examined energy storage alternatives show that during the lifetime of 15 years the additional investment cost cannot be compensated for, despite the associated electricity cost savings and revenue for any of the cases. Neither of the additional storage options are cost effective for these boundary conditions (investment, tariffs, electricity price, climate, loads). Especially the battery option results in great net cost savings, but the option has also the highest capital cost. However, the thermal storage is not far off the base case life cycle cost. It should be noted that no capital subsidy is considered for the battery storage purchase.

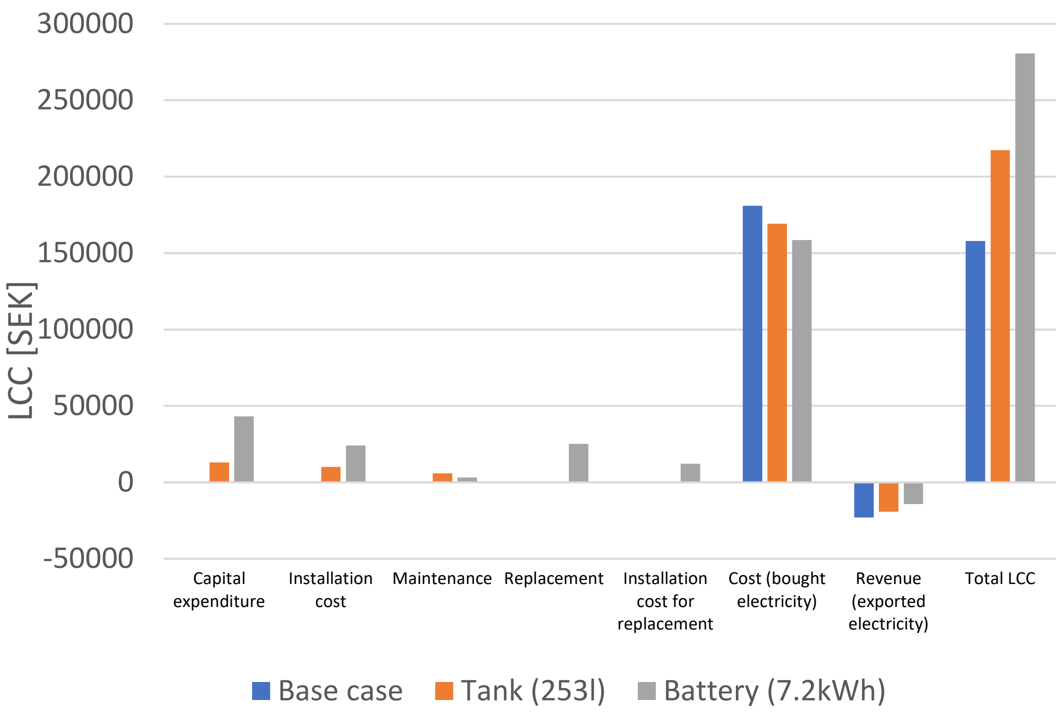


Figure 41. Life cycle cost of the addition of the two energy storages (tank and battery) compared to the base case excluding the capital cost of the photovoltaic system and the heat pump.

8.3.d Comfort cooling, IDA ICE simulations

System Design

In the simulations, passive cooling with a direct and an indirect system were modelled. In the direct system, brine from the borehole heat exchanger is directly connected to the fan coil and thus cools down indoor air directly. For the indirect system, there is an indirect water loop distributes cooling between the brine and indoor air. The major difference between the two systems is that water vapour condensation (on pipes etc.) is allowed in the direct system while this is not allowed in the indirect system. Thereby, for the direct system one need to handle the condensed moisture in order not to case problems. On the other hand, with a direct system one will have a larger cooling power due to larger temperature differences, compared to an indirect system. The minimum set temperature for air leaving from the fan coil and sent back to the room is 15 °C for the direct system, and it is 18 °C for the indirect system. The actual air temperature leaving the fan coil (i.e., simulated) is 15-25°C depending on the cooling demand. In the IDA model, room cooling set point is 25 °C in base case (this means that fan coil starts to cool down the house when the temperature exceeds 25 °C). In Table 17 the simulated cases are summarized.

Case number	Type of cooling	Cooling set point for indoor temperature (°C)	Ventilation flow rate (l/s)
1	Direct	25	60
2	Indirect	25	60
3	Indirect	25	Jul 16 – Aug 31: 100 l/s, Rest of the year: 60 l/s

Case number	Type of cooling	Cooling set point for indoor temperature (°C)	Ventilation flow rate (l/s)
4	Indirect	Jul 16 – Aug 31: 21°C Rest of the year: 25°C	60
5	Indirect	Jul 16 – Aug 31: 21°C Rest of the year: 25°C	Jul 16 – Aug 31: 100 l/s, Rest of the year: 60 l/s

Table 17 – Summary of IDA ICE case studies for both the low energy and normal Swedish single-family house.

One sensitivity analysis made was to decrease the comfort cooling set point, from the ordinary 25°C to start cooling at an indoor temperature of 21° during the summer period. Another variation simulated was to increase the ventilation flow rate during the summer period. Finally, the combination of increased ventilation flow rate and a cooling set point of 21°C was simulated. The windows are assumed to be closed during the entre simulation period for both the normal house and the low energy house. The results are evaluated in terms of cooling capacity, energy use and number of hours the house being overheated.

Simulation results

The simulation results for the normal and low energy house from different case studies are presented in below.

Figure 42 shows the cooling energy for each case simulated. The yearly cooling energy used by the indirect system is approximately 2/3 of the cooling energy with direct cooling. The graph also shows that an increased ventilation decreases the use of cooling from the CCB.

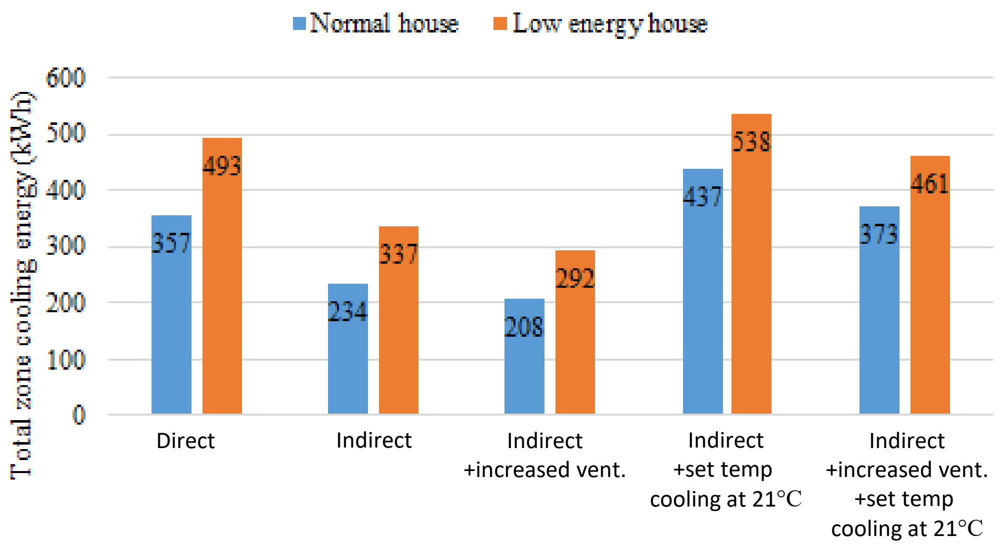
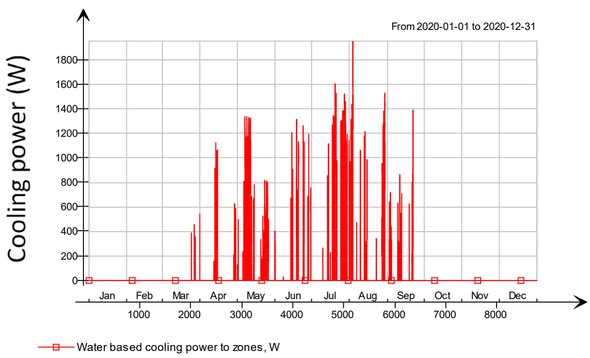
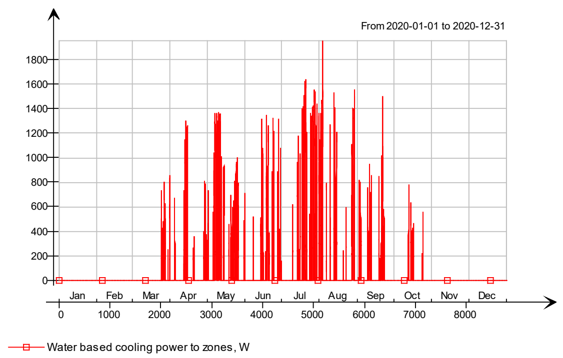


Figure 42. Zone cooling energy (sensible and latent) provided by the fan coil for a year.

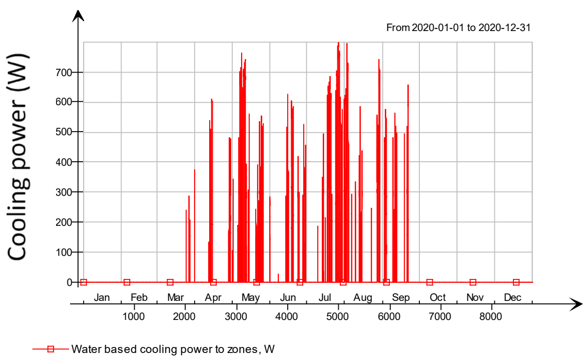
Figure 43 shows the required cooling power for direct cooling compared to the indirect cooling, for both the normal house and the low energy house. As can be seen, based on the simulations, the maximal cooling power provided by the direct system is about 1850W, which is about 1000W higher than that for the indirect system, which has a maximum cooling power around 820W. The reason for the lower cooling power for the indirect system is due to the smaller temperature difference for the indirect system compared to the direct system. With an indirect system there is an additional water loop distributing the cold from the brine to the fan coil, for the direct system the brine is heat exchanged directly with the indoor air in the fan coil.



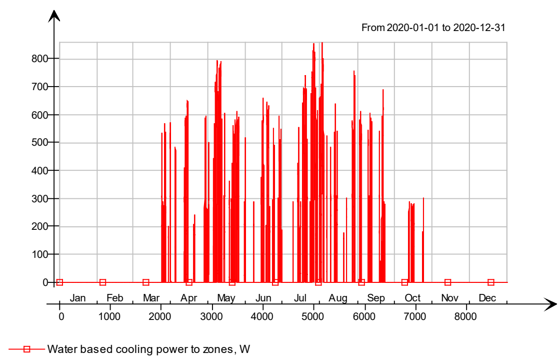
(a): direct cooling, normal house



(b): direct cooling, low energy house



(c): indirect cooling, normal house



(d): indirect cooling, low energy house

Figure 43. Cooling power (both sensible and latent) provided by the fan coil with direct and indirect system for the normal and low energy house.

It can be seen from Figure 44 and Figure 45 that the number of overheated hours is reduced greatly by both the direct- and the indirect systems. The direct system has a greater potential to reduce the number of overheated hours than the indirect system, but the difference is not very big. For the indirect system, increased ventilation flow rate and to start cooling earlier reduces the number of overheated hours among the studied indirect systems with different set-ups.

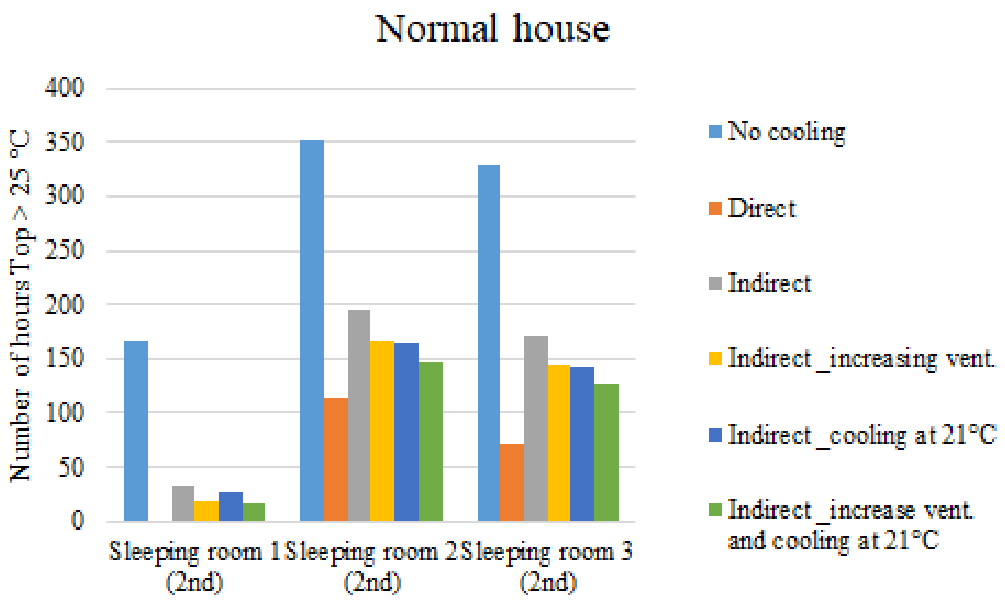


Figure 44. Comparisons of number of hours that the indoor temperature (Top) is above 25 °C from different case studies for the normal house

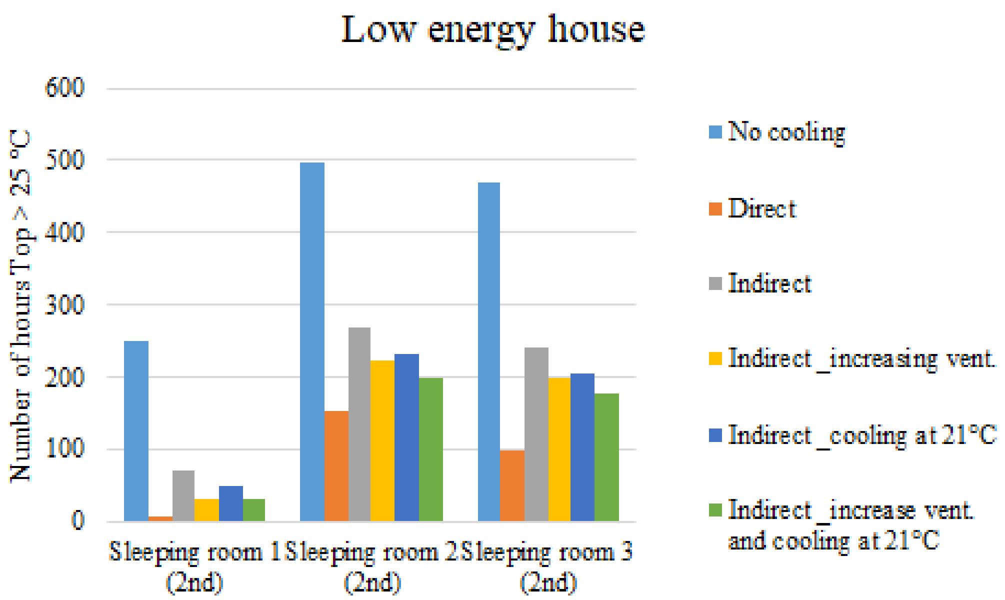


Figure 45. Comparisons of number of hours that the indoor temperature (Top) is above 25°C from different case studies for the low energy house

8.3.e Development and testing of CCB prototype

Within the project, a prototype was developed on the CCB concept based on a ground source heat pump. In addition, new control algorithms for an exhaust air heat pump were developed and implemented (in slightly modified form) in a heat pump, of which some are to be included directly in the products sold on the market.

Prototype CCB based on GSHP

A prototype of a CCB based on a ground source heat pump was developed within the project and evaluated in the lab. The different selections for the design of the prototype were based on the outcomes from the simulations performed within the project, discussions within the project group and the present product line of the manufacturer.

The prototype developed within the project is based on the concept for a GSHP including space heating (SH), passive cooling via the borehole and production of DHW. For energy storage the prototype is equipped with both a 300l buffer tank on the space heating side as well as a standard size DHW tank of 180l. A shunt between the SH buffer tank and the radiators makes it possible to have a higher temperature in the tank than the supply temperature to the radiators/floor heating.

Two “smart” control functions were developed for the prototype and evaluated. The control functions are:

- Price: The heat production is planned over the day to minimize the electricity cost, based on hourly electricity prices.
- Sun: The heat production is planned over the day to maximize self-consumption of internally produced electricity from PV panels.

Test method laboratory testing of a CCB prototype based on a GSHP

Test methods for evaluation of heat pumps performance in existing standards today are based on steady state performance. Normally the control system of the heat pumps is bypassed to be able to achieve steady state conditions, good repeatability and avoid interaction with the control system of the test rig. Existing alternatives to laboratory tests at steady state are field measurements or a “hardware in the loop” test method.

In this project a new laboratory test method was developed for testing of the functionality (control) and performance of the prototype. The method developed is a trade-off between complexity and the possibility to get reliable results when testing function and performance of the prototype with focus on the smart control functions. The test method simulates the conditions for a CCB installed in a single-family dwelling in Stockholm, Sweden for one up to six days. The method includes an emulator which updates data for the outdoor temperature, the forecast for produced PV power and electricity prices once per hour.

The prototype was tested in RISE laboratory in Borås, Sweden, during the summer and autumn 2021. During the test the performance of the prototype was evaluated based on a compensation method developed within the project. This means that the control system of the heat pump adjusts its heating capacity to match a cooling load of the test rig (predefined for different test points). During the test, the SH and DHW heating performance are tested and evaluated simultaneously, and the prototype is free to alternate between SH and production of DHW as it is in a real installation.

Not testing the performance at steady state operation makes the test more realistic and the results and learnings are closer to the outcome from measurements in a real installation in the field, but with the advantage of being in a laboratory and thereby to be able to control the outdoor temperature profile independently of the weather conditions outside. In this way one can test the performance for all season in a shorter time. The method is also less complex compared to a "hardware in the loop" method.

Figure 46 shows an overview of the prototype and the test method used to evaluate the prototype in lab.

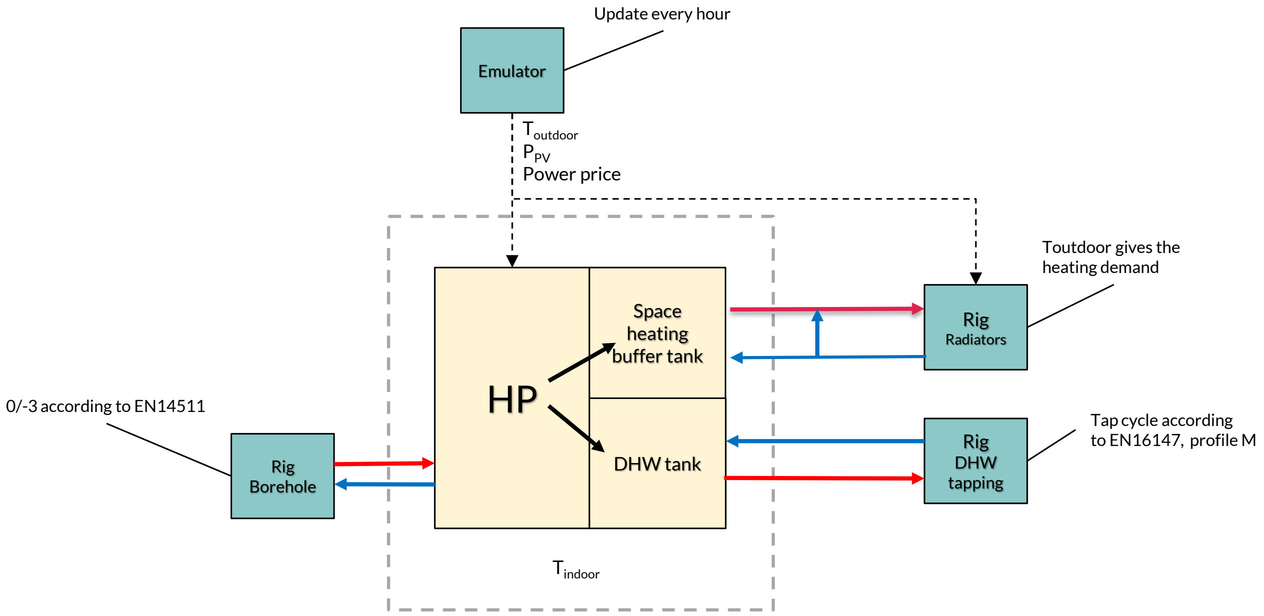


Figure 46. Overview of prototype and the test method.

Results laboratory testing CCB prototype GSHP
Two different tests were performed in order to evaluate the prototype; test of functions and a 6-days system testing.

Test of function, test method
The functionality of the prototype and the smart control algorithms were evaluated using a 24-hour test simulating a fictive Swedish day in April, giving a day with both space heating demand and production of solar PV electricity. The fictive day has relatively large variations in outdoor temperature between night and day as well as production of PV electricity during the day, see Figure 47 below.

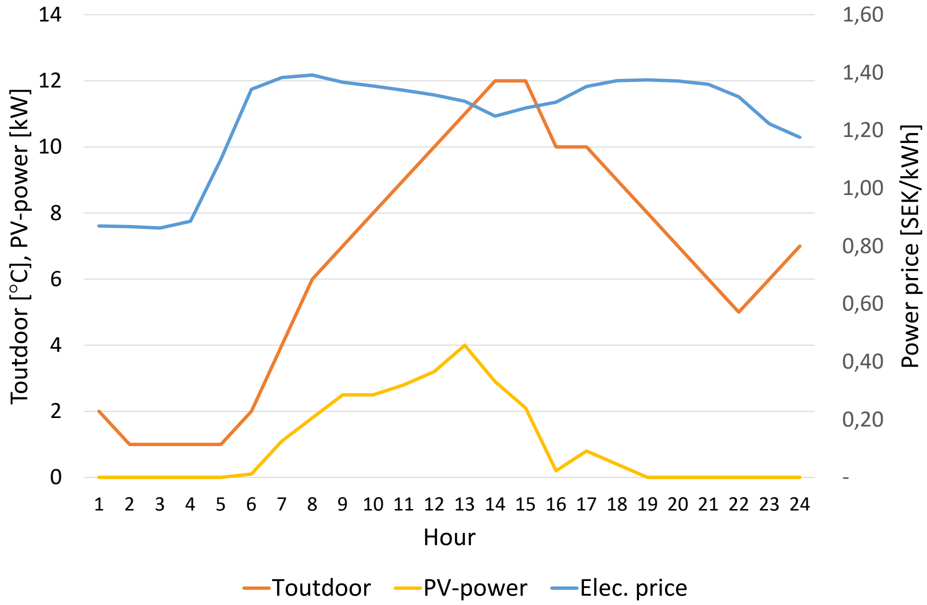


Figure 47. Hourly variations in outdoor temperature, production of PV power and electricity price used for test of functions of the GSHP CCB prototype.

The following tests were carried out in order to test the functions of the prototype and the integrated smart control.

- Base case: 24 h test of space heating (SH) and DHW production without any smart control functions activated.
- Price: 24 h test of SH and DHW production with price function activated.
- Sun: 24 h test of SH and DHW production with sun function activated.
- Price+Sun: 24 h test of SH and DHW production with both price and sun function activated.

Test of function, results

The distribution of the electricity used per hour by the CCB prototype with the different control functions activated is shown Figure 48 below. In the graphs one can see how the distribution of the electricity use is changed over the day based on the activation of the different control functions.

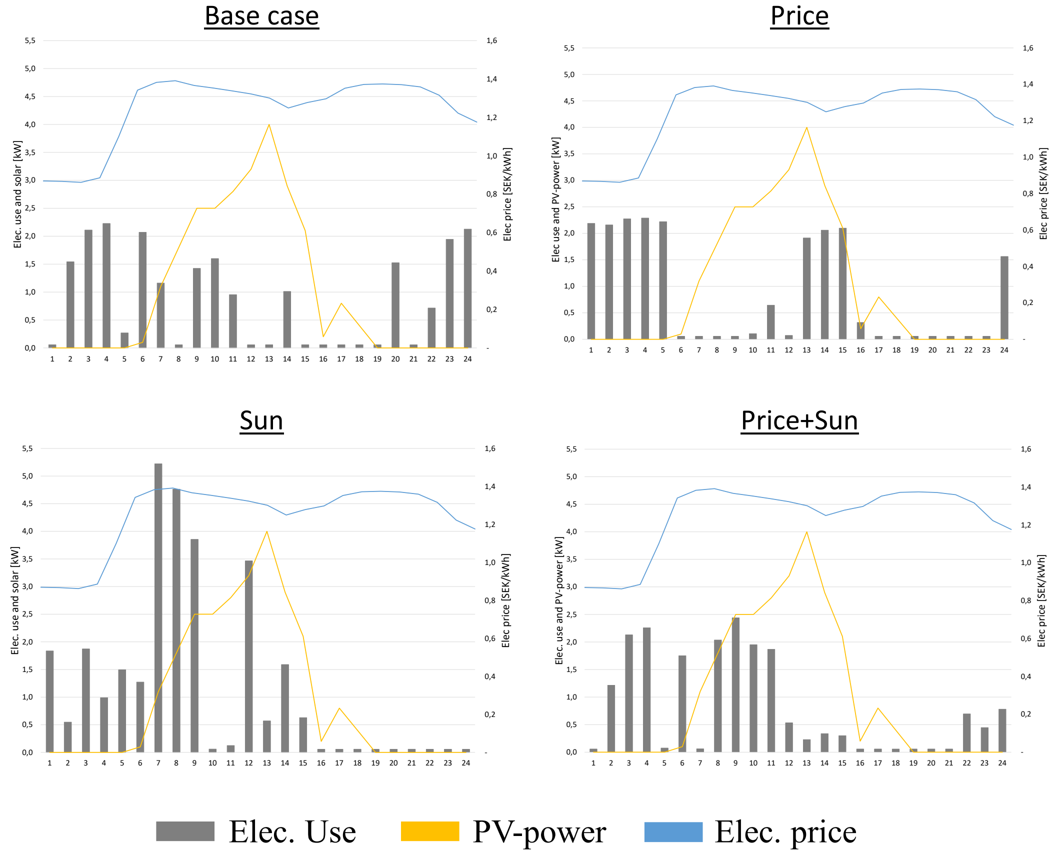


Figure 48. Comparison, distribution of total electricity used by the prototype during the 24h test of function with different functions for smart control activated.

Figure 48 shows the total electricity used by the prototype, including for both space heating, DHW production and other electricity consumers, such as internal pumps. One can see a clear change in the pattern of the electricity use over the day when the different control functions is activated, compared to the base case. With the “Price” algorithm activated the prototype follows the electricity price curve well and produces heat when the electricity price is low. The combined algorithms “Price+Sun” follows the price curve as well but also produces heat during the morning hours when there is production of solar PV power. In the results from the test of the “Sun” algorithm one can see that at around 07:00 the backup heater starts. This is due to low temperatures in the DHW tank, which triggers the backup heater to start. This indicates the need for further fine-tune of the settings of the prototype to avoid unnecessary usage of the backup heater.

Figure 49 shows the distribution of total electricity power (usage) and heating power to the space heating buffer tank for the same test as presented in Figure 48. During the test, there were no possibilities to measure the heating power of the DHW-tank. Thereby, in the graph time periods of electricity consumption (usage) without any corresponding heating production indicates production of DHW.

Base case Price

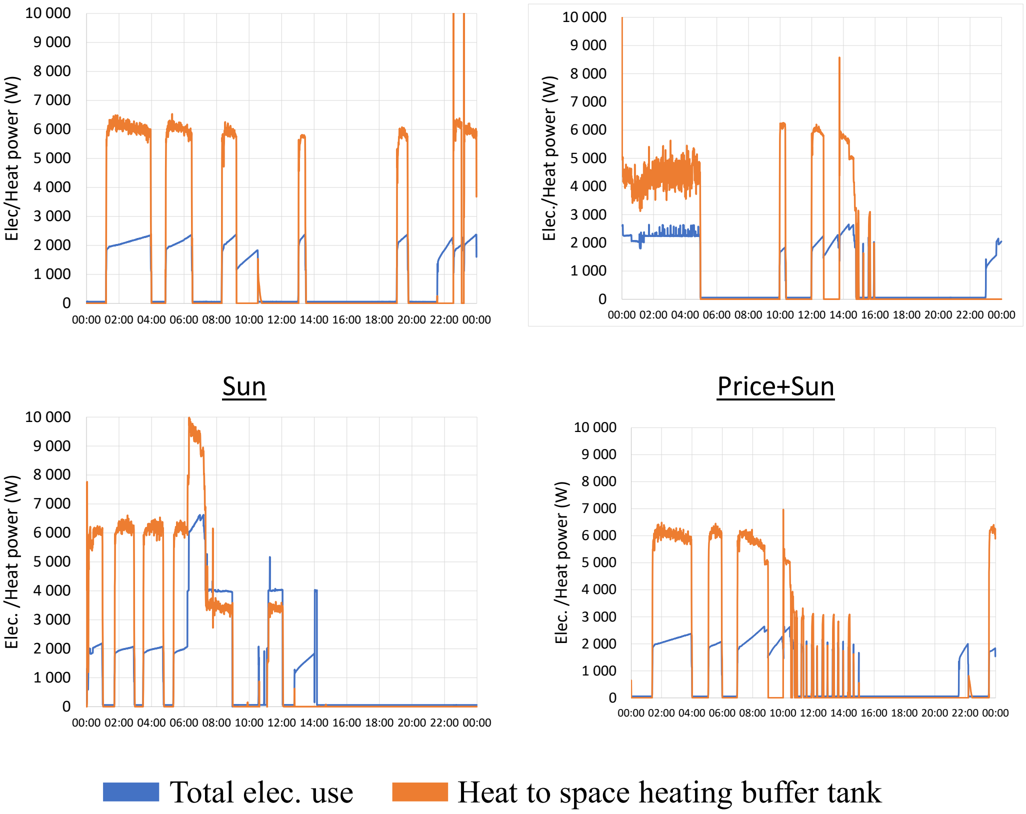


Figure 49. Comparison, distribution of total electricity used and heat to space heating buffer tank by the prototype during the 24h test of function with different functions for smart control activated.

6-day test, test method

In order to test the performance of the prototype and its smart control functions for a longer period and evaluate the prototype in conditions representing all seasons, a 6-day system testing was developed following the general method described above. The test conditions were chosen to represent the conditions in Stockholm, Sweden during a full year. The test includes 2 winter days, 2 summer days and 2 spring/autumn days, see Figure 50 below.

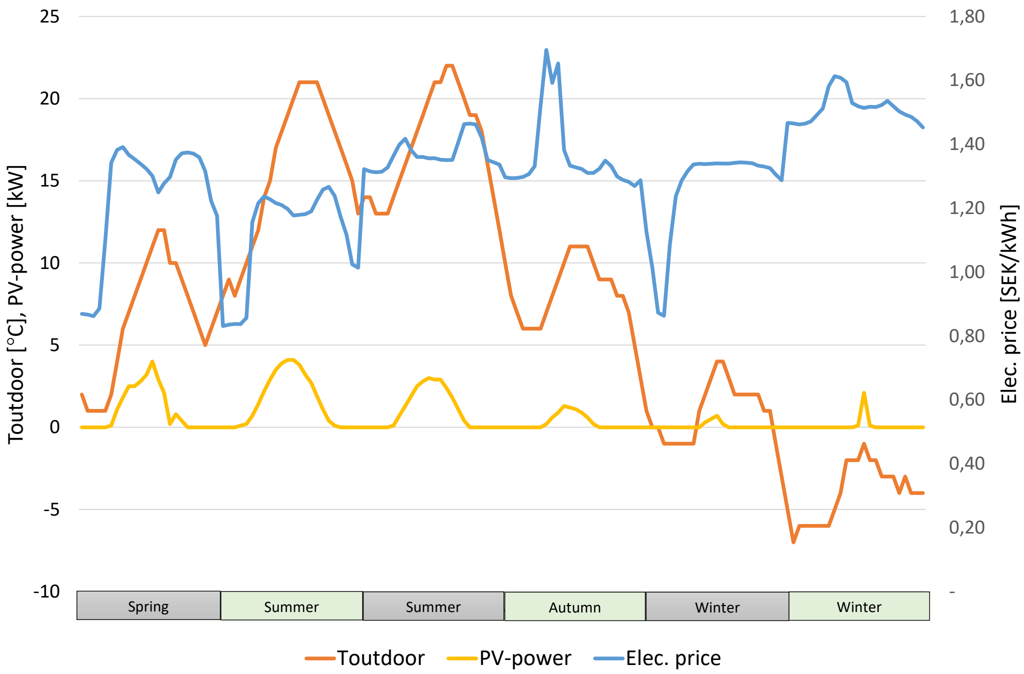


Figure 50. Hourly variations in outdoor temperature, production of PV-power and electricity price during the 6-day test including 2 summer days, 2 winter days and 2 autumn/spring days for test of the CCB prototype.

One drawback with testing a full year in 6 days is the short time periods of each season and compared to a real installation it gives quick and sometimes unrealistic changes from one season to another. Depending on how the CCB is working and planning the heat production there is a risk that the test method does not capture the functionality and performance of the test object in a correct way.

6-day test, result

The prototype was evaluated using the 6-day system test described in chapter 0. The results from the system tests have given valuable input to further adjustments needed for the prototype's control. The challenge when developing a smart control system based on response on external signals, is to make it operate correctly with the built-in control for safety functions (to avoid that a component breaks or are unnecessarily worn). Therefore, it is important that the smart control is integrated with the other control system of the heat pump. An external control system, which only allows the heat pump to start or stop or which only controls the heat pump through "deceiving" the input signal from the outdoor temperature sensor, could result in harmful or very inefficient operation for the heat pump (e.g. the compressor is not allowed to start and the back-up heater covers the heating demand). The results also show the complexity of testing a prototype using a new test method lasting for six days in laboratory with a data collection every 30s. In total three 6-day tests have been carried out, all with the "Price+Sun" algorithm activated.

Input from the tests to the further development of the prototype's control has mainly been related to how the prototype should alternate between space heating (SH) and production of DHW in a good way. During the first two test runs, the prototype had a tendence to allow low DHW temperatures without prioritizing production of DHW. Instead, this finally resulted in a start of the backup heater. The problem with too low DHW temperatures was also accelerated by an earlier version of the test method, where each tapping stops first when the correct amount of energy is tapped. With low DHW temperatures this can lead to a continuous tapping and thereby that the DHW tank is completely emptied of hot water.

After adjustments of the CCB control, to make sure the prototype starts to produce DHW in time, and adjustments of the test method, to reduce the risk that the test method triggers a continuous tapping in case of low DHW temperatures, a third 6-day test was started. This time the testing failed the second day due to a “Operating pressure alarm” caused by high pressure in the compressor. This alarm prevents all production of DHW and stops the compressor until it is manually offset. The reason for the alarm is likely a combination of condition. The prototype was running close to its outer limits of the operating range, but the alarm is not directly related to the test of the smart control functions. Unfortunately, the alarm was not noted until after the test was completed and in addition the data logging failed during the last day of the test.

Figure 51 shows the distribution of the total electricity use and production of heat to the space heating tank. As can be seen in the figure the compressor is not running after the first day and no DHW is produced.

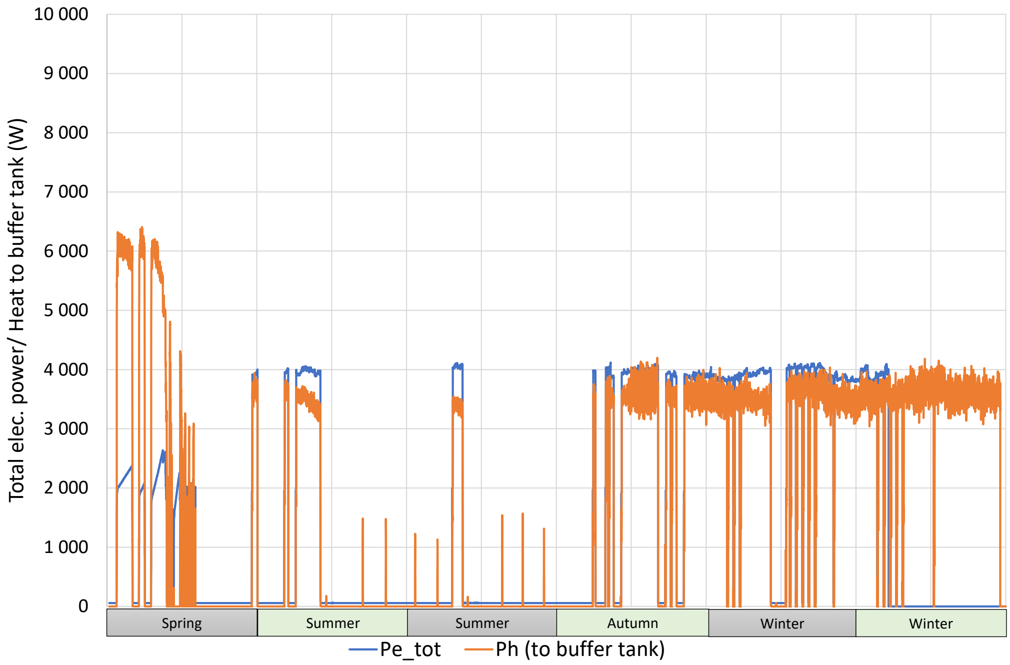


Figure 51. Distribution of total electricity used and heat to space heating buffer tank by the prototype during the 6-day test with the “Price+Sun” control activated.

Prototype of a CCB based on an EAHP

Within the project new control algorithms for an exhaust air heat pump were developed and implemented (in slightly modified form) in a heat pump, of which some are to be included directly in the products sold on the market shortly. The plan and hope were to be able to test an EAHP in the lab together with a Ferroamp EnergyHub used as inverter which would communicate the PV production to the heat pump controller that then adapts its control to optimize self-consumption. However, the communication between these two units has not worked and this was not solved by the end of the project, so no testing of the full prototype including the implemented algorithms could be performed. The system itself was tested in the lab (but without the advanced control features) using a six-day test sequence based on a “hardware in the loop” and the test data were used to calibrate the model of the PV and EAHP system simulated in the studies.

8.4 Lessons learnt

A Comfort and Climate Box (CCB) is defined as a heat pump in combination with energy storage and integrated control. In this Swedish project it has also included control in combination with PV-panels and, for some of the CCB concepts comfort cooling. A CCB can have different focus areas, but this project has in first-hand focused on the archetype "Flexibility".

The energy storage makes it possible to plan the heat production in time and shift heating, and thereby electric loads, to hours with e.g., low electricity price or high production of solar PV-power. A CCB can be used to shift loads over the day, but it is not a solution for long time storage from one season to another. The project has shown that it is possible to efficiently control the electricity consumption over time using a CCB, including a heat pump, energy storage and integrated control. This has been proven first with simulations and thereafter by laboratory testing of a prototype developed within the project.

The result from the simulations showed that the economical savings of the control functions evaluated are modest with the electricity prices for 2019 in Sweden. The main reason is that the variation in electricity price over the day is small for the year evaluated. However, higher fluctuations in electricity price and an increasing use of power tariffs are to be expected in the future, in Sweden as well as in other parts of Europe.

A CCB includes extra energy storage in addition to the ordinary DHW-tank normally used in today heat pumps. But additional storage results in additional heat losses and the heat losses will decrease the potential energy efficiency. Storage at higher temperature or larger storage volumes lead to larger losses and there is a clear trade-off between the thermal energy storage and increased losses, where the losses consume some of the benefits with the storage. It is therefore recommended to store the heat at as low temperature as possible, e.g. in a DHW preheating tank with a lower temperature than the ordinary DHW-tank, a buffer tank for space heating or to use the building's thermal inertia to store energy. Moreover, there must be a clear gain to make (e.g. relatively high electricity price volatility, high peal power tariffs or high difference between purchase and sale price of on-site produced electricity), since the "smart control" could result in somewhat lower overall efficiency and interference with safety control of the heat pump.

Since the potential savings in running cost are relatively low (at least for the electricity prices in the level of the ones for 2019 in Sweden), there is a need to keep the investment costs low to get an acceptable life cycle cost. Therefore, it is beneficial to use already existing storage alternatives as long as possible, e.g. the DHW tank or the building's thermal inertia. Cost for develop new control algorithms on the other hand is a one-time cost for a heat pump manufacturer, when done there are low costs to implement it in each new heat pump. Therefore, the additional investment cost for control can be kept modest.

The results and the outcomes from this project have resulted in that heat pumps manufacturers can be well prepared for the future when the price structure for electricity and power will change – for the benefit for the end-users as well as for the grid operators and utilities. This applies especially for the heat pump manufacturers who have been actively involved in and contributed to this project, but also to other manufacturers, and grid operators and utilities in Sweden as well as abroad, who will be able to take part of the results. Moreover, standardization organisations could benefit from the results from the developed test method for system testing of a CCB.

9 (UK) Smart Community Demonstration Project in Greater Manchester

Country	UK
Contact	http://media.ontheplatform.org.uk/sites/default/files/Daikin%20Hitachi%20Mizuho%20GM%20Smart%20Communities.pdf
Status	Completed (2014-2016)
Main CCB implementation strategies	Affordability Flexibility

9.1 Goal of the Project

Three areas of Greater Manchester (Manchester, Bury and Wigan), the replacement of gas boilers was enacted with heat pumps in 550 homes. The demonstration was conducted based on the following three themes:

- Theme 1: Demonstration of Heat Pump Implementation
- Theme 2: Demonstration of an aggregation system
- Theme 3: Development of a business model

9.2 Project Setup

Most of the air-source heat pumps were Daikin LT units (a mixture of split and monobloc units) and stratified hot water storage to provide domestic hot water and space heating to larger radiators. The following images illustrate the housing styles and equipment.

Figure 52 – Building styles and equipment types.

9.3 Results

Typical results are illustrated below where the external power requirement is seen to increase for a decreasing external temperature.

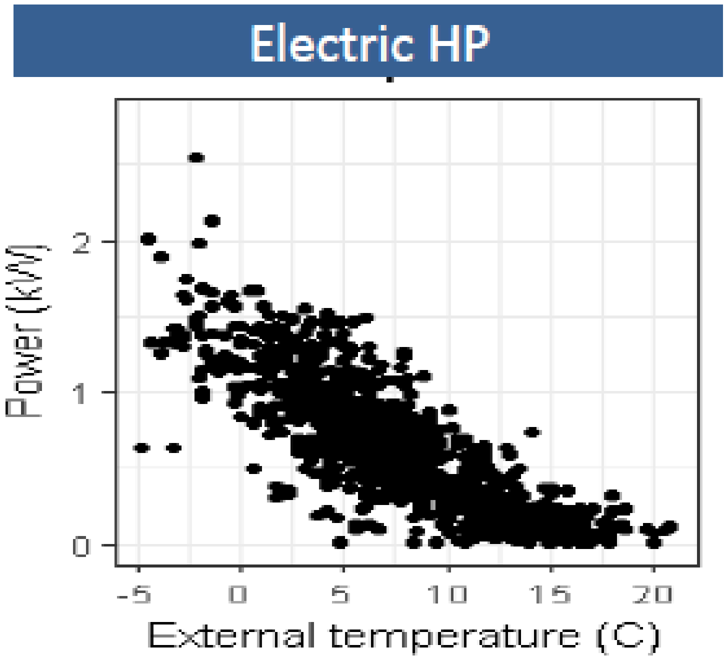


Figure 53 – Electric air-source HP power consumption.

Electrical demand increases have driven the assessment of demand response approaches. Demand Response is achieved through "turning off" at individual household level for 300 minutes to 2 hours. And example is illustrated below:

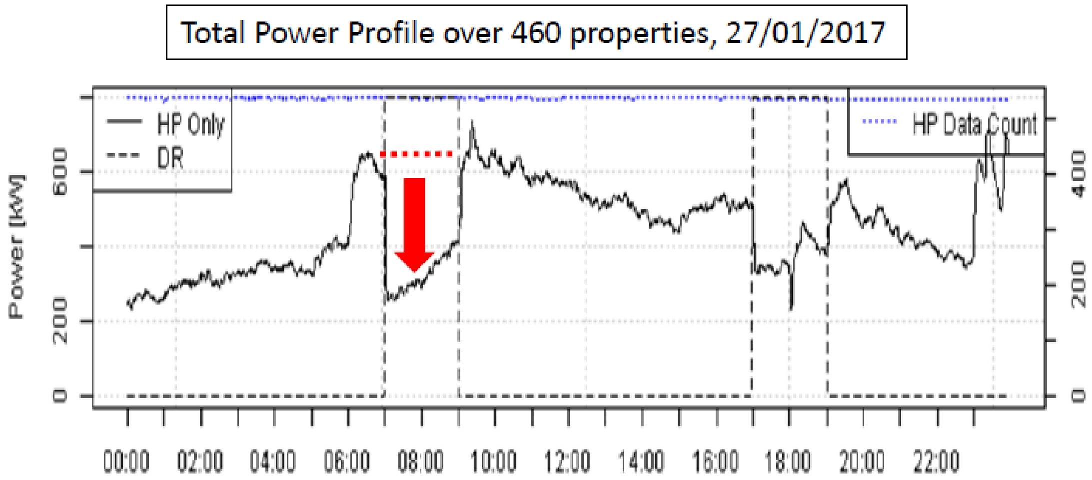


Figure 54 – Demand reduction strategy reduces electricity consumption by 50%.

9.4 CCB Implementation Strategy

From this extensive field study, key findings included education of the residents on heat pumps and demand response. Residents were able to achieve positive electricity utility savings when they availed of educational supports. Regarding demand response (without thermal energy storage), the following figure illustrates those short-term aggregated responses to "off-cycles" when called for were fully responded too while longer term aggregation of "off-cycle" calls had lesser success. The business model analysis revealed that at least 60,000 heat pumps would need to participate in a demand response programme with the then UK electricity market structure for a successful aggregation based ESCO business to be realised. Therefore, *Affordability and Flexibility* were assessed.

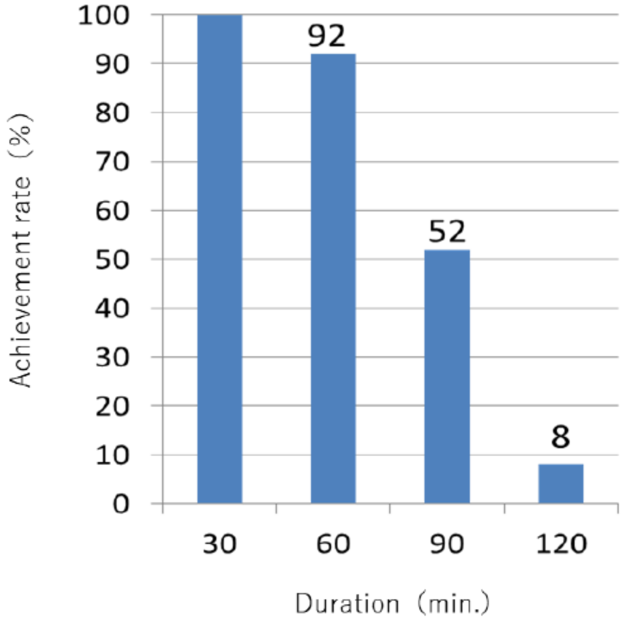
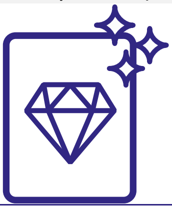


Figure 55 – Voluntary participation in demand response calls of different durations.

10 (UK) Heat Pump Data from the Renewable Heat Premium Payment (RHPP) Scheme

Country	UK
Contact	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/606818/DECC_RHPP_161214_Final_Report_v1-13.pdf
Status	Completed (2014-2017)
Main CCB implementation strategies	 Energy Efficiency

10.1 Project Goal

The opportunity to conduct a large-scale field trial of heat pumps in the UK arose from the Renewable Heat Premium Payment (RHPP) policy that provided subsidies for private householders, Registered Social Landlords, and communities to install renewable heat systems in residential properties.

10.2 Project Setup

The key objective of a field trial is to gain understanding of HP system operation and performance in-situ. The objective not only concerns the overall typical estimated performance of the sample, but also to identify the spectrum of issues, technical and socio-technical, some of which will be wholly unexpected, that are only likely to emerge when a large number of HP systems are installed and monitored in diverse, real-world settings. The key metrics used for the study were Seasonal Performance Factors (SPFs).

10.3 Results

Seasonal Performance Factor Heating (including supply air fan, leading SPFH2) is noted below based on electricity consumption, heat meters and temperature sensors.

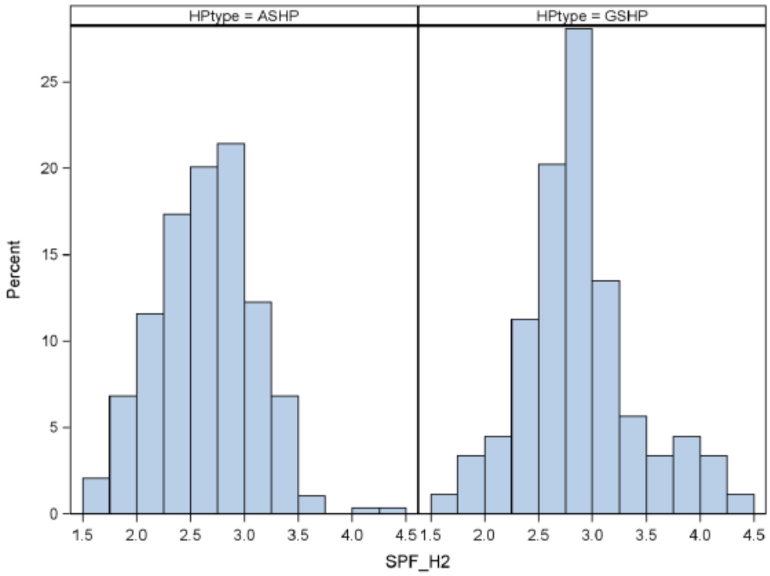


Figure 56 – RHPP sampled HP performance.

Relatively high levels of satisfaction were obtained.

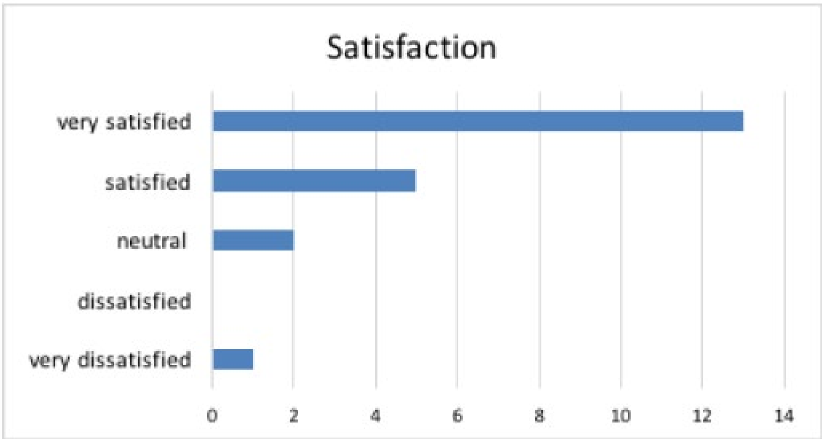


Figure 57 – Levels of satisfaction.

A wide distribution of SPFs was observed, thought to be partly due to metering error and partly to real differences in heat pump performance. The latter in turn related to differences in heat pump technology (for example, ground source and air source), and to differences between dwellings, patterns of use, and occupants' lifestyles.

10.4 CCB Implementation Strategy

The statistical analysis showed higher SPFs of ground source compared to air source heat pumps, and of air source heat pumps with underfloor heating, compared to those with radiators. In addition to the statistical analysis, detailed case studies of 21 heat pumps were undertaken. These showed additional factors at work. Among these was the effect of heat pump load factor, which appeared to have a strong effect in a sub-group of three similarly sized dwellings with identical heat pumps. A large proportion of air source heat pumps displayed high frequency cycling behavior, with periods of 10-minutely (on-to-on) cycles. This problem did not significantly affect ground source heat pumps. Winter space heating flow temperatures were generally below 50°C. Some sites showed excessive use of immersion heaters for domestic hot water heating, and there were several clear examples of poor control related to immersion heaters. The RHPP field trial did not reveal the performance of heat pumps during a period of very cold weather.

11 (UK) Freedom project

Country	UK
Contact	https://www.westernpower.co.uk/projects/freedom
Status	Completed (2016-2019)
Main CCB implementation strategies	Energy Efficiency Flexibility

11.1 Project Goal

The FREEDOM project addressed the ability of the hybrid heating system to switch between gas and electric load to provide fuel arbitrage and highly flexible demand response services. It demonstrates the consumer, network, carbon and energy system benefits of deployment of hybrid heating systems with an aggregated demand response control system and derive value from the demand flexibility.

11.2 Project Setup

75 homes with hybrid heating systems deployed with three heat pump manufacturers (MasterTherm, Samsung and Daikin), sized as small as possible (5kW, except MasterTherm units at 8kW). Almost all the installations involved fitting new gas combi boilers and air source heat pumps, with no radiator upgrades or additional insulation fitted.

11.3 Results

For all homes, a 5kW heat pump capacity was enough to deliver this heat load and having a bigger unit could compromise efficiency. The situation was different for off-gas-grid homes on much more expensive LPG, where the heat pump could offer the householder significant running cost savings and took 78% of the heat load. Here the fuel switch to gas happened for appliance capacity (rather than economic) reasons, and automated switching to the boiler when the heat pump was unable to keep the house warm was demonstrated, without any noticeable thermal comfort challenges on the householders.

Sun et al[24] noted the coefficients of performance of the air source heat pumps.

[24] Mingyang Sun, Predrag Djapic, Marko, Aunedi, Danny Pudjianto, Goran Strbac, (2019) Benefits of smart control of hybrid heat pumps: An analysis of field trial data, Applied Energy, Volume 247, 1 August 2019, Pages 525-536, https://doi.org/10.1016/j.apenergy.2019.04.068

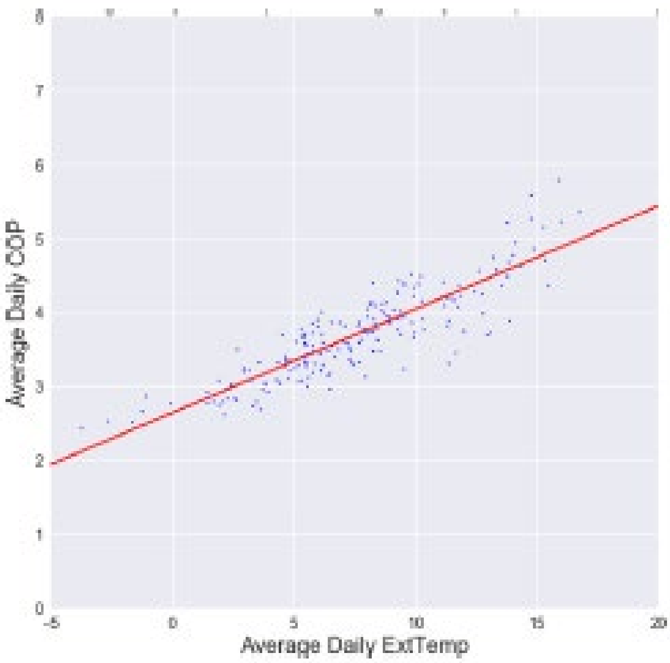


Figure 58 – Heat pump performance.

Load shifting through the initial use of natural gas and future potential use of hydrogen, biogas etc., and that improved smart hybrid heat pump control will reduce the volume of firm electrical capacity required.

12 (UK) H2020 CHESS-SETUP – Corby Demonstrator

Country	UK
Contact	https://www.chess-setup.net/corby
Status	Ongoing
Main CCB implementation strategies	Energy Efficiency Affordability

12.1 Project Goal

These are a new build homes and the Corby houses address various issues of new-build houses in the UK by building higher quality, energy efficient homes. The houses have been built using off-site build technology with well-insulated build fabric, built in Priors Hall Park in Corby, Northamptonshire. As a result, the houses will be very representative of the average new houses in the UK. However, each home has roof mounted PVT and a ground coupled heat pump, based on shallow vertical geothermal under the homes, known as an earth energy bank. The specification of the components involved is noted in Table 18.

System Components	Characteristics
Hybrid PVT Panels	Solar Angel DG-01 (59 % thermal efficiency, 16 % electric efficiency) 2,25 kWp 14,4 m2 9 panels Slope (Roof integrated)
Photovoltaic Panels	Romag 60 (16,2 % electric efficiency) 2,75 kWp 17,7 m2 11 panels Slope (Roof integrated)
Seasonal Thermal Energy Storage	Earth energy bank 21-24 underground boreholes (1,5 meters deep)
Battery	Lithium BYD B-PLUS 2.5 2,5 kWh flexible module
Water to Water Heat Pump	AquaMaster AQ22IC Heat Power 3 kW COP 4,3
Buffer Tank	170 litres 55˚C set-point temperature

Table 18 – House energy components.

12.2 Project Setup

The combination of PV, PVT, water-to-water heat pump, battery and ground heat source/seasonal thermal store is to evaluate the concept of zero-energy bill living but at the time of writing, there is limited practical data to support this aspect.

12.3 Results

Initial heat pump performance is noted below:

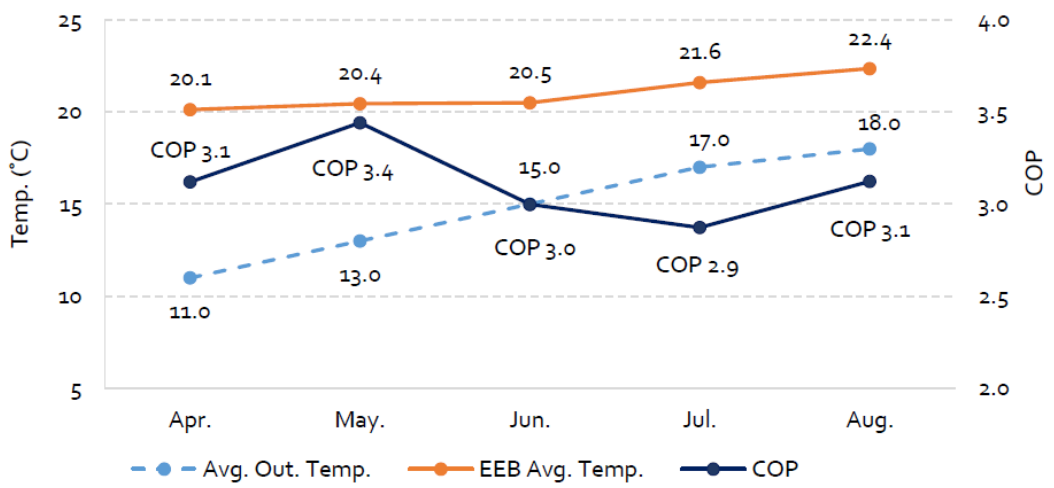


Figure 59 – H2020 Chess-Setup HP performance.

The package identified above was noted to provide 46% energy savings compared to traditional approaches and saved 1.8 tonnes of CO_2 annually.

13 (UK) Ulster University terrace street

Country	UK
Contact	Neil Hewitt Ulster University nj.hewitt@ulster.ac.uk
Status	Ongoing
Main CCB implementation strategies	Energy Efficiency Flexibility Affordability

13.1 Project Goal

The initial rational for this work was to evaluate the direct replacement of fossil fuel heating with an air-source heat pump, with no change to the original home hydronic radiator system. Thus, this required a high temperature heat pump and a Daikin Altherma HT 11 unit was selected to heat one of the terraced houses in "Terrace Street". Terrace Street consists of two family occupied direct copies of early 1900's solid wall (220 mm brick) domestic construction, of which there is approximately 8 million (1/3 of the UK housing stock) in the UK with about 100m^2 of required heated space.

13.2 Project Setup

A base year of the homes heated by natural gas was then succeeded the air source heat pump supplying hot water for space heating and domestic hot water at >70°C that was instrumented with flow meters, temperature sensors and electrical power measurement over a period of years of operation.

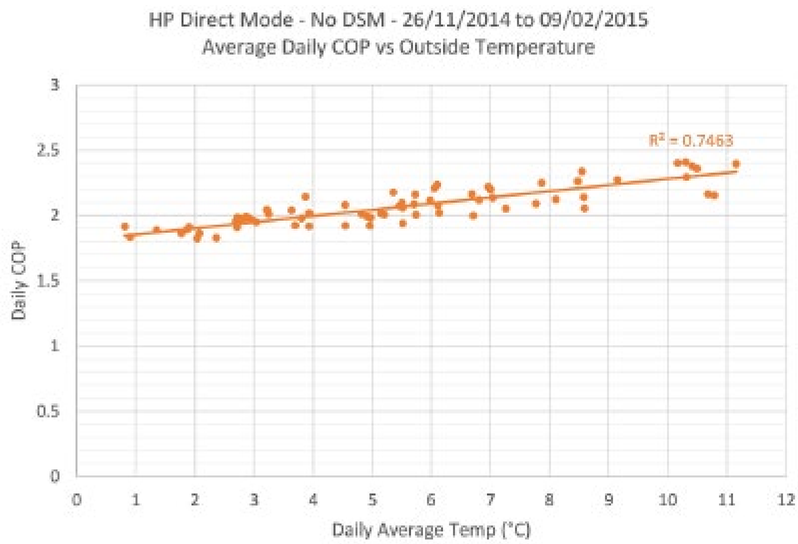


Figure 60 – Terrace street ASHP performance.

13.3 Project Results

To evaluate the role of thermal storage and demand side management, 600 litres of water were added to give approximately 4 hours of demand response. A series of strategies were assessed (Table 19).

Description	SR¹	HP²	Thermal Storage³	Gas⁴	Demand Signal		Market Price Signal		Data Source⁷	Date		Days
					LP⁵	HP⁶	LP⁵	HP⁶		From	To	
HP + Thermal Storage NI forecast grid demand	3.4.3.1	76	75/55		0.1	0.9			EirGrid (24 hours ahead forecast)	09/06/2015	11/06/2015	2
HP + Thermal Storage NI forecast grid demand	3.4.3.1	76	75/55		0.1	0.85			EirGrid (24 hours ahead forecast)	11/06/2015	01/12/2015	173
HP + Thermal Storage NI forecast grid demand (thermal store discharged at first call for heat)	3.4.3.2	76	75/55		0.1				EirGrid (24 hours ahead forecast)	01/12/2015	27/09/2016	301
HP/Gas Boiler Hybrid Mode: System Demand Signal	3.4.3.3	76		76		0.85			EirGrid (24 hours ahead forecast)	14/03/2017	13/04/2017	30
HP/Gas Boiler Hybrid Mode: Market Price Signal	3.4.3.4	76		76				0.85	EirGrid (00:00 to 23:45 all-island SMP)	13/04/2017	17/07/2017	95
HP/Gas Boiler/Thermal Store Hybrid Mode: System Demand & Market Price Signal	3.4.3.5	76	75/65	76	0.1	0.95		0.95	EirGrid (00:00 to 23:45 all-island SMP and system demand)	04/08/2017	08/10/2017	58
HP + Gas Boiler in series test	3.4.3.6	65		75						24/11/2016	31/12/2016	37

¹Section reference; ²Heat pump flow set-point (°C); ³Thermal store charge-to-set-point/discharge-to-set-point (°C); ⁴Gas boiler flow set-point (°C); ⁵Low-percentile calculation parameter; ⁶High-percentile calculation parameter; ⁷ (EirGrid Group, 2017); Grey shading – parameter not applicable

Table 19 – Strategies applied to terrace street.

The overall coefficient of performance is noted below:

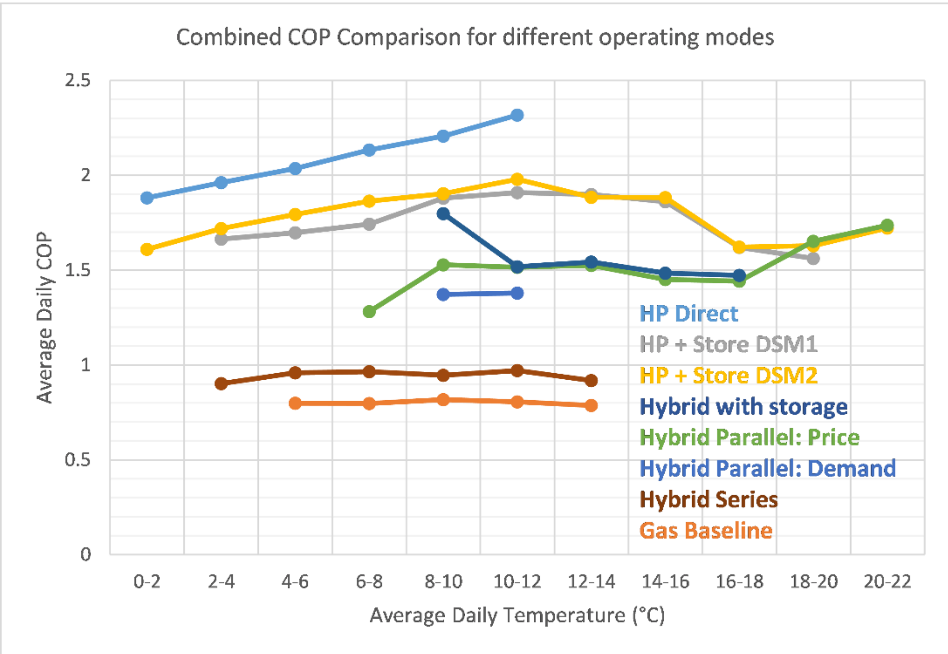


Figure 61 – Summary of HP performance and DSM strategies.

The heat pump operating on its own reveals the best COP, which increases with increasing ambient temperature. Reduced heat pump performance was found with the inclusion of thermal store and this was due to heat losses from the thermal storage. DSM2 (responding to excess wind power and avoiding peak electricity demand times) performs slightly better than DSM1 (night storage), again due to tank losses with DSM1. Hybrid strategies (operating with the gas boiler) needs further optimisation.

Costs are noted below, with the challenge of direct retrofit without adapting radiator delivery temperature through incorporation of larger sizes is well noted.

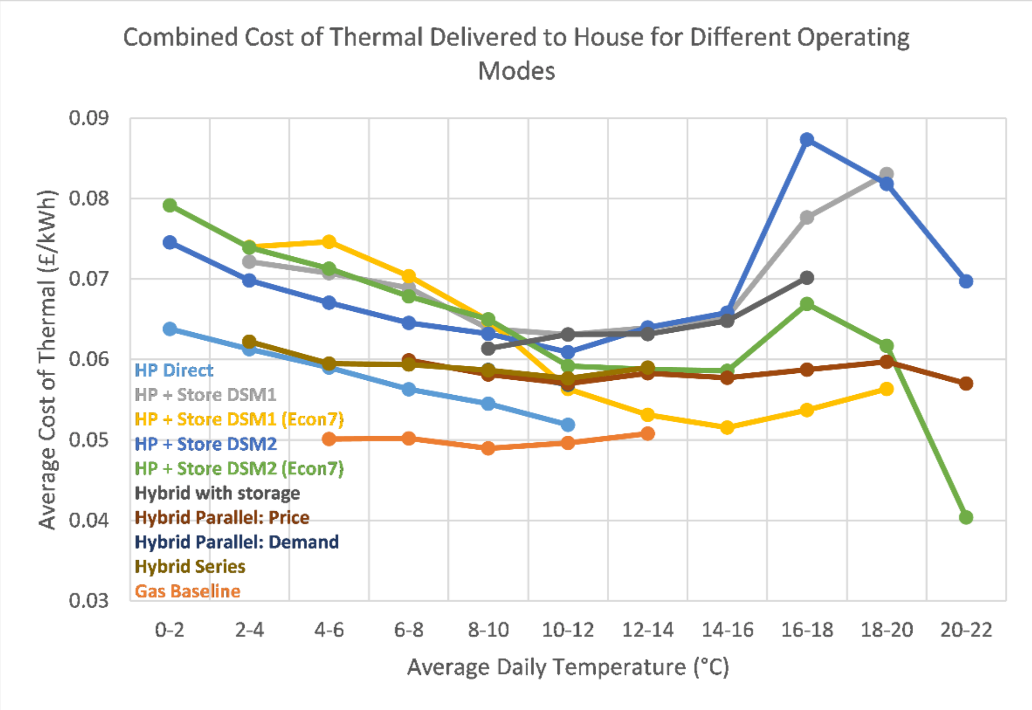


Figure 62 – Operating costs.

And finally, GHG emission are noted below:

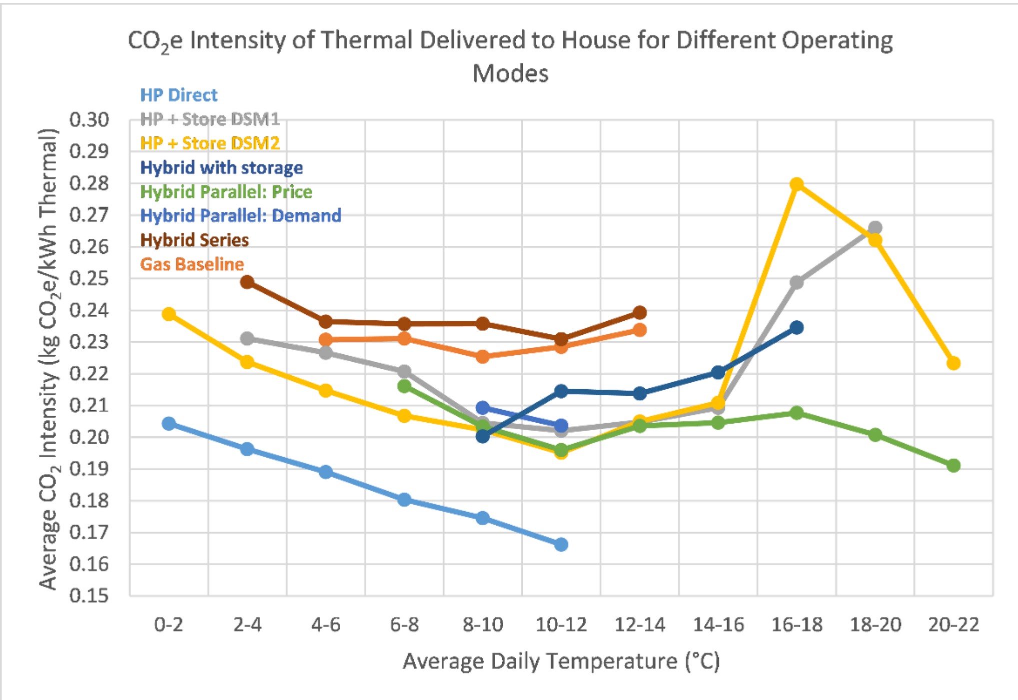
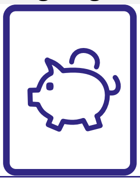


Figure 63 – CO_2 emissions (UK based).

14 (USA) Low cost PCM

Country	US	
Contact	Kyke Gluesenkamp Oakridge Research National Laboratory gluesenkampk@ornl.gov	
Status	Ongoing	
Main CCB implementation strategies		Affordability

14.1 Project Goals

Primary objectives for this project include identifying, evaluating and developing thermal energy storage (TES) technologies that offer significant potential for building heating and cooling systems that employ phase change materials (PCMs). This includes developing novel material systems for TES that can be deployed for grid services to enable demand response solutions for thermal energy dispatch during periods of peak demand. PCMs can provide high energy density thermal storage, which can enable TES solutions that are more effective than employing electrical storage (batteries). However, low-cost materials are needed to ensure an economical system. This research supports DOE objectives for development of next generation thermal storage materials with a maximum cost of \$15/$kWh_{thermal}$ (https://www.energy.gov/eere/buildings/thermal-energy-storage).

14.2 Project achievements

A primary focus of the research was on the stability and thermal conductivity enhancement of salt hydrate-based (SH) PCMs. The project has demonstrated stability of optimized SH PCMs, with thermal storage capacity showing very consistent results for over 150 cycles. With the addition of 10% graphite material and chemical stabilizers, the thermal conductivity of the optimized material was increased by a factor of 5-10 times, with a reduction in the energy storage capacity of only 15-20% relative to the pure salt hydrate. With this formulation, the supercooling was also maintained to within a few degrees Celsius. Using an enhanced SH PCM formulation, a low-cost prototype heat exchanger was constructed to demonstrate 50 W thermal power and 100 Wh energy storage capacity.

The research included fundamental material evaluations via advanced analytical techniques including X-Ray diffraction, scanning electron microscope and neutron scattering evaluations. In addition, molecular dynamics simulations were conducted to consider supercooling and phase stability based on fundamental physics at the atomic scale.

At the system level, the project team has conducted modelling to evaluate cost requirements necessary for achieving simple paybacks of less than 5 years with thermal storage in HVAC equipment. The simulations considered PCM-based TES systems in heat pumps or air conditioners operating in several locations and time-of-use tariffs within the United States. Annual cost savings were determined and used to determine the allowable first cost to achieve a 5-year simple payback period.

14.3 Status/timing of the project

The total project duration is 3 years and we are currently near the middle of the final year. Additional material development and evaluations are planned during this time and additional testing of material cycling stability will be conducted. The team has a final target to demonstrate stable energy storage capacity (less than 20% degradation) and supercooling <4K over 1000 cycles. Continuing development will address approaches for scaling of PCM heat exchangers for manufacturing, and a 200 W / 800 Wh prototype will be fabricated and demonstrated.

14.4 Implementation strategy

This research most directly contributed to the Affordability implementation strategy. Although the research was rather fundamental in nature and did not solely address CCB implementations, the key goal is to develop low cost PCMs and TES systems, which directly supports the affordability of CCBs.

14.5 Project dissemination

1. Monojoy Goswami, Navin Kumar, Yuzhan Li, Orlando Rios, Damilola O. Akamo, Jason Hirschey, Tim LaClair, and **Kyle R. Gluesenkamp** (2021). "Comparison of water nanodroplet properties on different graphite-based substrates", ***AIP Advances***, 11, 035009. https://doi.org/10.1063/5.0042414
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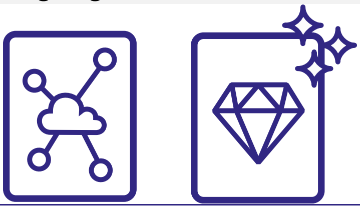
15 (USA) Energy Savings and Demand Reduction for a Heat Pump Integrated with Thermal Energy Storage

Country	USA
Contact	Tim Laclair Oakridge Research National Laboratory laclairtj@ornl.gov
Status	Ongoing
Main CCB implementation strategies	 Flexibility Efficiency

15.1 Project goals

This project will evaluate a new thermal energy storage (TES) approach that reduces temperature lift during discharge instead of displacing compressor usage. It allows significant reduction in peak loads and energy savings for electrically driven heating and cooling systems and provides year-round demand flexibility. Such demand reductions are critical for "smart grid" operations, and utilities are actively seeking new technologies that provide significant opportunities for peak load shifting. A novel TES configuration including a phase change material (PCM) integrated with the building's heating, ventilation and air conditioning (HVAC) system will be evaluated in detail via simulation to determine if the new configuration can lead to a better solution than more traditional TES approaches. A design target is to enable a 50% demand reduction for up to 4 hours while also boosting efficiency in both heating and cooling modes.

15.2 Project setup

In this project we are developing a detailed design for a PCM-integrated heat pump system that meets the requirements for the targeted demand response capabilities of 50% power reduction for 4 hours or more. A comprehensive thermodynamic and heat transfer model will be created, and the model will be used to evaluate the performance of the system under different operating conditions. The research includes the following tasks:

1. Development of 1-dimensional discretized PCM heat exchanger model
2. Integration of the PCM heat exchanger model to a detailed heat pump simulation model
3. Developing several control strategies to maximize the load shifting of the system while providing improved energy efficiency and cost benefits for the PCM-integrated heat pump

15.3 Status and time planning

This research will be completed over a 12-month period. The project initiated in March 2021.

15.4 Preliminary results

An initial PCM heat exchanger (HX) model has been developed based on an enthalpy formulation. The model creates segments dynamically and applies heat transfer rates provided as inputs to the PCM HX. The HX model calculates temperature and melt fraction changes as a function of time. The HX model will be integrated with a heat pump transient solver to characterize the transient performance of the integrated systems.

15.5 Implementation strategy

This project directly addresses both Flexibility and Energy efficiency of CCBs. The system design aims to provide a high level of demand flexibility and load shifting capabilities while improving efficiency of the PCM-integrated heat pump system.

16 (US) Ground Source Heat Pump System Integrated with Underground Thermal Storage for Shifting Building Electric Demands

Country	USA
Contact	Xiaobing Liu Oakridge Research National Laboratory liux2@ornl.gov
Status	Ongoing
Main CCB implementation strategies	Energy Efficiency Compactness

16.1 Project Goals

Primary objective for this project is to develop an on-site diurnal thermal energy storage system integrated with a heat pump to enable flexible behind-the-meter electric demand at residential buildings and light commercial buildings, where space is limited to install conventional thermal storage systems. This project will develop, characterize, and field test a dual-purpose underground thermal battery (DPUTB), which integrates a shallow borehole large-diameter ground heat exchanger with a hybrid thermal energy storage (TES) system using water and phase change materials (PCMs) for storing heating and cooling energy. This project will also develop a dual-source heat pump (DSHP) with the capability to condition a building and charge TES. By integrating the DPUTB with the DSHP, the TES can be charged when thermal load or electricity price is low and the stored thermal energy can be discharged to directly condition the building without running any heat pump when electricity is more expensive, or when the demand reduction is called on by the electric grids. This research supports DOE's objectives for the development of Grid-interactive Efficient Buildings (GEB) (https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings).

16.2 Project achievements

The project has developed a lab-scale prototype of DPUTB and characterized its performance in various operation modes through a series of tests. A numerical model of the DPUTB was developed and validated against the measured data. A prototype dual-source (ground and air) heat pump integrated with thermal energy storage was also developed and is undergoing lab tests to verify performance and flexibility. Coupled with the validated numerical model of DPUTB and other existing component models, a dynamic system simulation of the integrated DPUTB and DSHP system was developed with the Modelica program. Simulation results indicate a full-size DPUTB can provide 14 kWh (4-ton hour) thermal storage capacity for space cooling and space heating. Annual simulation results demonstrated the integrated system can shift 40-80% electricity consumption from on- to off-peak hours without compromising building occupants' thermal comfort. It also achieves 17% annual total energy cost savings at a single-family house in Knoxville, TN where the climate is mild and a Time-of-Use tariff is used.

16.3 Status/timing of the project

The total project duration is 3 years and we are currently in the middle of the second year. We are improving the performance of the DPUTB by refining the heat transfer design and applying new PCMs with higher latent heat and better thermal conductivity. We are also testing and improving the prototype DSHP to reach the desired performance and functionality. Besides, a Model-Predictive-Control (MPC) will be developed to improve the control of the integrated system, which will optimize the operation of the DSHP and DPUTB based on the forecast of weather and electricity demand in the next day. We plan to test the integrated system at a flexible research platform at Oak Ridge National Laboratory in 2022. The goal is to demonstrate a 4-hour electric load shift for meeting thermal demand while maintaining room condition thermally comfortable. The targeted energy efficiency of the integrated system would be at least 20% higher than the conventional air-source heat pump and the installed cost would be the same or less than the conventional ground source heat pump system.

16.4 Implementation strategy

This research utilizes at least three implementation strategies, including flexibility, compactness, and energy efficiency. It also has the potential to be more economically competitive than the conventional ground source heat pump system due to increased value from the additional thermal storage capability.

16.5 Publications

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