Technology Collaboration Programme
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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 49

Field monitoring in nZEB with heat pump

Final Report Part 2

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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.

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Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise 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 organisations. 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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IEA HPT Annex 49

Design and Integration of heat pumps for nearly Zero Energy Buildings

49 Report Annex 49 part 2 Monitoring

Final report IEA HPT Annex 49 part 2
Field monitoring in nZEB with heat pump

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Imprint

IEA HPT Annex 49 "Design and integration of Heat pump for nearly Zero Energy Buildings"

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Abstract

The IEA HPT Annex 49 "Design and integration of heat pumps for nearly Zero Energy Buildings" deals with the heat pump application as core component of the HVAC system for Nearly or Net Zero energy buildings (nZEB/NZEB) and is structured into the following Tasks:

- Task 1. State of the art in different countries
- Task 2: Integration options for multifunctional heat pumps in nZEB
- Task 3: Field monitoring of marketable and prototype heat pumps in nZEB
- Task 4: Design and control of integrated heat pumps for nZEB

A strong focus of the Annex 49 contributions of the participating countries were in total more than 15 monitoring projects in different types of nZEB with heat pump. Thereby, the focus was set in many projects on larger residential and also non-residential buildings, which put higher challenges on the building concepts to achieve ambitious performance targets for the nZE balance. Actually, many projects set an even higher ambition level in the project than would be required by the national legal requirements in the countries. Thereby, however, also the limits are partly much stricter and the design targets could not be achieved in all projects. On the other hand, by the stricter requirements, limitations become clearly visible and optimisation potentials can be assessed. Henceforth, some of the monitoring projects are also accompanied with in-depth investigations by simulations.

Many of the projects also comprise long-term monitoring over several years, which enables to evaluate year-to-year changes in the system performance and to assess the energy reduction achieved by applied optimisation measures.

As general conclusions the performance of the heat pump in the different investigated nZEB applications yield high seasonal performance factors (SPF), which facilitates to fulfil the nZE balance requirement. In many projects SPF values in the range of 5 and higher are reached, which surpass market averages. By the combination of the high performance building envelope and thereby high heat pump performance due to low temperature requirements, in particular in the new built sector, the necessity for on-site renewable energy productions is reduced which may be a challenge in particular for larger buildings. Thereby, nZEB legal requirements can be a market driver for the application of heat pumps also in larger and non-residential buildings, since other system options may not be able to meet the requirements, in particular if higher ambition levels are envisaged.

Furthermore, projects confirm a robust operation of the heat pump over the multi-year monitoring periods, but also optimisation potentials can be found in the monitoring, in particular in the first year of commissioning. Especially for new integration options and system concepts a monitoring shall necessarily be provided for function control and derive a stable and regular operation in the commissioning phase and to gather experience with the system for optimisation.

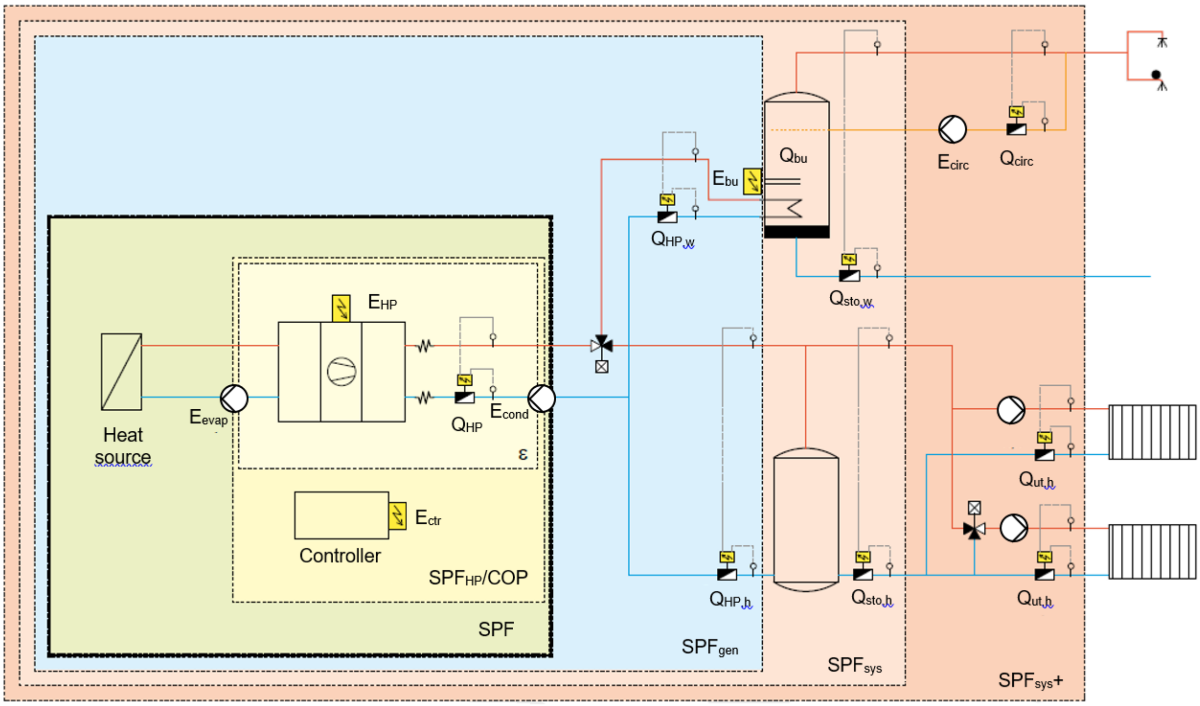
Besides the general conclusions from the monitoring different particular aspects of the heat pump application in larger nZE buildings were investigated, which comprise

- Plus energy balance in larger multi-family buildings
- Increase of self-consumption by thermal and electric storage
- Integration of solar PV and solar thermal systems
- Integration of an absorber and ice-storage as heat source
- Solar thermal integration for larger hotels
- Heat export of recooling energy from supermarket refrigeration
- Energy piles and agrothermal fields as heat and cold source
- Regeneration of boreholes and other ground collectors by waste heat and free-cooling
- Adapted heating emission system design for the application of a CO_2-heat pump

This report covers the results of monitoring projects. Accompanying investigation by simulation linked to the monitoring projects are given in the Report Annex 49 part 3 regarding system integration option, control and design, while information on developed prototypes are given in the Report Annex 49 part 4.

Contents

System boundaries and characteristic numbers



Power related

Performance Number (ε)

$$\varepsilon = \frac{\dot{Q}_{HP}}{P_{el}}$$

Coefficient of Performance (COP)

$$COP = \frac{\dot{Q}_{HP}}{P_{HP} + P_{evap,int} + P_{cond,int} + P_{ctr} + P_{defrost}}$$

Energy related

Seasonal Performance factor heat pump (SPF_{HP})

$$SPF_{HP} = \frac{Q_{HP}}{E_{HP} + E_{evap,int} + E_{cond,int} + E_{ctr} + E_{defrost} + E_{carter}}$$

Seasonal Performance factor heat pump (SPF_{HP})

$$SPF = \frac{Q_{HP}}{E_{HP} + E_{src} + E_{cond,int} + E_{ctr} + E_{defrost} + E_{carter}}$$

Seasonal Performance factor generator (SPF_{gen})

$$SPF_{gen} = \frac{Q_{HP} + E_{bu}}{E_{HP} + E_{src} + E_{sink} + E_{ctr} + E_{defrost} + E_{carter} + E_{bu} + E_{bu,aux}}$$

Seasonal Performance factor generator (SPF_{sys})

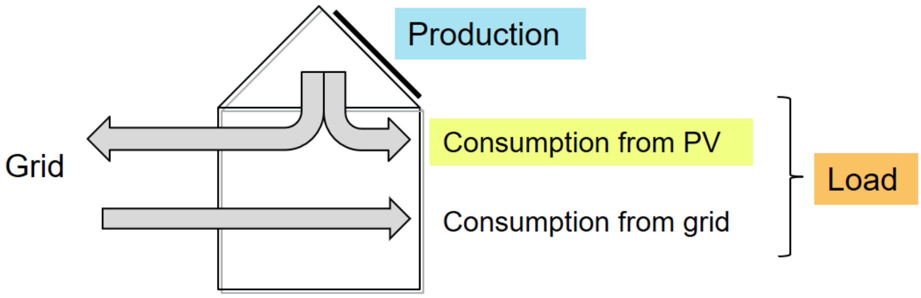
$$SPF_{sys} = \frac{Q_{sto}}{E_{HP} + E_{src} + E_{sink} + E_{ctr} + E_{defrost} + E_{carter} + E_{bu} + E_{bu,aux}}$$

Seasonal Performance factor generator (SPF_{sys+})

$$SPF_{sys+} = \frac{Q_{ut}}{E_{HP} + E_{src} + E_{sink} + E_{ctr} + E_{defrost} + E_{carter} + E_{bu} + E_{bu,aux} + E_{h,aux} + E_{w,aux}}$$

Figure 1: Definition of system boundaries for the seasonal performance factor (SPF) (source: SFOE)

The closest system boundary for the heat pump is the performance number ε, which is an instantaneous value of the ratio between the heating power and the electric compressor power. The more common value known from standard testing is the Coefficient of Performance (COP) which additionally considers the auxiliary power inside the system boundary of the unit, namely the internal power of source and sink pump or fan to overcome the pressure drop inside the unit, the control, the defrosting in case of air-to-water heat pumps and an additional supplementary heating. If the COP is integrated over time, the SPF_{HP}/COP results in the boundary of the COP.
The SPF, however, is also often defined including also the external pressure drop on the source side, so the total source is included in the definition.
The heat generator seasonal performance factor SPF_{gen} considers the heat produced by all generators divided by the total electricity and back-up heaters and thus characterises the total heat production side without taking into account system losses.
The system seasonal performance factor SPF_{sys}, in contrast, relates the used heat, i.e. the produced heat minus storage, distribution and emission losses to the total expenditure for the heat generation. The SPF_{sys} only includes storage losses, while the SPF_{sys+} includes the total system losses including distribution and emission. Thus, the system seasonal performance factor gives the overall performance of the whole system.
The single boundaries for the SPF can also be separated by the energy use, i.e. according to the building services space heating, DHW, space cooing and dehumidification.



$$load\ cover\ factor = \frac{W_{el,\ consumption\ of\ local\ production}}{W_{el,\ total\ electric\ load}}$$

$$supply\ cover\ factor = \frac{W_{el,\ consumption\ of\ local\ production}}{W_{el,total\ local\ production}}$$

Figure 2: Definition of load cover factor and supply cover factor (source: FhG-ISE)

Figure 2 gives the definition of the load and supply cover factor. The supply cover factor (SCF) relates the on-site use of PV-electricity to the total on-site generated PV-electricity and is thus a characteristic for the self-consumption on the supply side. The load cover factor (LCF) relates the totally covered electrical load to the total on-site generated PV-production and is thus the characteristic for the load or demand-side. It is also called autarky rate, since is describes the degree of autarky by on-site PV-production. The factors are based on the system boundary of total energy consumption. The supply cover factor has typically high values in wintertime, since in winter, the PV-yield is low and nearly all the produced energy can be used on-site, i.e. the PV surplus in winter is low. In contrast, in summer, the PV production is high and the loads are lower due to less illumination and heating demand, so the PV surplus is high, and thus, the supply cover factor is low. The load cover factor has the opposite characteristic, since in winter only a small part of the total load can be covered by on-site PV production, but in summer, nearly all the load may be covered by on-site PV-production.

1 Monitoring of heat pumps in nZEB

Nearly zero energy buildings are still a new design for buildings, even though several prototypes in different residential and non-residential building application have been built since the beginning of the century (see for instance Voss et al. (2012) for demonstrator projects). Heat pumps, often in combination with solar PV systems, established in these built nearly zero energy buildings as an archetype building system technology due to the high performance of the heat pump and for the enhanced self-consumption of solar PV on-site production. This is basically due to the unique features of heat pumps for the application in nearly zero energy buildings:

- Heat pumps are highly efficient generators at low loads of nZEB enabling low emission system temperatures
- In nZEB the space heating loads are no longer dominating and multiple building function have the same impact on the overall energy consumption. In particular, the DHW operation can make up more than half of the total heat demand and also a cooling function in Europe or an additional dehumidification function in the USA and Asia get more prevalent. Heat pump as generator can serve multiple building services, which is ideal for new built high performance buildings like nZEB.
- System integration of multiple functions covered by the heat pump can have further performance advantages, since a simultaneous production of different buildings services can enable the use of internal heat recovery for other building services, e.g. space cooling (or dehumidification) and DHW production. Simultaneous operation yield higher performance values due to multiple functions covered by the same electricity input.
- Use of the same components for multiple building services can justify investment in high quality components (e.g. capacity controlled units with variable speed drives (VSD))
- Heat pumps are capable to transform electricity to heating or cooling energy, which offers energy flexibility for on-site generation or the electricity grids and unlocks additional storage capacities as thermal storage

However, in order to prove the advantages in practical operation, a monitoring is very useful, in the first place to verify the system performance in real application, which also comprises meeting the nZEB requirements, which are currently mainly planning values. This is the reason, why some countries already require a basic monitoring to approve the nZEB balance, e.g. the certification according the Swiss MINERGIE-label for larger buildings and the MINERGIE-A® label for all buildings.

Moreover, detailed monitoring enables in-depth evaluation of the practical building operation in order to approve technology functions and subsystems, the design and control of the system and optimisation potentials. In the context of nZEB, due to the active energy generation on-site, this is not limited to the buildings itself, but may also refer to the integration into energy grids and thereby connected buildings.

1.1 Overview of nZEB monitoring projects

The focus of monitored buildings in IEA HPT Annex 49 was on larger buildings. Most of the realised nZEB are residential buildings, but for single family buildings, the nZEB balance is relatively easy to achieve, since the space in the building envelope in relation to the building load is rather large and thus enough energy can be produced for an annual balance.
In larger buildings, though, the surface in the building envelope for energy production can be scarce in relation to the building loads, thus on-site energy production is limited and fulfilling the nZEB balance can be more challenging, emphasizing a higher requirement on excellent building and system performance in order to reduce the need for on-site energy generation.
Furthermore, the monitoring projects performed in the Annex 49 often comprise multi-year monitoring periods. This has the advantage that the building performance in the first year of operation can be distorted, e.g. by drying-out of the building structure and commissioning of the building, which may be improved after the first monitoring period, so multi-year monitoring can deliver more consolidated performance results. Additionally, year-to-year differences in the performance can be analysed and applied optimisation measures can be verified.
As mentioned before, one basic result of the monitoring is the evaluation of fulfilling the intended nZEB balance. Thereby, the monitoring projects have partly different ambition level regarding the balance. While some buildings were planned to fulfil the balance regarding the balance boundary of the building technology system, others intend to reach a plus energy balance, which also includes the plug loads and appliances of the building users, which requires a significantly higher effort and design for energy production on-site and higher requirements for the building envelope and system performance.
On the other hand, most of the buildings include other particularities regarding the applied system technology or system integration, or the building operation, e.g. regarding control and demand response, which was particular focus in some of the investigated buildings. Also regarding building labelling, some of the monitored buildings are among the first buildings to be certified according to a particular label, and experiences with the label requirements shall be gathered by the monitoring. Therefore, for some of the monitored buildings, accompanying detailed investigations on particular research items has been performed, which is documented in the Report Annex 49 part 3.
Table 1 gives an overview on the monitoring projects. The categories and the individual buildings are linked to the respective chapters in the report, so Table 1 can also be used as a table of contents. A click on the photo leads to the chapter of the respective monitoring project itself.

Table 1: Overview of nZEB monitoring projects in Annex 49 regarding building type and other project features

	Photo	Monitoring period	Ambition level*	Particular research/ investigations
Single family houses				
Berghalde Leonberg-Warmbronn, Germany Monitoring: IGS, Franziska Bockelmann		4 years	Energy Plus	• Load management by control and thermal/electric storage
Twin houses, Borås and Varberg Sweden Monitoring: RISE, Ola Gustafsson		1 year	nZEB	• Two identical houses one occupied and one with tuneable loads • Combination HP - storage – floor heating
Multi-family houses				
Social housing NTH 2 multi-family buildings Innsbruck-Vögelebichl Austria Monitoring: UIBK, Fabian Ochs		4 years	NZEB building Passive house plus	• First passive houses plus • nZEB in social housing • integration solar/PV

	Photo	Monitoring period	Ambition level*	Particular research/ investigations
Multi-family houses				
Sonnenpark Plus Wetzikon, ZH Switzerland Monitoring: HSR, Carsten Wemhöner		1.5 years	Energy Plus	• Multi-family plus energy building • Façade-integrated PV • Self-consumption residential building
Allmendhölzli Horgen, ZH Switzerland Monitoring: HSR, Carsten Wemhöner		1 year	Energy Plus	• Load management and self-consumption by storage integration in residential buildings
Riedberg Frankfurt a. M. Germany Monitoring: IGS, Franziska Bockelmann		4 years	Energy Plus	• Multi-family plus energy building • Façade-integrated PV • New absorber heat source with ice storage
Office buildings				
Neuwiesenstrasse 8 Uster ZH Switzerland Monitoring: HSR, Carsten Wemhöner		2 years	nZEB building technology	• First MINERGIE-A® with office use • Mixed residential/office • Self-consumption residential office
Post am Rochus Vienna Austria Monitoring: AIT, Tim Selke		Commis-sioning phase	nZEB	• Integral planning for complex office nZEB • Software aided design and commissioning
Black & White Pfäffikon SZ Switzerland Monitoring: HSR, Carsten Wemhöner		1 year	nZEB building technology	• Mixed residential/ office/commercial • Self-consumption office • Façade integrated PV
Non-residential use - School				
Willibald-Gluck-School Neumarkt in der Oberpfalz, Germany Monitoring: IGS, Franziska Bockelmann		4 years	Energy Plus	• Energy plus school • Energy piles and agrothermal horizontal field
Justvik Skole Kristiansand Norway Monitoring: NTNU, Jørn Stene		10 month	nZEB	• nZEB school • CO_2-heat pump system with adapted heat emission system
Medbroen Kindergarden Stjørdal Norway Monitoring: NTNU, Jørn Stene		1 year	nZEB	• 100 year-old retrofitted agricultural building to passive house

	Photo	Monitoring period	Ambition level	Particular research/ investigations
Non-residential use - Hotel				
Scandic Lerkendal Hotel Trondheim Norway Monitoring: NTNU, Jørn Stene		1 year	nZEB	• High performance hotel • nZE in hotels • Solar thermal integra-tion in hotel
Non-residential use - Supermarket				
KIWI Dalgard Supermarket Trondheim Norway Monitoring: NTNU, Jørn Stene		1 year	nZEB	• Regeneration with re-cooling of supermarket refrigeration • Heat export to adjacent residential buildings
Groups of buildings - residential				
Residential 8 terraced houses Herzo Base Herzogenaurach Germany Monitoring: THN, Arno Dentel, Christina Betzold		2 year	Plus energy	• Mid-temperature grid for group of residential buildings • Smart control of thermal/electric storages
Residential Aspern D12 Seestadt Aspern, Vienna Austria Monitoring: AIT, Tim Selke		1 year	nZEB	• Smart city integration • Multi-source thermal grid • Control and commis-sioning
5 office buildings Otto-Nielsens vei 12 A-D, E Trondheim Norway Monitoring: NTNU, Jørn Stene		2 years	nZEB	• Heat export of new office building for existing office buildings • Use of waste heat of server and processes for heating and bore-hole regeneration

* Ambition level refers to following balances for the evaluation:
nZEB – system boundary building technology; NZEB – balance boundary incl. appliances and plug loads, plus energy: PV surplus in the annual balance, passive house plus – label of the passive house institute (PHI- www.passiv.de) for passive houses, which reach a plus energy balance

2 Monitoring results in residential buildings

Nearly zero energy buildings are currently mainly applied in residential buildings, even though the number of non-residential applications is growing and there are dedicated projects on different types of non-residential and commercial applications. Since the introduction of nZEB requirements for all public buildings by January 2019 in the EU member states, more and more administrative and office buildings comply with nZEB requirements. Monitoring projects within Annex 49 for non-residential use are described in the following chapters.
In single family houses, it is normally not critical to reach the nZEB balance, since the space in the building envelope is large enough to produce the adequate amount of on-site renewable energy to fulfil the balance.
Thus, the focus of the monitoring projects in residential buildings within Annex 49 has been set on multi-family buildings, since depending on the balance boundary, i.e. with or without household electricity for plug loads and appliances, it can be challenging to reach the balance, and normally the roof does not offer enough space for larger multi-family buildings, which accommodate a larger number of flats, so also façade integration is more important in multi-family nZEB. The main focus of the monitoring was thus to characterise the nZEB requirements and the system performance.
Further aspects covered in the monitoring projects of residential buildings comprise:

- Plus energy balance in larger multi-family buildings
- Increase of self-consumption by thermal and electric storage
- Integration of solar PV and solar thermal systems
- Application of a desuperheater in multi-family passive houses
- Integration of heat pump, thermal storage and floor heating
- Integration of an absorber and ice-storage as heat source

2.1 Overview

The **Single-family house Berghalde in Leonberg-Warmbronn near Stuttgart, Germany** is designed as EnergyPlus building. The "all-electric" building concept comprises a maximum roof-integrated 15.3 kW_p PV system, a borehole heat exchanger of 3 ground probe of 100 m each connected to a 10 kW_{th} heat pump and a mechanical ventilation system with heat recovery and ground-to-air heat exchanger for preheating/ -cooling. The main focus of the research was with electricity self-consumption of the building, and therefore, an 825 l thermal water storage and a 2x10 kWh electric battery storage as well as an electric car, which is charged at the building garage are integrated in the building technology concept. The building has been monitored for 6 years from 2014 to 2019. Due to the rather large energy reference area of 260 m^2, the building is heating dominated with a space heating demand between 41-58 kWh/(m^2a) and a DHW fraction of only 15%. The plus energy balance has been reached with a surplus of about 23 $kWh_{el.}$/(m^2a) on average of the monitoring periods.

The **Twin houses in Borås and Varberg, Sweden** are two identical single family houses which correspond to the Swedish building standard and are equipped with heat pumps. The one building is located in the village of Borås in south-western Sweden and the other building in the village Varberg which is in the vicinity of Borås and thus has the same climate. The building in Borås is inhabited by a family of four persons, while the other building in Varberg is equipped with tunable loads, i.e. loads can be modified to simulate the presence of the family, but with reproducible load profiles. Moreover, the one building is equipped with an on-off controlled ground-source heat pump, while the other building has a capacity-controlled heat pump. In the two buildings, monitoring has been performed with the objective to evaluate the combination of the heat pump, the heat storage and the floor heating emission system. Furthermore, the integration of free-cooling operation by the ground source has been investigated.

The two **Multi-family houses Vögelebichl in Innsbruck, Austria** are two certified passive houses of the social housing company NHT, Tyrol. The buildings are the first multi-family buildings certified according to the passive house premium label implying also on-site energy production. Thus, the design objective was to reach a NZEB balance. The buildings comprise 26 flats on a total energy reference area of 2148 m^2. The buildings are equipped with solar PV of 24.5 kW_p and 73.6 m^2 of solar thermal collectors located on the two building roofs. The building technology consists of a two-stage ground-water heat pump linked to a 6 m^3 central energy storage, which is also connected to the solar thermal system and a direct electrical back-up. The building has been monitored for a four-year period and the building system has been modelled and validated with the monitoring data in order to optimise the energy system. Within the four years, the nZEB balance has not been reached, but simulation confirm that the nZEB can be reached by optimisations.

The **Multi-family house Riedberg in Frankfurt am Main, Germany** accommodates 17 two-to-four-room apartments on a total area of 1,600 m^2 on four floors plus an attic floor. The building envelope features U-values of 0.13 $W/(m^2K)$. The building system consists of a 50 kW_{th} heat pump which uses absorbers on the roof as heat source, which are located under the PV system. As source storage a 98 m^3 ice storage is integrated, which serves as heat source and for cooling, if the absorber yield is not enough to cover the entire heat source. A mechanical ventilation system with 84% heat recovery efficiency supplies the flat with an air volume for of totally 1600 m^3/h. In order to reach a plus energy balance the building envelope is equipped with a PV-system of 84 kW_p on the roof and a 15 kW_p in the south façade. As electric storage of 60 kWh battery is also integrated. The objective of the monitoring was on the one hand a verification that plus energy can also be reached in larger multi-family buildings. On the other hand, the performance of the building technology concept is investigated, in particular the newer system integration of the absorber heat source in combination with an ice storage system.

The **Multi-family house Sonnenpark Plus in Wetzikon, canton Zuerich, Switzerland** is five storey building with 10 flats on an energy reference area of 1706 m^2. The building has been commissioned in spring 2018 and monitored from the beginning. The measurement period for the evaluation was set to the year 2019. The building envelope is certified according to MINERGIE-P®, the Swiss implementation of a passive house. The building system comprises a 22.9 kW_{th} (B0/W35) ground-coupled heat pump, a mechanical ventilation with heat recovery and wall heating in the clay walls of the flats, which are also used for freecooling in summer time. One focus of the monitoring was the approval of a plus energy balance in a multi-family house. However, since the building is equipped with a large PV-system both on the roof and in the façade, a particular focus was also set on the self-consumption of the on-site produced solar PV electricity. The building is equipped with a smart energy management system which surveys the PV yield, the household electricity, a 73 kWh electric battery storage and further shiftable load of the heat pump and 3 electric cars, which are shared among the users.

The **Multi-family house Allmendholz in Horgen, canton Zurich, Switzerland**, has four apartments and is equipped with a 20 kW geothermal heat pump with two boreholes of 225 m each for space heating and DHW production. Moreover, a 13 kW_p PV system is installed on the roof. The heat pump has a speed control by inverter and is optimised for low temperature lift. Additionally, wood stoves are placed in the apartments, which could deliver back-up heat in winter, but are not only used for heating reasons, but also to create a cosy atmosphere in the apartments.

The heat pump shows high monthly performance factors up to PF=7 in space heating mode, i.e. particular in wintertime, which is due to the oversized geothermal probes, that are operated with water. Thereby, a plus energy balance is reached due to a good PV yield of 1112 kWh/kW_p, but also due to the energy-conscious behaviour of the residents with 647 kWh/pers. electricity use. The integrated monitoring system uses internal measurements of the heat pump and allows for an optimisation in operation of the control system.

2.2 Single family building Berghalde - Leonberg, Germany

In the future, the building sector will no longer be just a matter of reducing heating energy requirements, but of holistically considering energy flows, taking into account the total energy requirements. The interaction of buildings and the public power grid plays a crucial role here. Residential buildings faced the changing requirements of buildings early on, which make up todays major issues of the turnaround in energy ("Energiewende") due to the expansion of renewable energies and e-mobility and the associated rebuilding of infrastructures.

Figure 3: Bird's eye view (left) south-east view and north-west view (middle) and terrace area (right) [IGS]

From the beginning on, the building "Berghalde" was designed as smart building to optimally use and store the energy in the building and intelligently communicate with the power grid.
In 2010, Leonberg-Warmbronn (Germany) in Baden-Württemberg, finished one of the first residential buildings as a pioneer of a new type of building, which generates more energy than it consumes in the annual balance and thus makes the transition from consumer to producer and network service provider. Completed in September 2010, the two-storey detached house with a floor space of approx. 260 m² fits into the existing building structure on a nearly 900 m² large south-facing hillside plot. The building itself is relatively closed to the north, which, following the topography, digs into the slope with the basement and opens on the south side from the ground floor to the first floor with generous window fronts to the valley side. The compact form of the building with generous glazing and consistent orientation of the residential zones to the south lays the foundation for minimized heating requirements. Compared to the south, the north, east and west facades are much less transparent. On the south side of the street level, next to the garage, stairs lead up to the entrance on the ground floor, alternatively the residents can also get from the garage via an internal staircase into the house. On the ground floor, following the entrance area, there are two children's rooms and a guest room with garden access, as well as technical function rooms arranged to the rear facing the slope. Upstairs, there is the spacious and contiguous living, dining and kitchen area with a southwest terrace. On the north side, in addition to the internal circulation, a toilet, bathroom and a bedroom, as well as a utility room are housed. The attic also offers space for a sizable study and storage area.
The research projects for the "EffizienzhausPLUS-Gebäude Berghalde" depicted in Figure 3 funded by the research initiative ZukunftBau and the Federal Institute for Research on Building, Urban and Spatial Development (the BMVBS and BMUB) aims to document and evaluate holistic monitoring of the performance of the building including its facilities in order to implement optimization measure focused on increasing the share of the internal use of generated electricity.
The building "Berghalde" is part of the network EffizienzhausPLUS of the BMUB and was evaluated as a model project within the framework of an accompanying scientific program. The research and implementation objectives of the Efficiency House Plus buildings include the following aspects:

- Reduction of the annual final energy demand for heating and hot water
- Reduction of the annual electricity demand for household appliances and lighting
- Efficient energy production and distribution
- Use of solar energy for heat and power generation
- Direct use of solar generated electricity for e-mobility and storage in batteries
- Building control system for the control and implementation of load management

2.2.1 Energy Concept

The integral building concept is based on the interaction of architectural considerations for alignment (active and passive use of solar energy) and building form, a high-quality building shell and an innovative building technology for heat and power supply. Despite the focus on the EnergiePLUS standard, future users were at the centre of planning. They should not feel that their residential building is a high-tech facility, but a comfortable home. Therefore, the technology stays visually consistent in the background, necessary control elements integrate discreetly into the interior concept with its minimalist details and clear architectural lines. The storage mass of the massive components, the low-temperature surface heating system, the high quality building envelope and a coordinated combination of natural and mechanical ventilation create a comfortable indoor climate, which is supported by the natural and high-quality surface materials.
The building was designed as an "all-electric building", which means that the sole source of energy to meet the used energy demand is electricity. Energy sources include the public power grid, an entire roof PV system of 15.3 kW_p and 120 m² and near-surface geothermal energy with borehole heat exchanger. A brine-to-water heat pump of 10 kW_{th} with three vertical boreholes sunk 95 m into the ground serve for heating and hot water preparation. For the energy storage the thermally effective building masses, a buffer storage (water, 825 l) and electrical storages (20 kWh) are used. The heat is distributed in the house by the floor heating, only the two bathrooms have additional radiators installed. In the summer months cooling can be enabled by the floor, in which the water from the borehole heat exchanger and the pipe network is circulated for free cooling, thus also supporting the regeneration of the soil. The domestic hot water (DHW) heating is carried out centrally in a flow principle via an external heat exchanger on the buffer tank. In addition, direct electric back-up heaters are installed at the tapping points for decentralized reheating.
The entire building is ventilated by the windows. During the heating season and in midsummer, the mechanical ventilation system with heat recovery is switched-on and supplies the living areas with fresh outdoor air. A ground heat exchanger additionally preconditions the air.

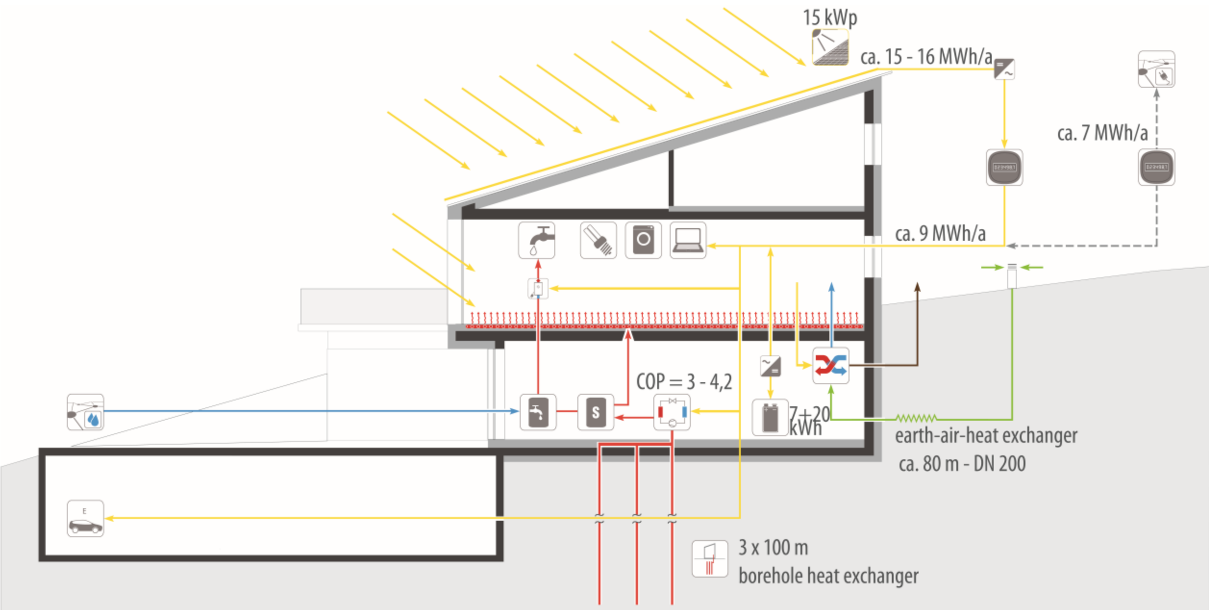


Figure 4: Energy concept - "all electric building"

Electric load management ensures that as much solar PV power as possible can be used directly on-site, and that only a small amount of electricity is fed into the grid from which it has to be bought back. The energy concept and the internal electricity use also include the use of e-mobility. Two electric vehicles are powered by a charging station in the garage.

Table 2: Technical data building technology

	Systems technology	Performance/Area/Volume-flow
Heating	Ground source heat pump	max. 2.2 kW_{el}, and 10 kW_{th} thermal buffer storage 825 l
Cooling	Free cooling via borehole heat exchanger, Air supply via ground-to-air heat exchanger	
Electricity	Photovoltaic on the roof	15.3 kW_p, PV area 120 m² electrical storage 20 kWh
Ventilation	Controlled supply and exhaust air system with heat recovery	max. 250 m³/h heat recovery 90%

2.2.2 Building envelope

As part of the holistic concept, extra attention was paid to the avoidance of thermal bridges and creating an airtight design during the planning, construction and detailing of the building envelope. The solid structure increases the thermal storage capacity, which is included in the load management in conjunction with the high-quality insulation to reduce heat loss through the building envelope. The thermally insulated of the building envelope is accomplished circumferentially. After completion, the airtightness of the building envelope was verified by a blower door test according to DIN EN 13829. In the EnEV 2009 the maximum permitted air exchange rate of $n_{50} \leq 1.50$ 1/h was significantly undercut with $n_{50} = 0.50$ 1/h, achieving excellent airtightness.
All external walls are made either of concrete or of sand-lime brick masonry with a composite thermal insulation system (22 cm PSCarbon, $\lambda \leq 0.032$ W/(mK)). The pent roof consists of a rafter construction, which is completely filled with a mineral fiber insulation ($\lambda \leq 0.035$ W/(mK), 22 cm) with inward facing sub-rafter insulation made of 5 cm polystyrene ($\lambda \leq 0.035$ W/(mK)) to reduce heat losses through the rafters. The transparent elements of the building envelope (fixed windows, turn-tilt and sliding doors) are triple-glazed throughout the house. On the south side, glazing was installed with a total energy transmittance of 0.35 to 0.48 [-]. In conjunction with the external sun protection on the upper floor and the structural overhang on the ground floor, the summer heat protection is maintained.

Table 3: Characteristics of building envelope

	U-Value [W/(m²K)]
Exterior wall / Roof / Floor slap	0.15 / 0.15 / 0.3
Window	0.60 – 0.80

Due to the thermally insulated and airtight building shell, the use of passive solar gains and the controlled ventilation with heat recovery, an annual heating demand of 40.5 kWh/(m^2_{AN}yr) is achieved. According to the EnEV 2009, the annual primary energy is 34.3 kWh/(m^2_{AN}yr).

2.2.3 Comparison with design data

With regard to the electricity requirement for the building, the planning results in a final energy requirement for the provision of heat, household electricity, lighting and auxiliary energy of 42.3 kWh/(m^2_{AN}yr). According to the planning, the PV system delivers a yield of 55.8 kWh/(m^2_{AN}yr) based on the living space. In the planning, this results in an annual electricity surplus of 3,507 kWh/a. Table 4 shows a comparison of the monitoring data with the design data. In comparison to the design data the monitoring data have quite low deviations.

Table 4: Comparison of the design data with the results of the monitoring

	Calculation	Monitoring	Deviation
Space heating + DHW	11.4 $kWh_{el.}/(m^2a)$	11,5 $kWh_{el.}/(m^2a)$	+0,9%
Total electricity consumption	42.3 $kWh_{el.}/(m^2a)$	30.6 $kWh_{el.}/(m^2a)$	-28%
Electricity production PV	55.8 $kWh_{el.}/(m^2a)$	61.8 $kWh_{el.}/(m^2a)$	+11%
SPF of heat pump	4.4	4.9	

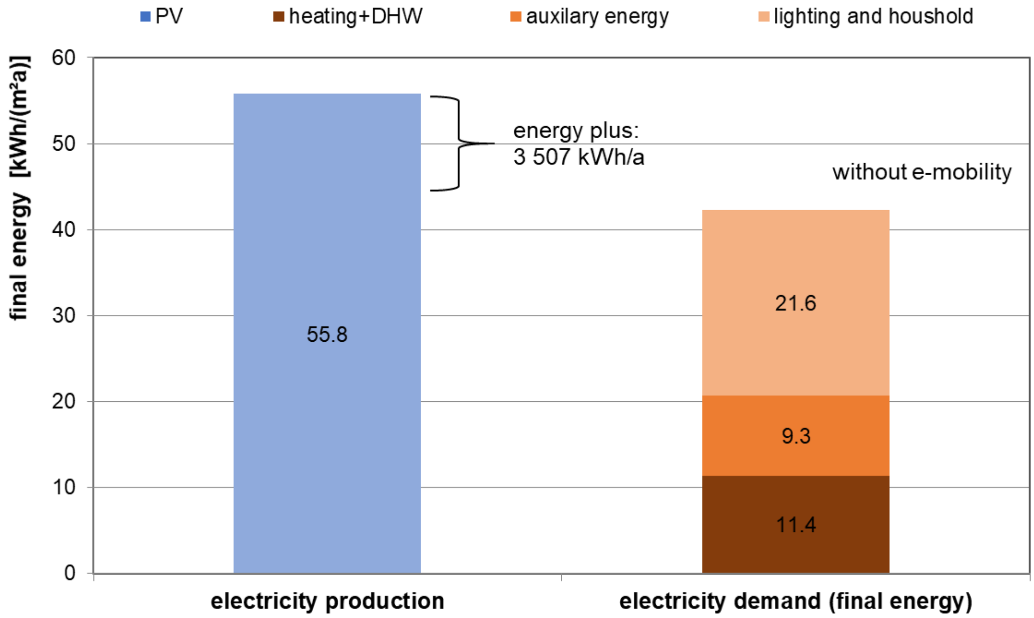


Figure 5: Calculated final energy demand and PV production in planning

The electricity consumption for space heating and DHW is more or less the same as calculated. The total monitored value of the electricity use of 30.6 kWh/(m²yr) including the building technology as well as the household appliances is 28% lower than the estimated value in the design phase of 42.3 kWh/(m²yr). The PV yield delivered about 11% more electrical energy than calculated.

2.2.4 Monitoring concept

As a basis for a detailed evaluation of heat and electricity consumption and for the preparation of energy balances of the building, a differentiated measurement concept is implemented.

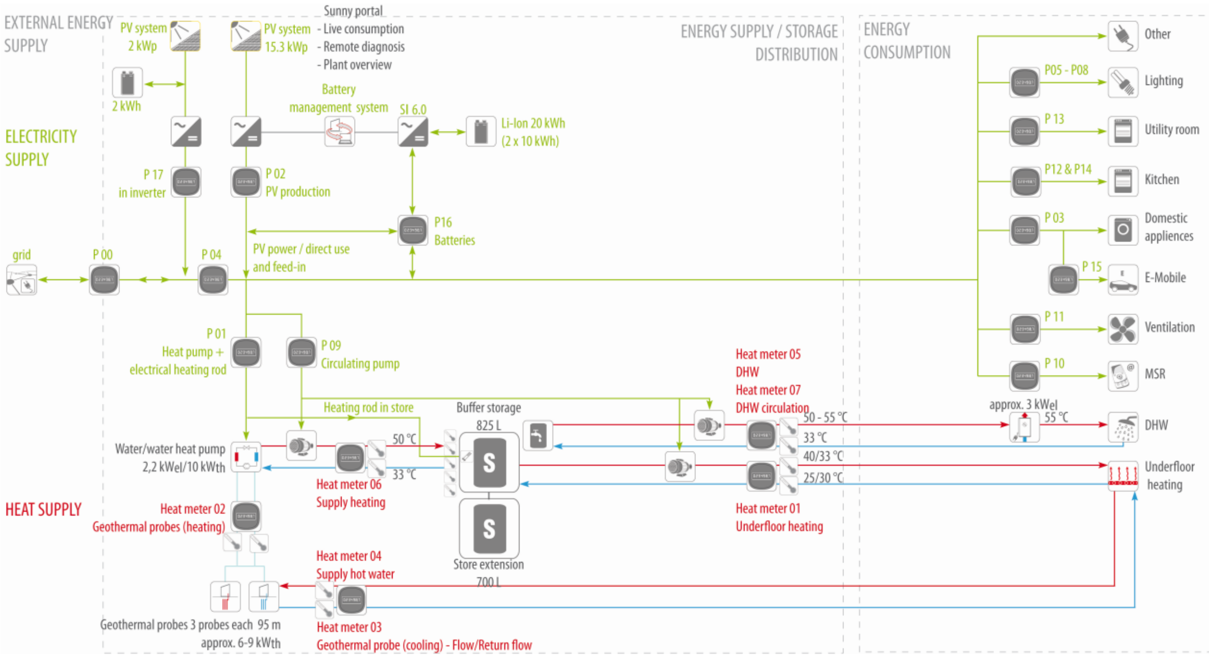


Figure 6: Monitoring concept single family house Berghalde

The measuring interval for data acquisition is 2 minutes in order to be able to evaluate the system efficiency. A simple energy monitoring system usually operates with a resolution of 15-minute intervals. Since the research project aims to coordinate renewable yields and building loads during operation and to identify and analyse optimisation approaches, the smaller time step is relevant.

The total electricity consumption of the building is composed of the consumption of heat pump, controlled ventilation with heat recovery, measurement and control technology (MSR), user and household electricity as well as electric mobility. For the analysis of heat supply and consumption, the heat quantities of the heat pump as well as the heat transfer for heating and domestic hot water preparation are recorded. In addition to the meters for determining all relevant energy quantities, further sensors are installed to record temperatures, operating states, outputs, valve positions, etc.

2.2.5 Monitoring results

2.2.5.1 PV yield and own electricity use

The building technology primarily envisages the direct use of solar yields from photovoltaics. Only surpluses that cannot be stored will be fed into the public grid.

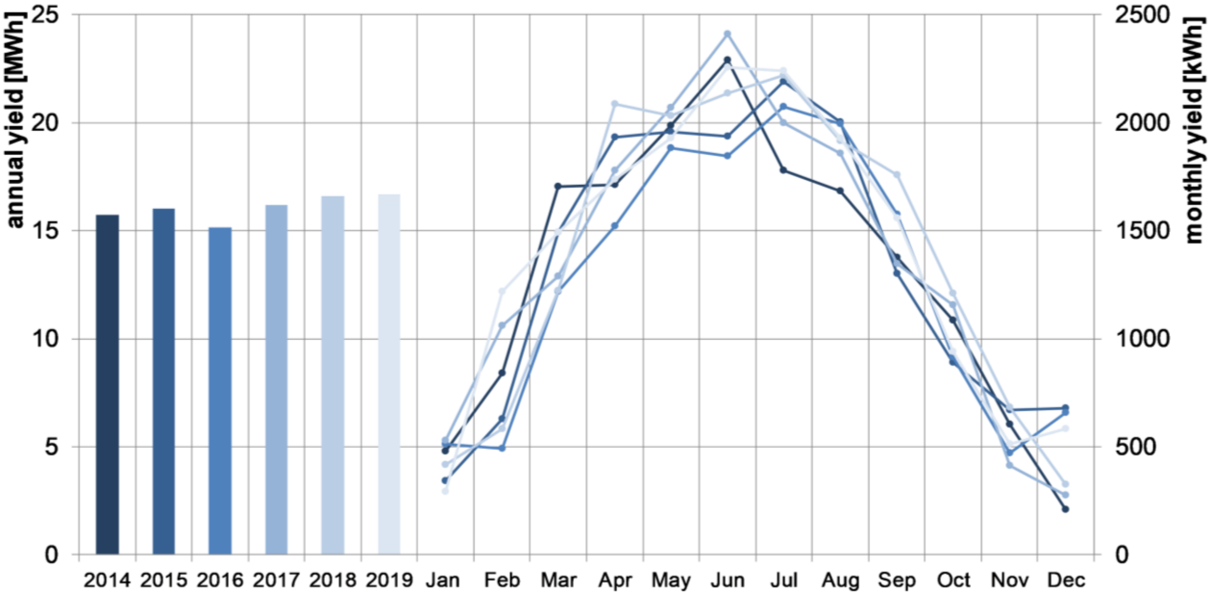


Figure 7: Annual and monthly electric yield of the PV panels, 2014 - 2019

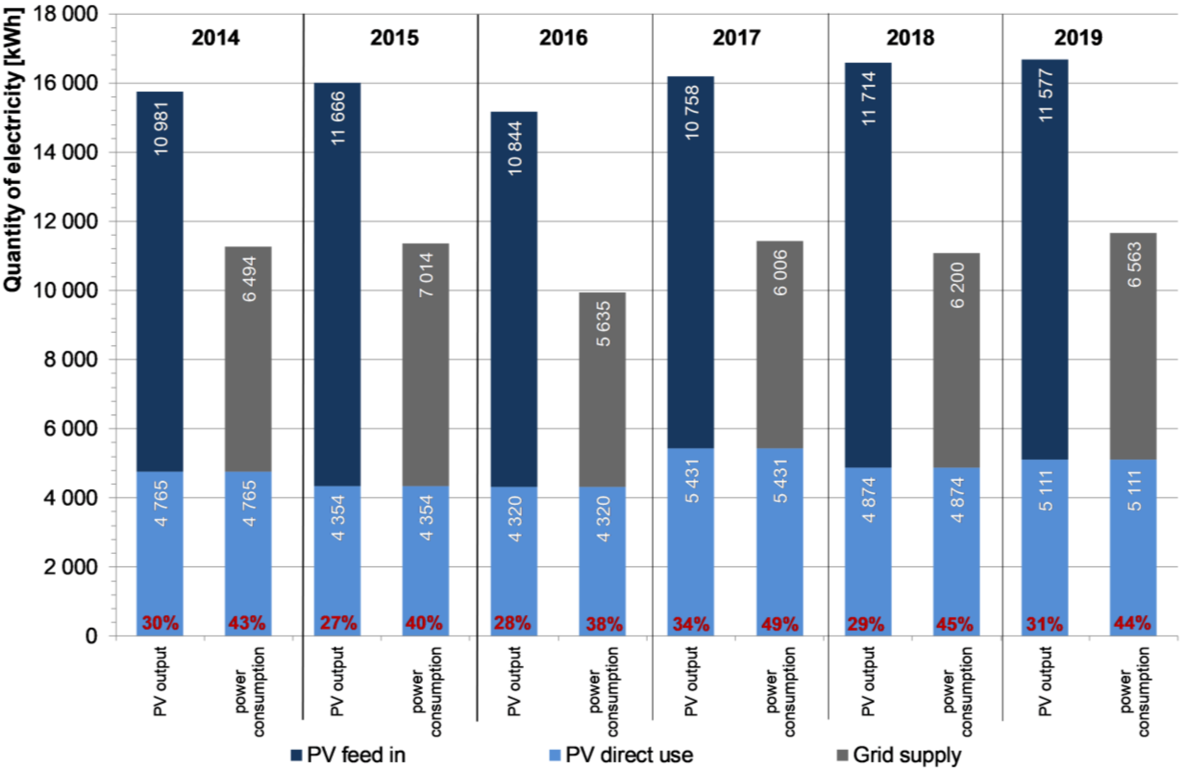


Figure 8: Annual balance of total energy, 2014 – 2019 (red = fraction)

The annual surplus energy balance calculated from the measured data exceeds the planning values. Compared to the calculated electricity yield of 14,500 kWh/yr from the PV system, approx. 16,000 kWh/yr were delivered, around 12 % more than assumed in the planning. In the last six years of operation, the PV system has delivered around 96 MWh of solar energy in total. This results in a mean energy yield per installed capacity of ca. 1,070 kWh/kW$_p$, see Figure 7.The average annual electricity surplus is about 6,000 kWh/yr (about 54% of the electricity consumption). Over the period under consideration (2014 -2019), about 33% of solar energy was used in the house itself, the vast majority being fed into the public grid. The load cover factor varies between 32% and 49% over the years, reaching an average of 41% over the six years, see Figure 8 and Figure 9.

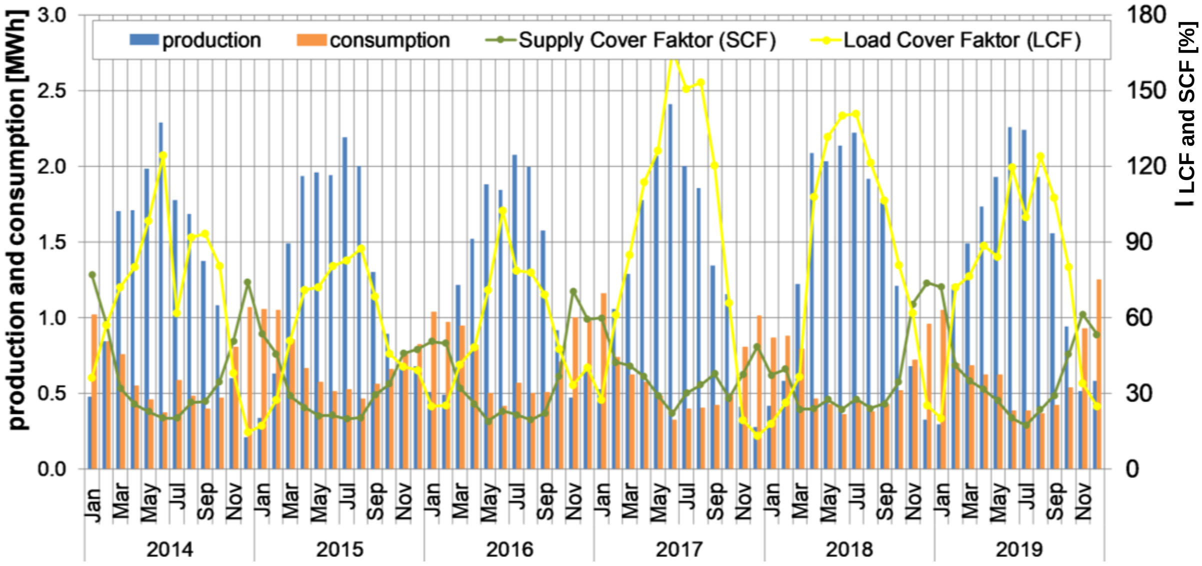


Figure 9: Monthly load/supply cover factor, 2014 - 2019

2.2.5.2 Final and primary energy and CO_2-emissions

The annual balance of final and primary energy from 2014 to 2019 is shown in Figure 10. In accordance with the German standards DIN V 18599-1 and DIN 4701-10 / A1, a primary energy factor of 2.8 is applied to the electricity feed-in and a primary energy factor of 1.8 to the electricity purchase.

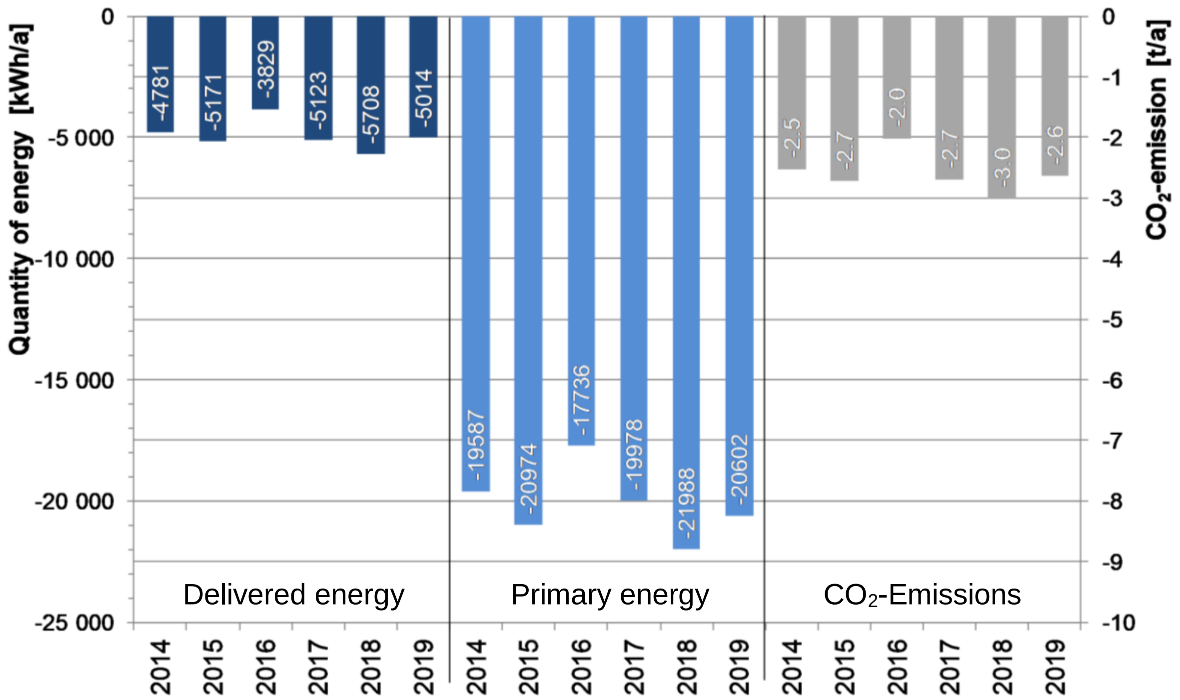


Figure 10: Delivered energy, primary energy and CO_2-emission (2014 to 2019)

From 2014-2019, a primary energy surplus in the range of 17,700 to 22,000 kWh/yr was achieved. Regarding the delivered energy surplus, values between 3,800 and 5,700 kWh/yr could be reached.
For CO_2 emissions, CO_2 equivalents of 527 g/kWh are used for both electricity savings and grid purchases. This results in CO_2 credits of 2.0 to 3.0 t/a.

2.2.5.3 Electricity balance

The total electricity consumption in regard to the floor space (about 10,900 kWh/yr, including e-mobility) of the building is about 42 kWh/(m²yr). Figure 11 shows the annual electricity balance according to the individual consumers or consumption areas (heat pump, MSR, ventilation, e-mobility) for the years 2014-2019. With a clear lead, the largest power consumer in the building is the heat pump with about one third of the total power consumption. Building conditioning (heating, cooling, ventilation and domestic hot water) accounts for around 35% of electricity consumption. With about 40%, the share for the household electricity (household, lighting, other) turns out much larger. The category Other (17.5%) includes the power consumption of all devices not separately listed (small consumers (vacuum cleaner, coffee machine, etc.), ICT, computers, printers and all sockets). For lighting (8%), an average of approx. 880 kWh/yr or approx. 3.4 kWh/(m^2_{Net}yr) was determined. The household electricity without lighting measures approx. 32% (about 3,425 kWh/yr). The unusually high power consumption of more than 1,200 kWh/yr (11%) for the measurement technology and the computer-assisted BMS is not representative for detached houses, or even for the Efficiency House Plus standard, but caused by the accompanying scientific program. For e-mobility, around 11% of total electricity consumption (1,200 kWh/yr) was used on average. The electrical battery storage contributes to a growth of the self-consumption.

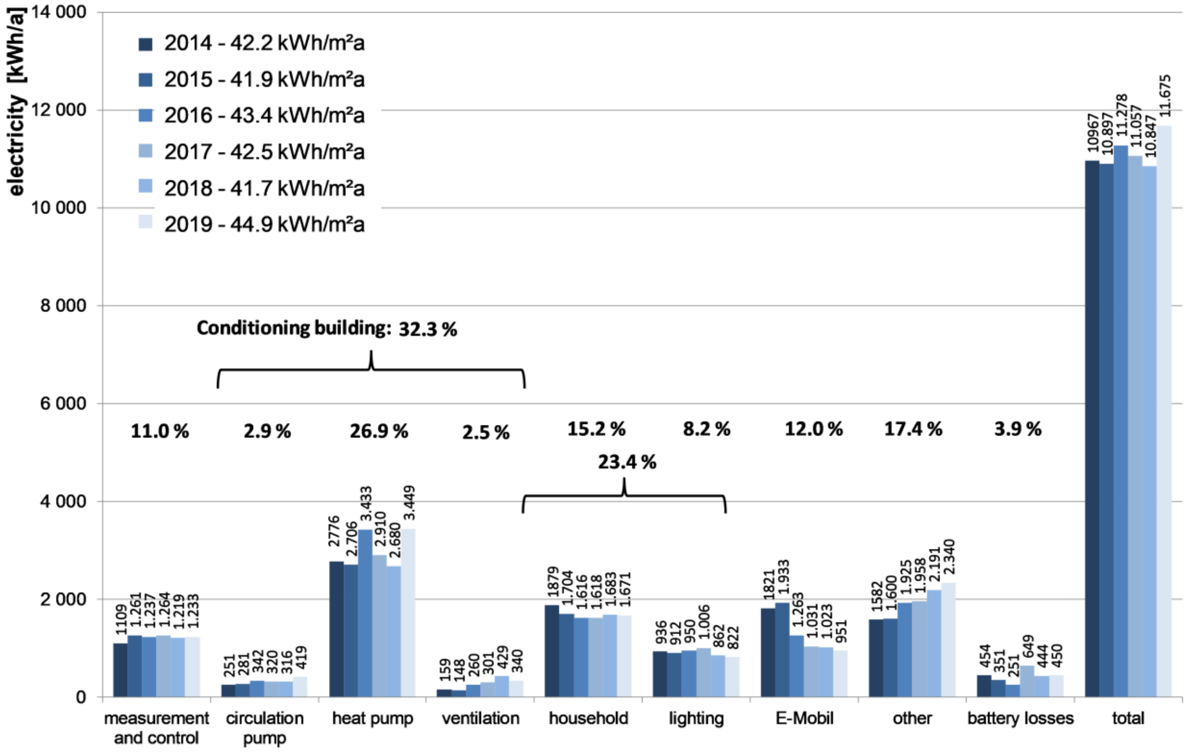


Figure 11: Electricity consumption by category, 2014 - 2019 (absolute and based on floor space)

Figure 12 shows the shares of electricity for the heat pump and household. The total annual electricity consumption is about 30.6 kWh/(m²yr) (7,970 kWh/yr). The heat pump accounts for approx. 38%, household for approx. 62% of the annual energy consumption. The area-related electricity consumption in the operating years of 2014-2019 ranges from 27 to 34 kWh/(m²yr). Between 7,200 and 8,900 kWh/yr of electricity are consumed.

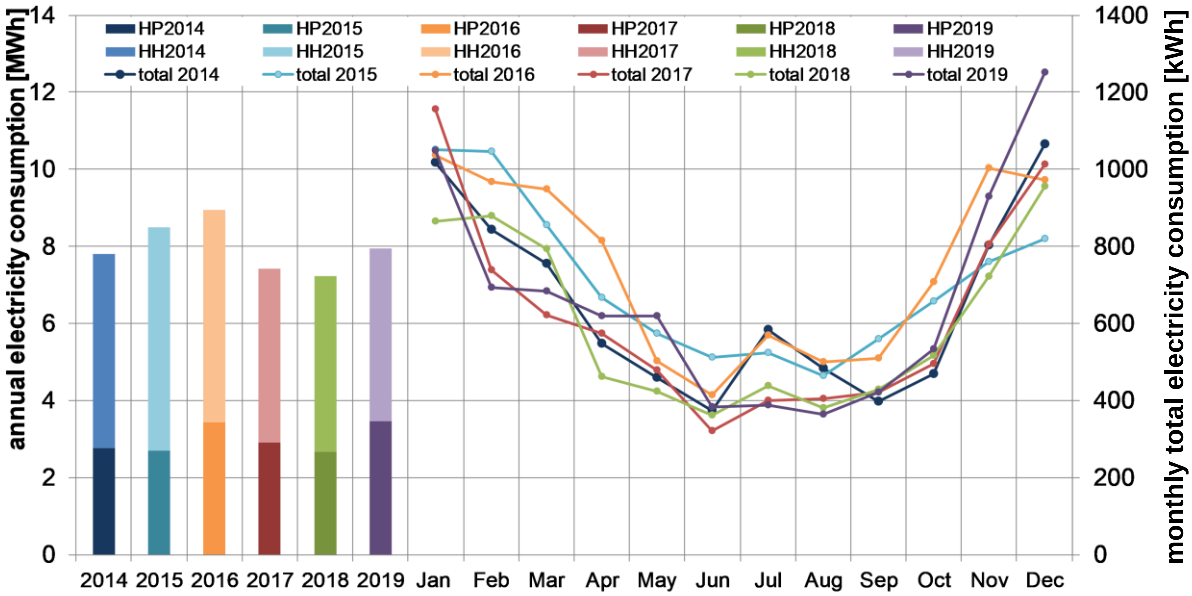


Figure 12: Monthly and annual electricity consumption – heat pump and household, 2014 - 2019

2.2.5.4 Heat balance

Figure 13 shows the shares for heating and DHW for the six years of operation until 2019. The proportions are broken down into heat transfer for space heating and domestic hot water. The annual energy consumption (heating, DHW) is ca. 50 kWh/(m^2yr) (1,290 kWh/yr) The room heating accounts for approx. 85%, DHW, storage and distribution losses for approx. 15% of the annual energy consumption. The area-related heating energy consumption in the operating years of 2014 to 2019 ranges from 41 to 58 kWh/(m^2yr). The generated heat is between 10,700 and 15,100 kWh/yr.

Therefore, the share for domestic hot water production is well below the energy efficiency requirement of 12.5 kWh/(m^2_{NGF}yr) required by the EnEV, which in the example of the single family house Berghalde is due to the ratio of residents to the effective floor area.

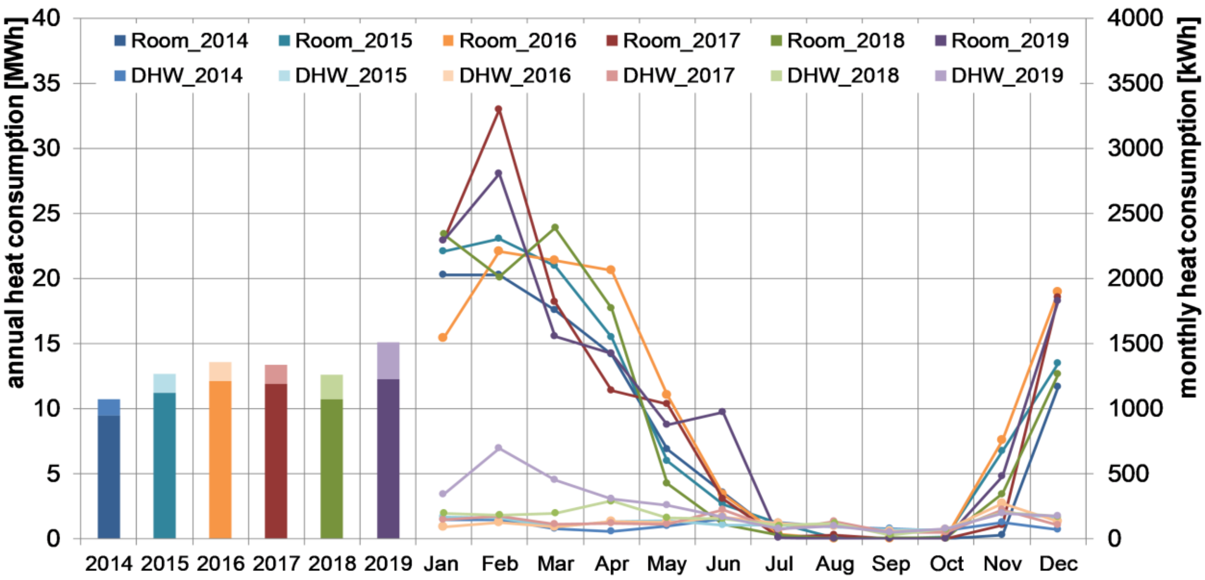


Figure 13: Annual and monthly heat consumption divided into domestic hot water and space heating, 2014 to 2019

2.2.5.5 Seasonal Performance Factor (SPF)

During the summer months, the heat pump is used exclusively for hot water. During this time, it only runs with short operating times, but at a relatively high temperature level.

Although this operating condition is less energy efficient for the heat pump than the heating operation, yet seasonal performance factor of up to 4.5 can be achieved as shown in Figure 14.

During the heating season the performance factor rose up to 6.0 in the years under review. The seasonal performance factor ranged from 4.7 to 5.1 in the past six years.
The heat pump is the largest single consumer in the "all electric" concept. An adjustment of generation and consumption therefore offers the largest opportunity to increase the share of own electricity consumption. In order to use as much as possible the proportion of the PV yield on-site and thus contribute to increasing the use of own electricity, the runtime of the heat pump is increased by implementing coordinated control strategies. The buffer storage tank is run to an upper temperature level of 60 °C in control operation to ensure DHW heating in the instantaneous heating mode. The flow temperature of the underfloor heating system is outdoor temperature-controlled and reaches a maximum of 35 °C at -20 °C outdoor temperature.

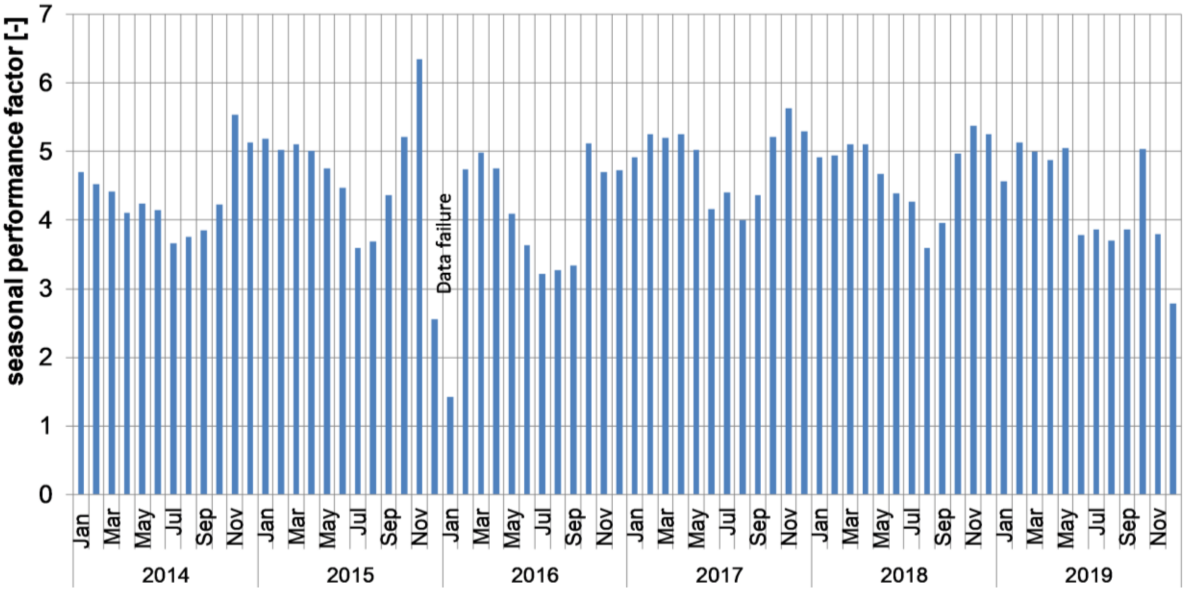


Figure 14: Monthly performance factor, 2014 to 2019

2.3 Twin houses Borås and Varberg, SE

The study is based on the evaluation of two different heat pump systems in two almost identical nZEBs in Sweden. One of the heat pump systems consists of an on/off controlled heat pump with an extra storage tank (see Figure 16) and the other nZEB has a heating system with an inverter controlled heat pump. The two houses are depicted in Figure 15. More information about the houses and their heating systems is also found in Table 10.

Figure 15: Twin houses, i.e. two almost identical nZEB buildings with same building envelope, but different heat pump system installed

The scope of this study was to:

- increase the knowledge of how different operating parameters are affected by the type of control (inverter-controlled compared with on-off), the different types of distribution system, to thereby provide data on how well the energy label correspond to reality for a heat pump in a nZEB building
- increase the knowledge of how the interconnection of a tank affects the operating parameters of a heat pump system, in order to obtain data for guiding how heat pump systems can be developed for future smart grids and use of electricity produced on-site (since the latter is important for nZEB definitions in several countries)
- Present life cycle cost comparisons of existing and newly developed heating systems for nZEB buildings in a Nordic climate

Table 5: Technical information about the two different nZEBs and their heating systems evaluated in this study

Place	Borås	Varberg
Size	• 166 m^2, 22 kWh/m^2/yr (projected space heating and DHW demand)	• 166 m^2, 20 kWh/m^2/yr (projected space heating and DHW demand)
Ventilation	• Balanced ventilation system with heat recovery	• Balanced ventilation system with heat recovery
Heating source	• Ground source heat pump (4.5 kW, on/off controlled) • Storage tank 150 L • Borehole 90 m (81 m active) • Dimensioning temperature: 0 °C	• Ground source heat pump (6 kW, inverter controlled) • Borehole 90 m (71 m active) • Dimensioning temperature: 0 °C
Heating system[a]	• Floor heating on upper and 1st floors • Dimension temperature: 36 °C at dimensioning outdoor winter temperature	• Low temperature radiators, upper floor • Floor heating, 1st floor
Solar	• PV-panels 3000 kWh/yr	• PV-panels 3000 kWh/yr
Habitants	• Simulated family	• Real family

[a]Controlled by an outdoor sensor and selected heating curves

2.3.1 Measurement Plan and Equipment

Operating parameters such as heating water temperatures, brine temperatures, heating water flow, electric power and outdoor air temperature were analysed in real operation in the two different nZEBs. Sensor type used for each parameter and the estimated expanded measurements uncertainty for the corresponding parameter (including sensor accuracy, sensor mounting, sensor stability, etc.) is listed in Table 6 below, together with expanded uncertainties for calculated parameters.

The results from the two systems were compared to see differences and similarities of the systems with an inverter controlled heat pump and a system with on/off controlled heat pump. The relevant measurement equipment is shown in Figure 16 including schematic representation of placement of flow meters and temperature sensors. This study presents data evaluated over measurement periods of a year, but also presents some examples of specific time events (from hours to days) to show upon cases where the differences of the systems become clear.

Table 6: Technical information about the different measurement parameters

Parameter	Sensor type	Measurement uncertainty
Supply temperature, heat pump to tank, $t_{w,hp\text{-}tank}$	Pt100[a]	±0.5K
Return temperature, tank to heat pump, $t_{w,tank\text{-}hp}$	Pt100[a]	±0.5K
Supply temperature to heating system, $t_{w,s,hs}$	Pt100[a]	±0.5K
Return temperature from heating system, $t_{w,r,hs}$	Pt100[a]	±0.5K
Brine temperature out from heat pump, $t_{b,out}$	Pt100[b]	±0.5K/±1.0K
Brine temperature in to heat pump, $t_{b,in}$	Pt100[b]	±0.5K/±1.0K
Heating water flow rate, heating system, q_{hs}	Armatec AT7500C	±1%
Electric power used by heat pump system, P_{hps}	Velleman EMDIN03	<±4%
Outdoor temperature, $t_{outdoor}$	Pt100	±1.0K
Specific heat, c_p	Tabulated value	<±0.5%
Density, ρ	Tabluated values	<±0.1%
Cold water temperature $t_{w,DHW,c}$	Pt500	±0.5K
Hot water temperature $t_{w,DHW,h}$	Pt500	±0.5K
Domestic hot water flow, q_{DHW}	Armatec AT7080	±1%
Heat losses, water tanks, Q_{losses}	Estimated value	±20%

[a]The Pt100 sensors were placed in thermowells to obtain lowest possible measurement uncertainty
[b] In the research villa in Borås there were both sensors placed in thermowells as well as surface mounted sensors. In the villa in Varberg, there were only surface mounted sensors.

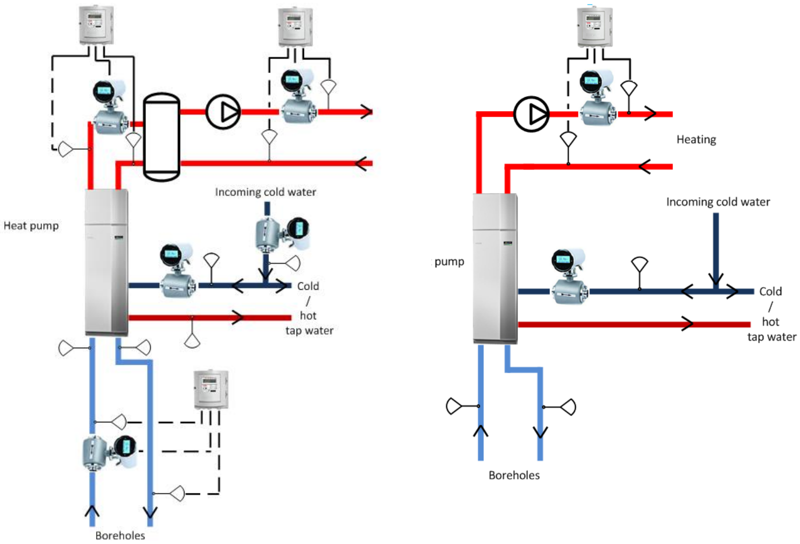


Figure 16: Schematics of the measurement equipment in the two heating systems with an on/off heat pump and an extra storage tank (left, Borås) and with the inverter controlled heat pump is shown (right, Varberg).

For the heating system with the on/off heat pump the supply temperature to the tank was also compared to the supply temperature out to the floor heating system to evaluate the efficiency impact of an extra storage tank and the on-off operation.
The evaluation done in this study is based on measurements performed from May 2015 to the April 2016 for the research villa in Borås and from March 2016 to February 2017 for the villa in Varberg. The reason for differing evaluation periods is that the houses were completed at different times. Even though the houses are identical in many ways, there are differing circumstances. First of all, the Varberg villa is placed in a somewhat milder climate. The yearly average climate is 8.0 °C compared to 6.6 °C in Borås according to SVEBY (2017).

But the largest difference is that there is a real family living in the Varberg villa, while it is a simulated one in the research villa in Borås. During the evaluated periods this has resulted in large differences in ventilation air flow (by choice) and use of domestic hot water. Nevertheless, since the heating systems have many similarities the study still offers many interesting comparisons.

2.3.2 Results and Discussion

In Figure 17 the heating demand for space heating and domestic hot water is shown together with the electric power consumption for the two houses. Also the average "SCOP" per month is shown. SCOP (system COP) is calculated according to equation 1 below.

$$SCOP = \frac{\sum\left(\left(t_{w,s,hs}-t_{w,r,hs}\right)\cdot q_{hs}\cdot c_p\cdot \rho+\left(t_{w,DHW,h}-t_{w,DHW,c}\right)\cdot q_{DHW}\cdot c_p\cdot \rho\right)+Q_{losses}}{\sum P_{hps}} \quad (1)$$

As can be seen the SCOP is relatively stable throughout the heating season in both nZEB houses (Figure 17) and is only lower during the summer months when the heating demand is very low. The bars for DHW energy include the losses from the DHW tank, Q_{losses} during the months with heating demand and for those months the losses have been included in the SCOP. However, during the months with very low heating demand (May-August), the losses have not been included in the SCOP, since they have been considered as not useful (and for those months they are neither included in the bars for DHW energy). The domestic hot water use varies over the year in the Varberg house, but only moderately. In the research villa in Borås the domestic hot water consumption is very low (almost only losses). Q_{losses} is not measured, due to difficulties in installing sensors for that, but is instead based on manufacturer data. It constitutes 5-10% of the total, so even if the uncertainty for the value itself is high, it has small effect on the overall uncertainty.

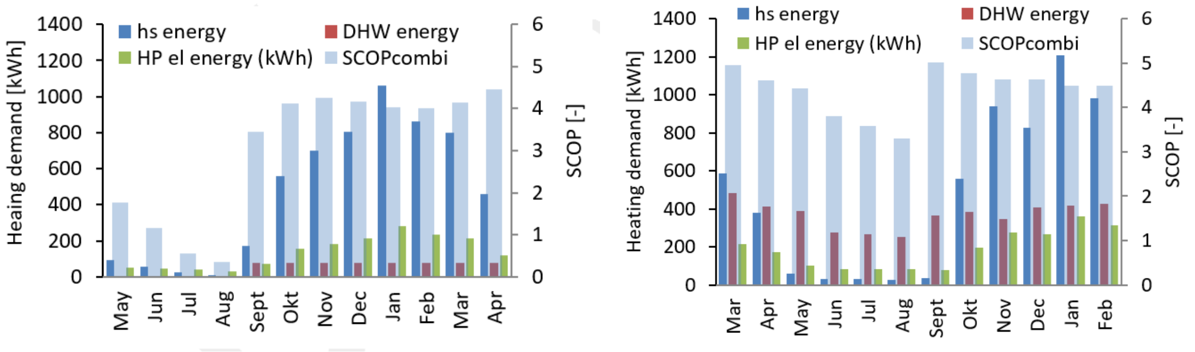


Figure 17: Measured heating demand and electric power (left axis) and average SCOP per month (right axis) for combined operation in the research villa in Borås (left) and in the villa in Varberg (right). The electricity to the heating system water pump is not included.

In Figure 18 the space heating demand is plotted versus outdoor temperature (the measurement interval is 5 minutes and all values have been backwards averaged for a 24 hour period to reduce the scatter in the graph. As can be seen there were no days that are as cold as the coldest hours of the cold climate defined in EN14825, -22 ˚C during the evaluation periods. The heat demand scatter is relatively large in the Borås villa. However, in the Varberg villa, where a real family is living in the house, the scatter is much larger. The data points that spread the most are probably a result of adjustments in heating settings made by the family. What also can be seen is that the space heating demand is larger in the Varberg villa compared to the Borås villa, it varies around 55 kWh/day compared to 35 kWh/day at an outdoor temperature of 0 ˚C, which is due to a higher ventilation air flow (compared to what is stated as minimum constant value in the building regulations) was selected by the family living in the house (observed by monitoring of the fan power). The space heating demand approaches zero around an outdoor temperature of 14˚C, which is lower compared to the standard EN14825 which assumes heating demand up to 16˚C, which is the calculation standard that the ecodesign and energy labelling regulations are based on.

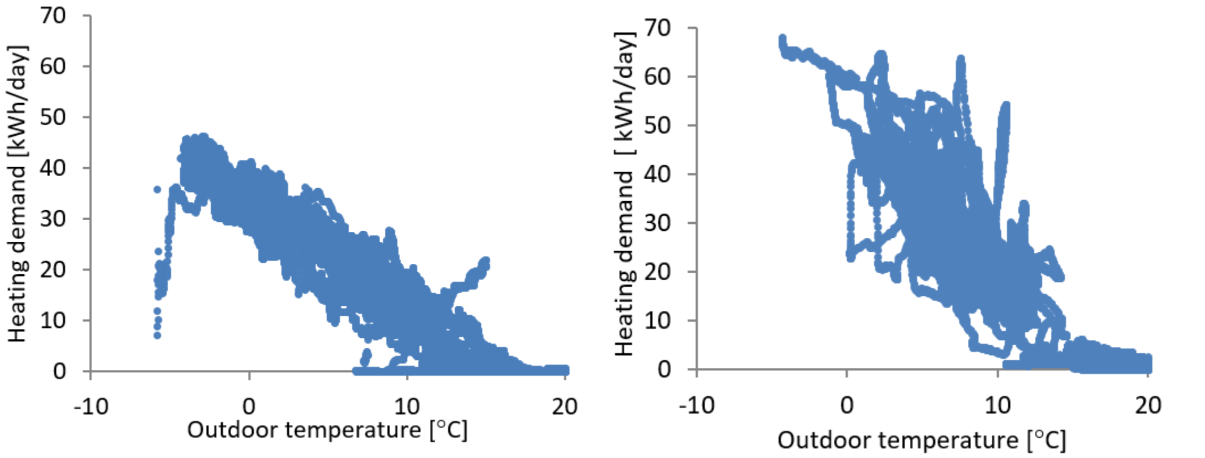


Figure 18: Space heating demand for the research villa in Borås (left) and in the villa in Varberg (right) as a function of outdoor temperature.

In Figure 19 the supply water temperatures for the two houses are displayed as a function of outdoor temperature. In the left graph there are two sets of values. The upper one is the temperature of the water that is flowing from the heat pump to the tank (see Figure 16 for schematic drawing) and the lower set of values are the temperature of the water from the tank out to the (floor heating) system. This is partly due to the on-off operation of the heat pump, which forces the heat pump to operate at a higher temperature during its on-periods to compensate for that there is no temperature-lift at all during its off periods (see also Figure 20). In addition, it is partly due to some extent of mixing in and losses from the tank. In the inverter controlled heat pump system there is no tank and hence only one set of values is shown. The large temperature deviation between the two villas is because different heating systems are used in the houses. In the Borås villa floor heating is used on both floors and in the Varberg villa radiators are used on the upper floor which need a higher supply temperature. The lines in the graphs represent the heating curves in EN 14825. In the Borås house with the on/off controlled heat pump the supply temperature to the heating system coincides well with the EN 14825 heating curve for a cold climate and a low temperature application. In the standard there is an equation correcting for that the heat pump work at a higher supply temperature during the on-periods, so performance data are taken from these higher temperatures when SCOP is calculated, which seems to be adequate according the measurements. In the Varberg house with the inverter controlled heat pump the heating curve coincides with the EN 14825 heating curve for a cold climate and a medium temperature application for the colder part of the measurement period (except for some scatter), but is higher at the higher outdoor temperatures measured values are higher. The reason is probably that the heat pump system has a variable liquid flow operation and lowers the flow rate at lower capacity and the heating curve of the standard assumes constant liquid flow.

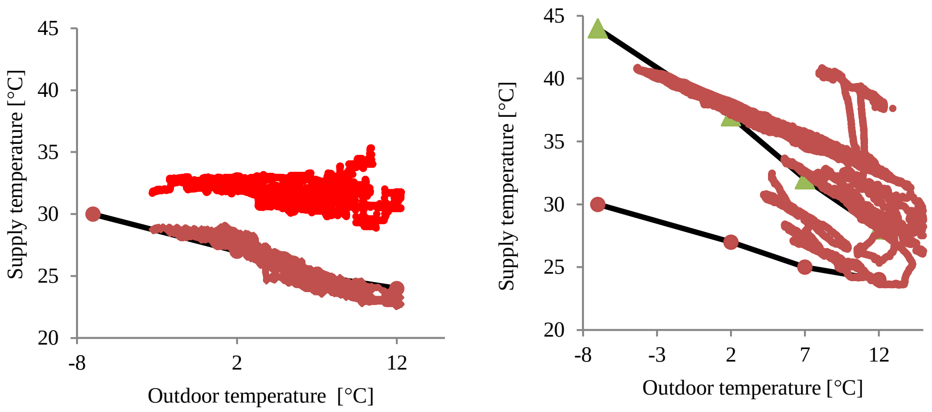


Figure 19: Heating curves, i.e. supply temperatures (to heating system and to space heating water tank) for the research villa in Borås (left) and the supply temperature to the heating system in the villa in Varberg (right) as a function of outdoor temperature. Also heating curves as described in EN 14825 at cold climate and low and medium temperature application is shown.

Figure 20 shows the on-off operation in detail for one operation cycle. As can be seen the supply temperature from the heat pump to the tank is somewhat higher than the temperature of the water that is leaving the tank to the heating system. The difference is shown in detail by the green dotted line and the average difference is 1.2 K. The fluctuations in the difference coincide with fluctuations in the return temperature from the heating system, which probably in turn is caused by closing and opening of the room thermostat valves. During the complete cycle, the average temperature to the heating system was 28.8 °C while the average temperature from the heat pump to the tank was 31.9 °C, which means that the heat pump has to work at 3.1 K higher temperature compared to what is delivered to the heating system.

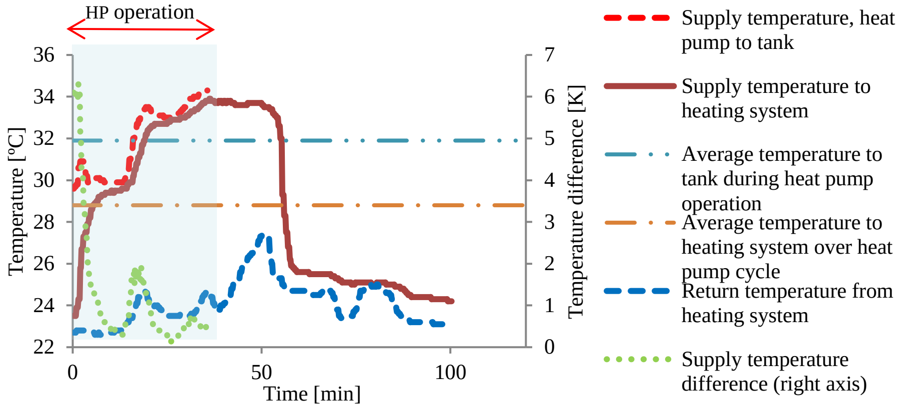


Figure 20: Supply (and return) temperatures to the tank and to the heating system during an on-off cycle in the research villa in Borås (left) during a period with an outdoor temperature of 2°C.

Figure 21 below shows two on-off cycles. The measured temperatures from the heat pump and from the tank, measured every 5 minutes, is displayed together with the inlet brine temperature to the heat pump. In addition, the instantaneous measured COP value, the "Carnot" COP and the ratio between those two COP values are shown. As can be seen, the measured COP seems to be instantaneously related to the temperatures of the outgoing heating water and incoming brine. Therefore, it would be beneficial for the efficiency of the heat pump system if the variations of the temperatures of the flows could be dampened. This proves that the heat pump and the heating system should be optimized together and not separately, which often is the case today.

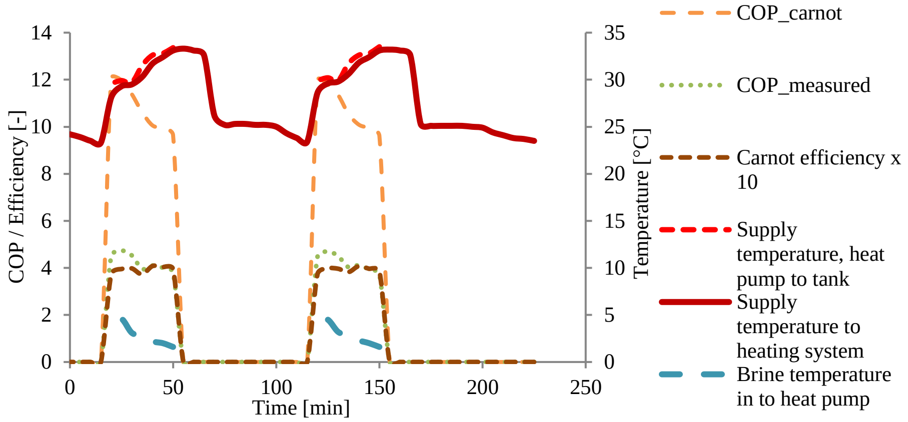


Figure 21: Supply temperatures to the tank and to the heating system, brine inlet temperature to the heat pump (right axis) and different Coefficients of Performance (COP) and the ratio of these during on-off cycles (left axis) in the research villa in Borås during a period with an outdoor temperature of 2.5°C.

Figure 22 below shows the measured inlet brine temperature to the heat pump in the Varberg house during one year (the measurement interval is 15 minutes and all values have been backwards averaged for a 24 hour period to reduce the scatter in the graph. The same applies for Figure 23. In EN 14825 heat pumps are tested at an inlet temperature of 0 °C and as can be seen, so low temperature was never measured during the whole year. The consequence of this is that the efficiency displayed on the energy label is underestimated.

In the Borås house, the brine temperature was only measured during the last part of the evaluation period and in Figure 23 a comparison is made.

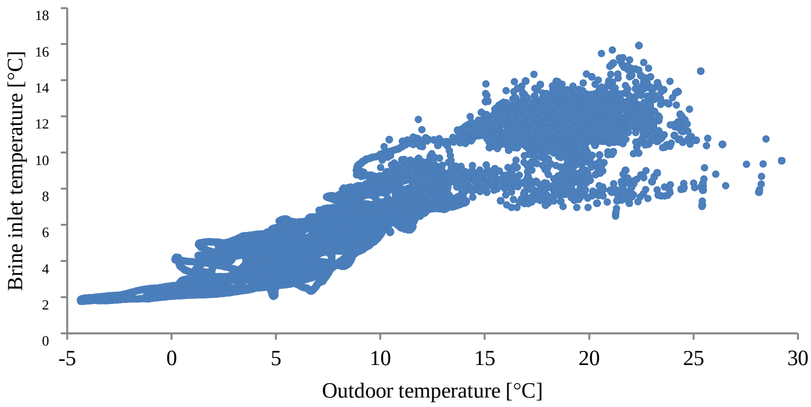


Figure 22: Brine inlet temperatures during on-periods of the operation cycle in the villa in Varberg as a function of outdoor temperature. Data from March 2016 to February 2017.

Since the heating demand of the houses differed the inlet brine temperature is plotted versus electric power input to the heat pump. The on-off system has approximately 1 K lower brine temperature than the other system. Considering that the borehole with the on-off heat pump has been in operation for one more heating season, this difference can be considered as small.

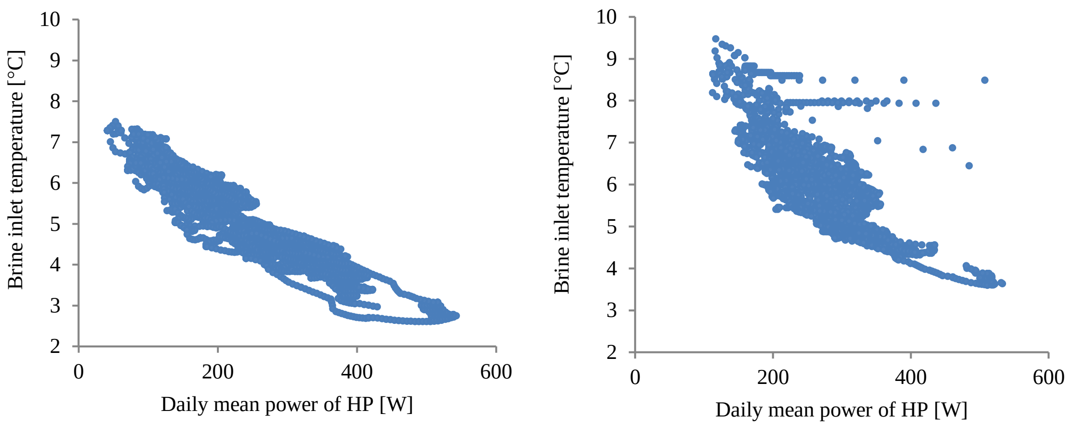


Figure 23: Brine inlet temperatures during on-periods of the operation cycle in the research villa in Borås (left) and in the villa in Varberg (right) as a function of daily mean power input to the heat pump. Data from 15th of February 2016 to 4th of May 2016.

2.3.3 Present value analysis of different heat generators for nZEB

The TMF program (2017) is a software tool developed by RISE Research Institutes of Sweden and is used to calculate the energy use of single-family and multi-family buildings based on the Swedish building regulations (BBR and BEN) by the National Board of Housing, Building and Planning in Sweden. In this study the software was used to evaluate the energy use of different heat generator solutions possible for an nZEB present on the Swedish market. These different systems are presented in Table 7.

In Sweden, an exhaust air heat pump is a common solution in new built single-family houses today. This heating solution requires an exhaust air system for the ventilation and therefore the other heat pump system solutions have also been compared with such ventilation system. Please note that heat pumps in combination with underfloor heating and an exhaust air ventilation system is a very common solution in Sweden in new built houses that have been practiced since the 90s. It offers a good indoor comfort and air quality.

In the case of the Mechanical Ventilation Heat Recovery (MVHR), the performance of a rotary heat exchanger was used in the calculations, with an efficiency of 82% with respect to the supply air at the standard point +7/+20 °C according to EN 13141-7 (2011). The efficiency is assumed to drop to 78.6% at the design outdoor temperature of -13.6 °C.

Table 7: Heating systems that are analysed with the TMF-simulation software.

Abbreviation	Description
AWHP+EAV	Outside air-to-water heat pump with exhaust ventilation
AWHP+HRV	Outside air-to-water heat pump with heat recovery ventilation
GWHP+EAV	Ground-source heat pump with exhaust ventilation
GWHP+ MVHR	Ground-source heat pump with mechanical ventilation heat recovery
GWHP+MVHR+PV	Ground-source heat pump with mechanical ventilation heat recovery + 3 kW (3000 kWh/year) solar photovoltaic electrical system
EAHP	Exhaust air-to-water heat pump
EAHP+PV	Exhaust air-to-water heat pump + 3 kW (3000 kWh/year) solar photovoltaic electrical system
E+ MVHR	Electrical boiler with mechanical ventilation heat recovery
E+TS+ MVHR	Electrical boiler including thermal solar and additional storage system + mechanical ventilation heat recovery
DH+ MVHR	District heating with mechanical ventilation heat recovery

Heat pump systems are well suited for combination with a solar PV-system. Therefore, a solar PV system has been added to the ground-source heat pump (with HRV) and the exhaust air heat pump system as an example. This could of course be combined with the other systems, as well, with similar results. In order to be able to include the contributions from the PV-panels the electricity use of household appliances is included in the comparison.

Table 8: Assumed input data for calculation of present value.

Investments: (during the calculation period)	Purchasing costs (EUR)	Installation costs (EUR)	Maintenance costs (EUR/yr)	Estimated lifetime (yr)
Exhaust air fan	279	186	18.6	15
Exhaust air duct system	1116	744	18.6	30
MVHR - air handling unit	1860	465	93	15
MVHR - duct system	2790	1860	27.9	30
Electric boiler	2511	744	18.6	25
Electric boiler with ST/storage	4371	1674	37.2	25
Outdoor A/W HP, outdoor unit	4185	465	55.8	10
Outdoor A/W HP, indoor unit	3255	930	37.2	20
GS heat pump	5859	1116	46.5	15
Borehole 100 m for GS HP	3255	465	0	60
Geothermal borehole 70 m	2325	465	0	60
Exhaust Air HP, excl. compressor	5394	744	46.5	15
Inverter controlled compressor	930	372	0	7.5
District heating unit	1395	930	18.6	25
PV solar panels	1860	930	0	30
DC-AC inverter	930	465	0	15

* exchange rate SEK to EUR of 2019-11-13 which was 10 SEK=0,93 EUR=1,0 USD

The present value is the estimated value of an investment's future cash flow, or in this case, savings relative to another alternative, discounted with a given interest rate. In this study the present value of the different system solutions has been calculated using the EU-level regulations and guidelines recommended to meet the requirements of the EPBD (2018). The reference is a system with an electric boiler in combination with an MVHR-system, since this is the system with the lowest investment but the highest operating cost on the Swedish market.

The assumptions, i.e. input data, used in the calculations are given in Table 8 and Table 9 below.

Table 9: Assumed data for calculation of present value.

Explanation	Value	Unit
Discount rate (excl. inflation)	4	% per year
Increase energy price, electricity	3	% per year *
Increase energy price, district heat	2	% per year *
Calculation period	30	year
Initial price, electricity (bought) (Sweden)	0.126	EUR per kWh **
Initial price, electricity (bought) (Europe)	0.186	EUR per kWh **
Initial price, electricity (sold)	0.088	EUR per kWh **
Initial price, district heat	0.08	EUR per kWh **
Initial flat rate price, district heat	186	EUR per year **

* Increase in energy price on top of inflation
** Including tax and service fees

These assumptions are based on openly available information, EN15459 (2007) and discussions with the project team where the group has agreed that these values are reasonable. For the PV-system, present conditions in Sweden regarding incentives and tax reduction for electricity sold have been adopted.

2.3.3.1 Energy use and LCC analysis of new types of heat pump systems

The results of the evaluation using the TMF program show that the system solution that is the most energy efficient is the one consisting of an inverter-controlled ground-source heat pump and a balanced (exhaust and supply air) ventilation system with heat recovery, see Figure 24. All the systems including a heat pump have somewhat similar energy use, the difference from the most efficient to the least efficient is approximately 1300 kWh/yr representing a difference of 17%. The difference to the systems with an electric boiler and district heat is much larger (up to 5500 kWh/yr).

Figure 25 shows the results for the present value calculations for the different heating and ventilation solutions for the research villa in Borås with a 0.126 EUR/kWh electricity rate that is a common price in Sweden. Note that the solution that has the highest present value is the investment that is most economically profitable from a life cycle perspective. Since the solution with an electric boiler in combination with HRV is the reference case, it receives a present value equal to zero. The exhaust air heat pump (EAHP) has the highest present value, closely followed by a system with a ground-source heat pump in combination with exhaust ventilation (i.e. without heat recovery).

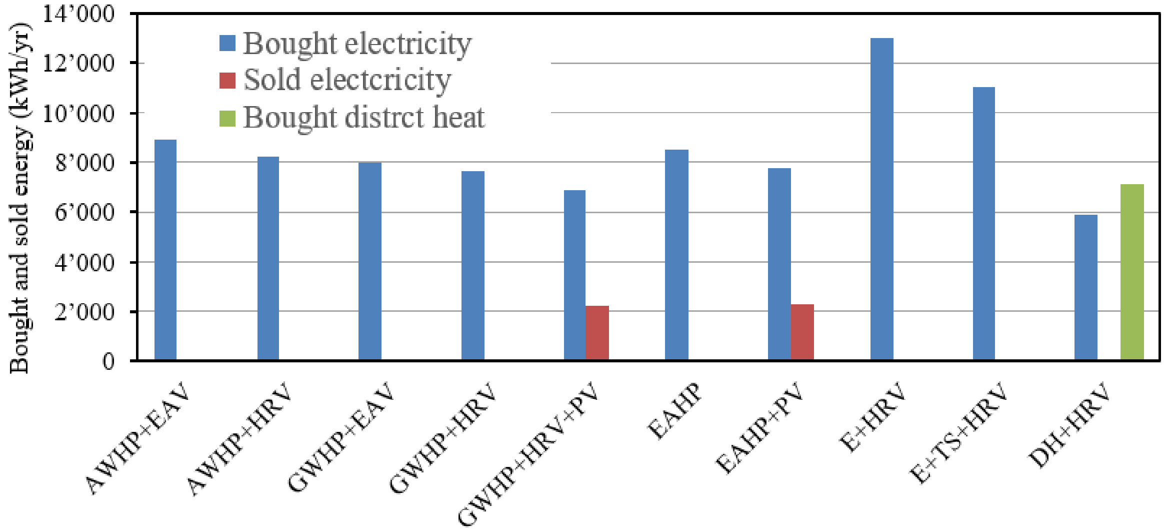


Figure 24: Result of TMF software of bought and sold energy for different heating and ventilation system solutions. Electricity for household appliances is included. See Table 7 for description of the different cases

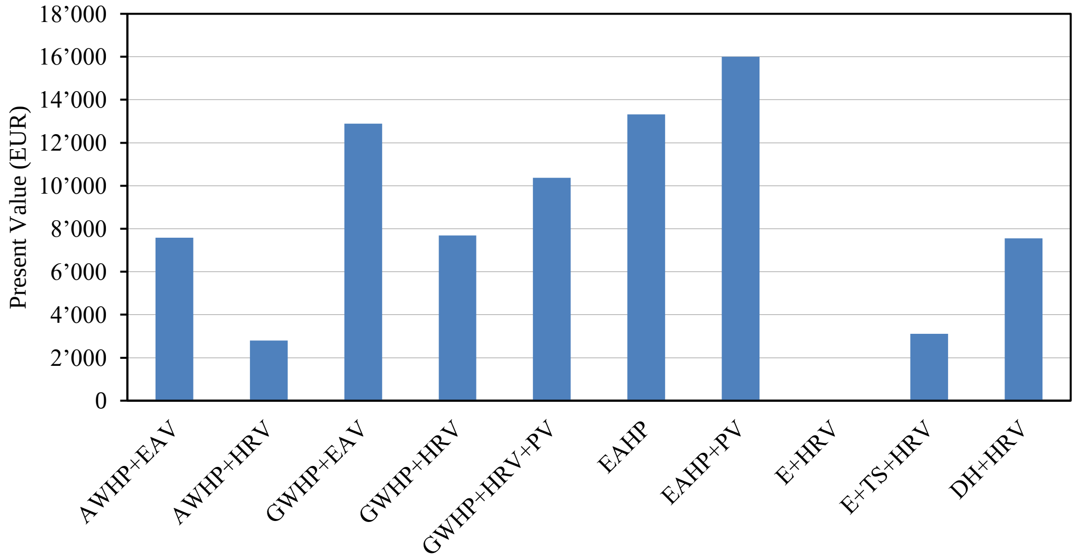


Figure 25: Present value of the different heating and ventilation system solutions. Note that a high present value is preferable to a low present value. Electricity price (bought) of 0.126 EUR/kWh.

Figure 25 shows that it is more energy efficient to combine the ground source heat pump with an MVHR, but under the conditions adopted here it is not economically profitable.

The calculations show that it is profitable to add a PV-system to the ground source heat pump system with MVHR and to the exhaust air heat pump (EAHP+PV). It would also be profitable to add a PV-system for the other heat pump system solutions. The results for the PV-system are valid provided that the conditions that apply in Sweden today regarding investment grants and tax reductions for electricity sold continue to apply, which of course is not certain.

The results show that a ground-source heat pump is always more profitable from a life cycle perspective compared to an outdoor air-to-water heat pump, even though the former has a higher investment cost. One reason is a lower cost for the ground-source heat pump in future replacement, due to the boreholes longer life expectancy compared to the heat pump itself. However, an outside air-to-water heat pump is a good alternative in cases where it is not possible or desirable to drill.

Figure 26 shows the results for the present value calculations for the different heating and ventilation systems for the research villa in Borås with an electricity rate of 0.0186 Eur/kWh.

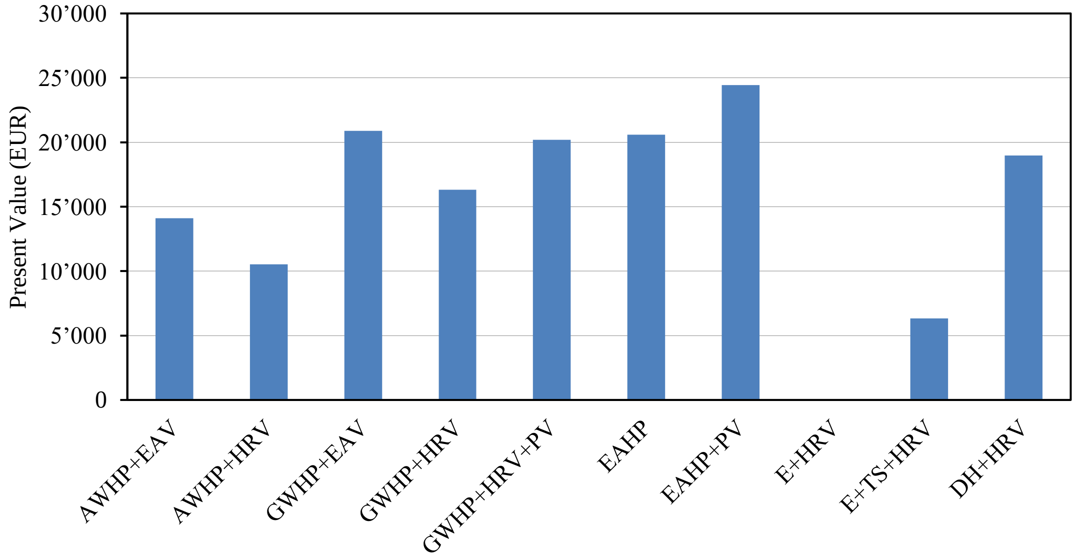


Figure 26: Present value of the different heating and ventilation system solutions. Note that a high present value is preferable to a low present value. Electricity price (bought) of 0.0186 EUR/kWh

Since all the systems investigated require less bought electricity than the reference case, the present value of all systems is higher with an increased electricity price.
Also the difference between the different systems is somewhat less. Another effect is that the most energy efficient system with a ground source heat pump with HRV and PV get a similar present value as the system with ground source heat pump and EAV and the system with an exhaust air heat pump. Hence, the HRV system also require a PV system to be economically profitable. However, the system with an exhaust air heat pump and PV is the most profitable solution also with a higher electricity price.

2.3.4 Conclusions

The conclusions from the field measurements are the following:

- The standard EN 14825, and the models based on it, predict relatively well the performance of the heat pump system. It is quite conservative in terms of the brine temperature and assumes a relatively low temperature.
- The standard EN 14825, do not fully manage the combination of a speed-controlled compressor and circulation pump, especially not at lower heat capacity.
- On-off control and a tank in the system results in higher working temperatures for the heat pump compared to variable capacity control which must be accounted for when calculating projected use of energy, especially in “oversized” heat pumps in houses with low energy demand.
- It is very important that the system is installed and controlled correctly to get the best possible performance. The measurements resulted in several observations that indicate that the heat pump systems do not always work optimally together with the heat distribution system. The heat pump and the heating system should be optimized together for best overall efficiency

The conclusions that can be drawn from the present value calculations are:

- In RISE’s research villa in Borås the most profitable heating and ventilation system based on the life cycle cost is an inverter-controlled exhaust air heat pump combined with a PV-system. This is true for both a “Swedish electricity price” and for a higher “European electricity price”.
- For a somewhat less well-insulated house than RISE's research villa, an inverter-controlled ground-source heat pump would likely be most profitable.
- The outdoor air-to-water heat pump does not get as high present value as the ground source heat pump, mainly due to its shorter assumed lifetime, but also partly due to its efficiency. However, it is a good alternative when it is not desirable or possible to drill.
- In combination with a heat pump system, the extra investment for an HRV does not pay off for a house that is as well insulated as the RISE research villa. However, it is the most energy efficient solutions and has other advantages.
- In case of a higher electricity price, the extra cost of a HRV system can be payed-off by installed PV-panels.

2.3.5 Discussion

The results indicate that an HRV (combined with a ground source heat pump) system is not favorable from an economic standpoint in comparison with an exhaust air ventilation. This could maybe be changed with a smaller heat pump with a lower investment cost. However, in this study the smallest heat pumps available on the market at the time of installation have been chosen in both cases. Nevertheless, an HRV provides other benefits than increased energy efficiency:

- It has a greater potential for flexibility in a smart electricity grid, since such a house has a higher heat inertia.
- An MVHR system provides a good opportunity for distribution of cooled air when the borehole is used for free cooling.
- It can ensure that all rooms are ventilated and enable efficient filtration of incoming outdoor air
- It can improve the thermal comfort in wintertime

The system with an exhaust air heat pump comes out very well when calculations are made for the research villa in Borås, which is a very well insulated house (average UA value of about 0.14 W/m^2). If calculations instead were made for a house with a less insulation or with a larger surface area, other system solutions would probably be more competitive. The reason for this is that ventilation air is a limited heat source.

The result from the present value calculation is sensitive to the electricity price. A higher yearly increase in electricity price reduces the importance of the initial cost of the system compared to energy costs. Thus, it becomes much more profitable to invest in a heat pump system. The difference between the different heat pump solutions also decreases with a higher electricity price.

2.4 Multi-family building Vögelebichl in Tyrol, AT

The case-study building was put into operation at the end of 2015. It consists of two building blocks: the north block has four floors and hosts sixteen flats; the south block is just three floors high and hosts ten flats. The roof of both buildings is covered by PV, but some area of the north block is used for solar thermal (ST) collectors. The technical room is in the north block and the distribution pipes to the south block run in the underground parking area (Ochs et al. 2014).

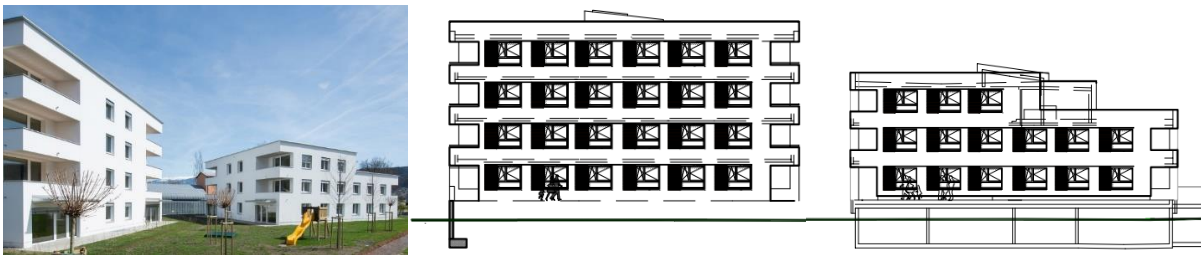


Figure 27: Views of the buildings (left north block, right south bock). Courtesy of Neue Heimat Tirol (NHT).

Table 10 reports most relevant data of the buildings, while Figure 27 shows a view of them.

Table 10: Most relevant building technology data

	North Building	**South Building**
Number of flats / heated surface [m^2]	16 / 1295.6	10 / 853.2
Design heating demand [kWh/(m^2a)] / design heat load [W/m^2]	11 /11	14 / 13
Infiltration rate (n_{50}) [1/h]	0.28	0.26
PV peak power [kW]	8.5	16
PV area / ST area [m^2]	52.5 / 73.6	99.8 / -

2.4.1 Building HVAC System

A simplified schematic of the HVAC system is shown in Figure 28. It consists of two parts: the hydronic system and the ventilation system. The ventilation units – one in the south and two in the north building – ensure hygienic air renewal, whereas the hydronic system provides space heating (SH) and DHW preparation. During the non-heating season, passive cooling is possible by transferring heat to the groundwater loop via a heat exchanger.

The hydronic system is composed of six hydraulic loops each of which provided with one or more hydraulic pumps. These are ST loop, condenser (CND) loop, desuperheater (DSH) loop, evaporator (EVP) loop, groundwater (GW) loop, DHW loop, and SH loop. All the loops but the EVP and GW loops, connect the BS with the other elements of the system, i.e. the ST panels and the HP.

The planning of the system was particularly focused on limiting the distribution losses, therefore the heating system is designed to work with very low flow temperature (below 30°C) and the pipes are highly insulated (insulation thickness equal to the pipe diameter; remark: original planning/recommendation considered insulation thickness equal to 2-fold or at least 1.5-fold of pipe diameter).

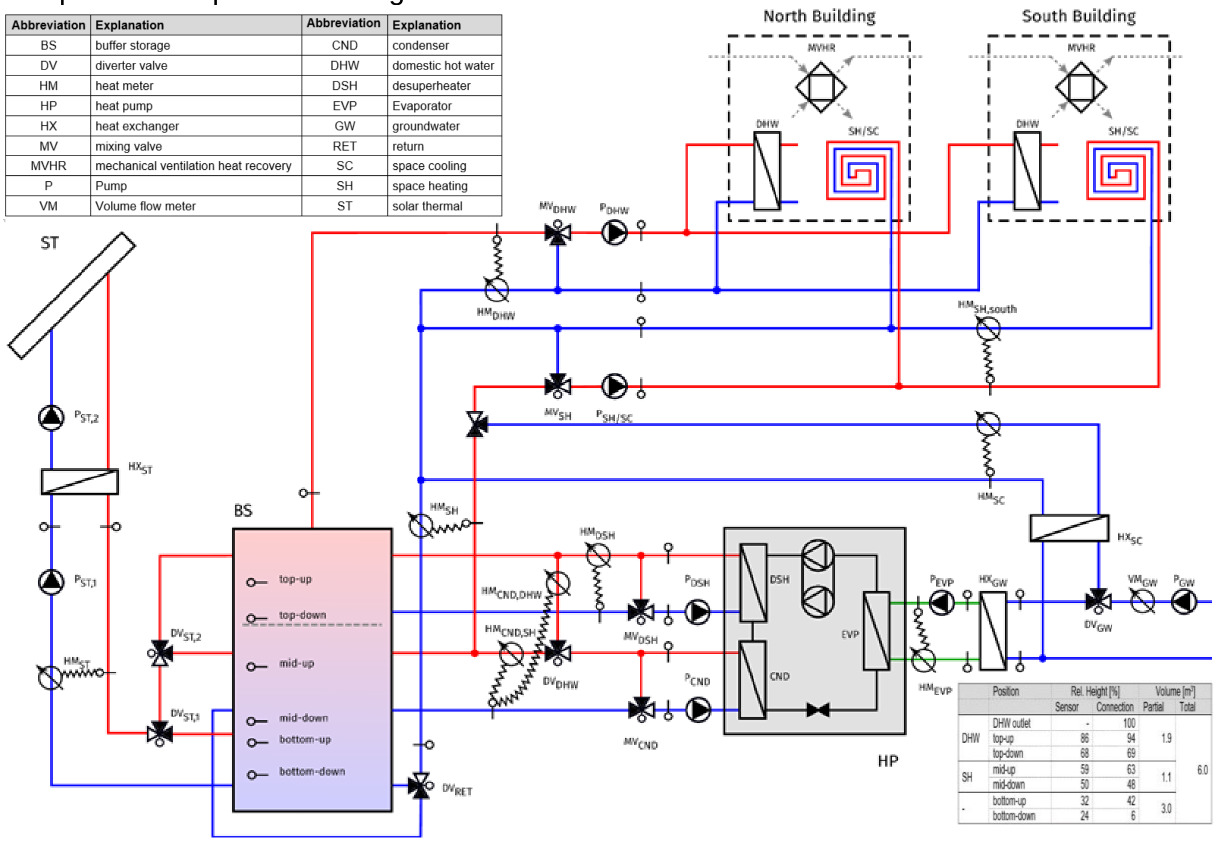
2.4.1.1 Ventilation System

The ventilation units (one for the south building and two for the north) are equipped with a heat-recovery heat exchanger with declared 81% recovery effectiveness. The heat exchanger is protected from frosting by receiving heated water from the hydronic loop in case via a brine cycle. The defrosting energy consumption accounts on average for 450 kWh/yr, which is less than 1% of the average annual total heating energy demand. It is noteworthy that due to the relatively high interior temperatures and moderate outside temperatures, the energy demand for frost protection is significantly lower than planned and the effort for frost protection does not seem to be justified.

2.4.1.2 Buffer Storage

The BS storages system-water for SH and DHW preparation and is charged by the heat pump and the solar thermal collectors.

This configuration is known as combi-storage (Haller et al., 2014) to highlight the combination of water at different useful temperature levels, saving the cost for additional storage.
Another advantage is that it stores system-water rather than drinking water – which is decentrally prepared in the flats with decentralized DHW heat-exchangers (so-called fresh water stations) – allowing for lower temperature levels and thus better HP and ST performances and without hygienic constraints, as Legionella is not an issue.
The total storage volume is 6 m^3 with a diameter of 1.6 m. The tank is insulated by 30 cm of mineral-wool with an average thermal transmittance of 0.15 W/(m^2K). Ideally, the storage tank can be seen as split into three volumes: the top part stores the water for DHW preparation, the middle is reserved for SH, and the bottom receives the colder return water and serves as an additional storage volume for the period of large ST contribution. The connections are located at the upper and lower end of each of these volumes.
Furthermore, the BS provides the housing for temperature sensors used to control the HP, as the following section explains. The position of the sensors also indicates the volume of each part. The table in Figure 28 reports the position as a percentage of the height of sensors and connections, together with the total and partial volumes. The reason for the top-up sensor being well below the corresponding outlet connection is to ensure a reserve volume at the very top to guarantee comfort conditions during DHW tapping. An overview of sensor and connection positions is provided in Figure 28.



Abbreviation	Explanation	Abbreviation	Explanation
BS	buffer storage	CND	condenser
DV	diverter valve	DHW	domestic hot water
HM	heat meter	DSH	desuperheater
HP	heat pump	EVP	Evaporator
HX	heat exchanger	GW	groundwater
MV	mixing valve	RET	return
MVHR	mechanical ventilation heat recovery	SC	space cooling
P	Pump	SH	space heating
VM	Volume flow meter	ST	solar thermal

	Position	Rel. Height [%]		Volume [m^3]	
		Sensor	Connection	Partial	Total
DHW	DHW outlet	-	100	1.9	6.0
	top-up	86	94		
	top-down	68	69		
SH	mid-up	59	63	1.1	
	mid-down	50	48		
-	bottom-up	32	42	3.0	
	bottom-down	24	6		

Figure 28: Hydronic system schematic with sensors. Note that the decentral, flat-wise DHW heat exchangers are represented by a single heat exchanger for sake of simplicity.

2.4.1.3 Heat Pump

As previously presented, the HP is double-staged – allowing it to work at two levels of power – and provided with an additional heat exchanger, i.e. the desuperheater (DSH). The purpose of the DSH is to deliver heat at a high-temperature level while not raising the condensation temperature, thus at higher energy performance. Specifically, it simultaneously delivers DHW while working in SH mode. In this configuration, the DSH is said to be connected in parallel to the CND. Therefore, there is no mixing between the two flows, except during DHW priority mode when both flows are directed to the top-most inlet of the storage and there mixed.

The HP is significantly oversized with respect to the predicted heating capacity – 58 kW of peak heating capacity in double-stage operation (W10/W35) with respect to 36 kW design heating capacity (Ochs et al., 2019).
Noteworthy is that the heating power predicted with the PHPP matches quite well with the monitored peak load, as it is reported in the Report Annex 49 part 3 on HP integration, design and control. Furthermore, the HP as sold by the manufacturer does not include a DSH, which was added by the contractor before installation. Monitoring and simulation results that follow in this report suggest that the DSH might be undersized and the refrigerant charge might be insufficient. However, before a final claim, further investigations are scheduled e.g., refrigerant cycle pressure measurement.
The characteristics of the HP theoretically allow several control options, as shown in the diagram developed by Monteleone (2019) presented in Figure 29. The control strategy distinguishes between two operating modes (SH and DHW) each of which leads to two options: a single compressor (stage 1) or both compressors (stage 2) running. For each stage operation, there is the option of whether to deliver heated water to the BS from the DSH by controlling the mixing valve. Figure 29 shows the optimal HP control as suggested by Monteleone (2019). This does not represent the actual situation, for which the DSH is on only in DHW priority mode, despite being the DSH purpose to provide DHW while the HP works in heating mode. It was therefore suggested to update the control setting with the one proposed by Monteleone (2019). Additionally, Monteleone (2019) suggested that in DHW mode the CND and the DSH should be hydraulically connected in series, rather than in parallel, which limits the rise in condensation temperature, thus improving the performance.

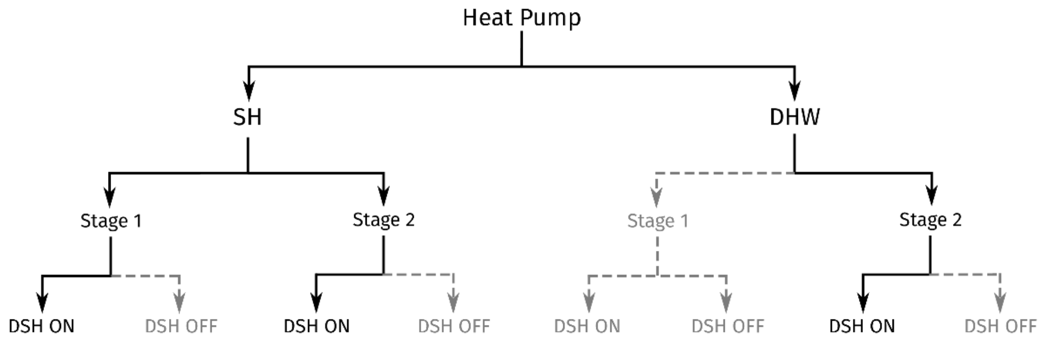


Figure 29: Heat pump (HP) control options (as presented by Monteleone, 2019). Gray dashed lines represent theoretically available control options, though not implemented.

The control signals are computed based on the temperature indicators of the BS: whenever the top-most sensor of each partial volume indicates a temperature lower than the supply set point, it sends the signal to start the HP, which turns OFF when the volume is loaded, i.e. when the bottom part has reached the set point temperature. DHW has always priority on heating and the HP is driven at full power (i.e. both compressors working). The second stage is sometimes started in heating mode to accelerate the BS loading based on a proportional-integral logic (Franzoi, 2020).
In the study by Monteleone (2019), a simulation model of this HP unit was realized and parametrized with monitoring data. It emerged that there is a significant mismatch between the power declared by the manufacturer and the measured on-site. Therefore, the monitoring of the refrigerant cycle is scheduled to identify the source of this difference.
Data regarding the HP are summarized in Table 11.

Table 11: Heat pump data at source temperature 5°C (B5), sink temperatures 35°C, 45°C and 55°C, and constant desuperheater (DSH) outlet temperature 55°C for both stages, as measured (Monteleone, 2019)

	Stage 1			**Stage 2**		
	B5/W35	**B5/W45**	**B5/W55**	**B5/W35**	**B5/W45**	**B5/W55**
Electric power [kW]	4.1	5.4	7.0	8.6	11.1	14.2
CND power [kW]	19.2	16.3	13.0	35.7	30.1	24.1
DSH power [kW]	1.1	2.9	4.8	2.9	6.2	10.0
COP [-]	5.0	3.5	2.6	4.5	3.3	2.4

2.4.1.4 Heating and Hot Water Distribution Loops

The flats are equipped with underfloor heating systems. Heated water is delivered to the flats by a variable speed pump that should regulate the mass flow to maintain a constant pressure drop. A mixing valve controls the flow temperature based on a heating curve varying between 30 °C for ambient temperature lower than -4 °C, to 22 °C for ambient temperature higher than 13 °C. The supply branch for SH stems from the CND supply branch to the BS. Consequently, SH could be delivered in three working conditions:

- directly by the HP because of balanced flow rates;
- directly by the HP, which also loads the BS as the SH flow rate is lower than the CND flow rate;
- from the BS when the HP is off.

As already said, DHW is prepared in the flats through freshwater heating stations. The loop is driven by a central variable speed pump controlled to keep the pressure drop in the loop constant. The heating station controls the flow rate through a thermostatic valve based on the tapping set point temperature. To guarantee a rapid response of the station, a minimum flow rate is expected. However, there is no evidence of that in the monitoring data.

2.4.1.5 Photovoltaic and Solar Thermal Panels

The on-site energy generation is ensured by the photovoltaic and solar thermal panels that cover both buildings' roofs.
The design of the system was the object of a study by Ochs et al. (2014), in which the optimal energetic share of PV and ST was determined for the north building's roof. The diagram in Figure 30 shows the trend of the difference between PV yield and HP and auxiliary electric energy consumption as a function of the ST collector area share. A maximum is achieved with a ST area share of about 30%. However, the actual share of PV and ST is different to what proposed in Ochs et al. (2014), in favour of larger roof surface dedicated to ST panels.
In the study, Ochs et al. (2014) highlighted also that, although small ST surface is favourable from the energetic point of view, the economic analysis suggests full PV panels coverage because of decreasing PV panels costs and consequent benefit also to the system complexity and maintenance effort. Since then the PV prices dropped significantly, while the prices for solar thermal plants are rather stagnating.

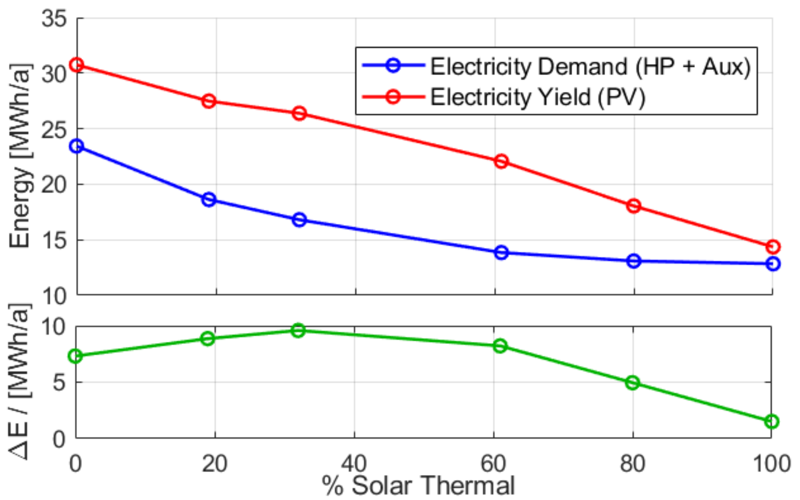


Figure 30: Electricity demand for heat pump and auxiliary energy and PV yield for both buildings relative to the solar thermal collector area on the north building's roof. The maximum difference between yield and demand (ΔE) is at about 30% corresponding to 50 m² as opposed to the actual 80 m² (Ochs et al. 2014)

2.4.2 Monitoring

The monitoring data analysis provided insight into the behaviour of the building and HVAC system, allowing for the identification of malfunctioning and suboptimal behaviours. The monitoring system's focus is the measurements of HVAC system performance, though also the south building thermal comfort is monitored.

Figure 28 shows a simplified representation of the position of the monitoring system sensors, which consist of 58 temperature sensors, 12 humidity sensors, 2 pressure sensors, 37 signals (e.g. controllers, valves, pumps, etc.), 22 heat meters (measuring energy, power, flow and return temperature, and volume flow), 7 electricity meters, and 2 volume flow meters. In the following subsections, four full years of monitored data are presented, with focus on 2018. These results are retrieved from the work in course of preparation by Dermentzis et al. titled "Lessons learned after four years of monitoring of two net-zero energy buildings in Austria".

2.4.2.1 Monitoring System Uncertainty Analysis

This section reports the monitoring system accuracy as estimated by Monteleone (2019) based on sensors' datasheets.

The volume flow is measured by an ultrasonic compact heat meter (HM) (i.e. *SHARKY 775* by *DIEHL Metering GmbH*) that measures also flow and return temperatures using platinum resistance temperature detectors (RTDs) (*Pt 100*). The sensor logs, other than temperatures and volume flow rate, also power, energy, and volume. Although the logging frequency could be as low as 12 s, the building management system stores average values every 15 min. Platinum RTDs are used also for logging flow and return temperatures with a logging frequency of 1 min. According to the energy meter datasheet, the relative uncertainty depends on the ratio measured-to-nominal volume flow, therefore, assuming correct sensor sizing, it could be estimated to be $\sigma_{\dot{v}}$ = ±1%. The accuracy of RTD conforms with class B of EN 60751 (2008), according to which the accuracy must vary with temperature and it is influenced by the length of connecting cables, therefore, given the monitoring temperature range (6 °C to 90 °C), the assumption of relative uncertainty of ±2% lies on the safe side. The electric power meter states in its datasheet an accuracy of ±1% and similarly to the HM, its data is logged every 15 min.

The uncertainty of indirectly measured quantities can be determined by applying the propagation of uncertainties neglecting correlations. The uncertainty of heat capacity and density is assumed to equal to temperature uncertainty. All the relative uncertainties are summarized in Table 12.

Table 12: Sensor and propagated uncertainties.

Sensor uncertainties		**Propagated uncertainties**	
Temperature	2.0 %	Temperature difference	2.8 %
Volume flow	1.0 %	Mass flow	1.4 %
Electric power	1.0 %	Thermal power	3.7 %

2.4.3 Buildings Monitoring Analysis

2.4.3.1 Thermal Comfort

Figure 31 shows the boxplots of temperature and humidity measured during the heating period of 2018 (i.e. from Jan.-April and from Nov.-Dec. 2018) in 9 flats out of 10 – because of malfunctioning in one flat – of the south building. The indoor temperature is above the suggested heating set point of 20 °C, with a median value between 22 °C and 23 °C, and it is rather constant in the flats. The relative humidity varies from flat to flat, but overall, the median lies above the too-dry-air limit of 35%.

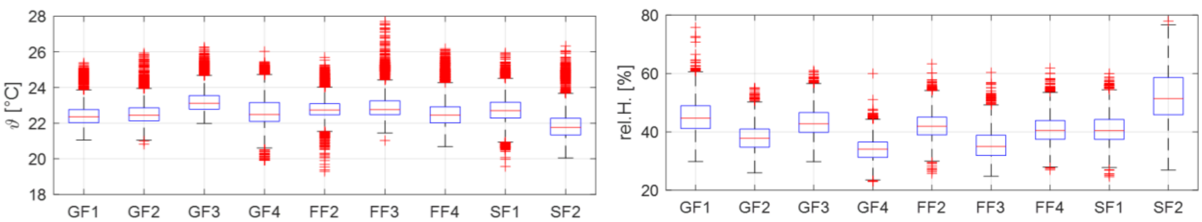


Figure 31: Indoor temperature and relative humidity of each flat in the south building for the heating period 2018.

Although the north building flats indoor temperatures are not monitored, the average value can be estimated thanks to the monitoring of the ventilation system extract air temperature. The analysis of the average indoor and exhaust temperatures of building south showed, indeed, a correlation between the two, namely a constant temperature difference of 1 K, as can be seen in Figure 32 left. Therefore, assuming a similar behaviour for the north building, the average flats temperature (both in south and north buildings) can be estimated Figure 32 right.

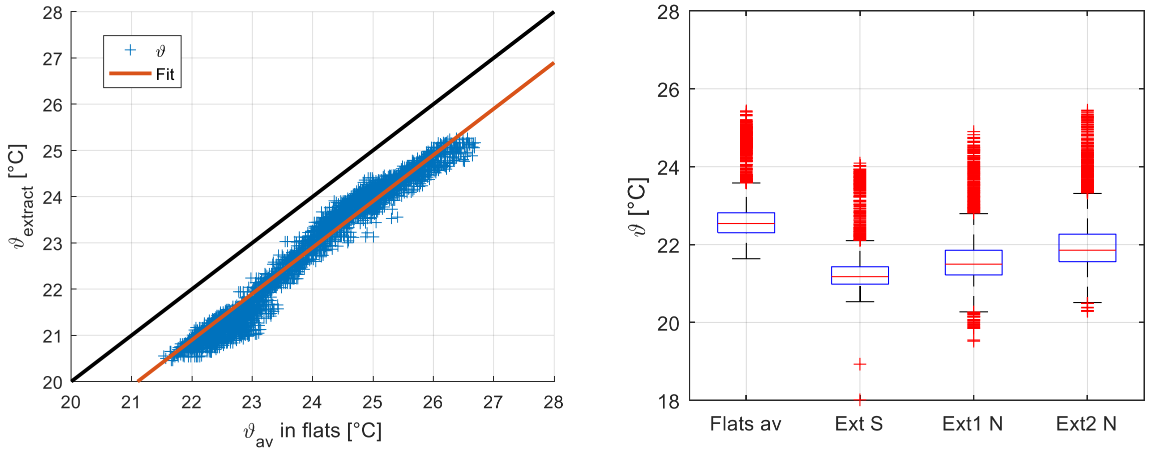


Figure 32: Correlation between average indoor temperature and extract air temperature of the centralized heat recovery unit in hourly resolution (left). The average indoor temperature of south building and extract air temperature of the heat recovery units installed in the south (1 unit) and north building (2 units) for the months of the heating season in 2018 (right).

2.4.3.2 Heating and DHW demands

Figure 33 shows an overview of the heating energy demand for SH and DHW during the monitoring years. The heating degree days (HDD) are also shown in Figure 33 which are computed as

$$HDD_{20/12} = \sum_{i=1}^{8760} (\vartheta_{indoor} - \vartheta_{outdoor})$$

The maximum energy demand is measured during the first year of operation, despite the heating degree days not being the maximum. This is probably related to the still ongoing concrete reaction. In 2019, there was a considerable increase in the energy demand with respect to the previous years, even though the HDDs were lower than in 2017 (maximum HDD so far). The south building resulted in requiring more SH demand than the north building only in 2019. The energy demand for DHW is almost constant during the years and, apart from 2019, larger than the SH demand. Distribution losses for heating range from a minimum of 1% to 3% of the total heating demand. The DHW demand is measured only in the technical room. Therefore, distribution thermal losses cannot be quantified.

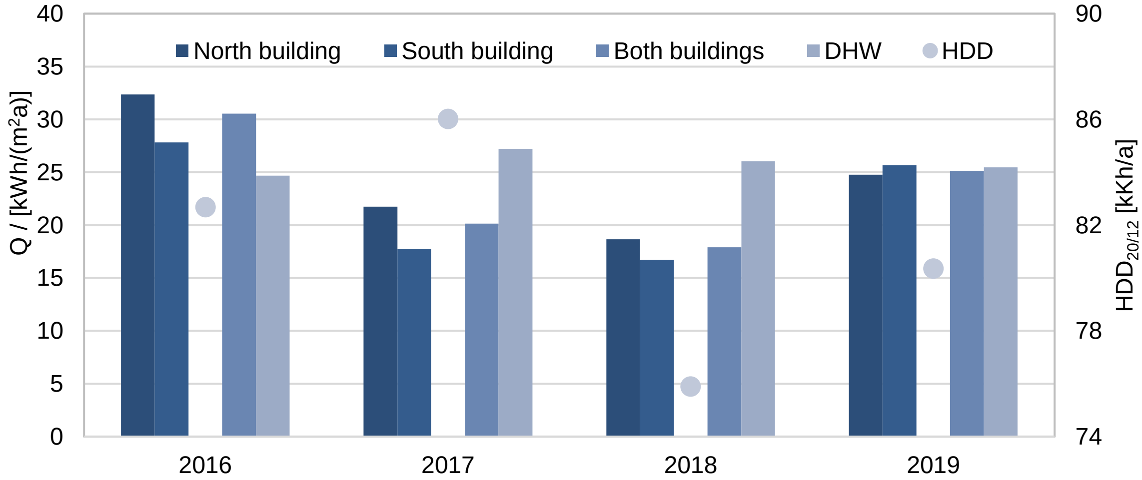


Figure 33: Heating energy for SH of the north, south, and both buildings, and DHW (including distribution losses) for the monitoring years. On the secondary axis the heating degree days are displayed.

2.4.4 HVAC System Monitoring Analysis

An overview of the energy flows in 2018 is provided in Figure 34 for both the heating and non-heating seasons. ST contributes to the energy demand prevalently during the non-heating season (85% vs. 20%). Also, the storage losses (which include pipe losses due to the position of the heat meters not being in proximity to the inlets and outlets) increase during the non-heating season, as well as the auxiliary electricity consumption. During the non-heating season, there is a significant surplus of PV electricity.

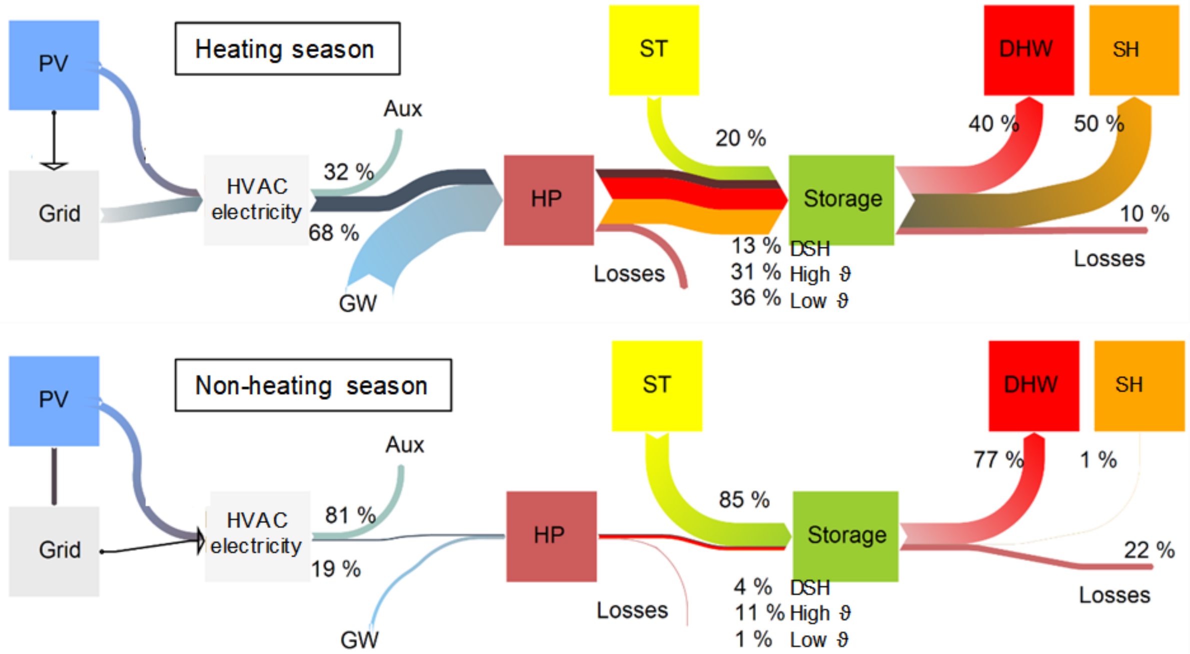


Figure 34: Energy flow for the heating season (November to April) (top) and non-heating season (bottom) in 2018.

2.4.4.1 Buffer Storage Monitoring

The energy inflows and outflows from the buffer storage (BS) are monitored by the heat meters. However, the measurements include, other than the buffer storage losses, also the piping losses, as the heat meters are not close to the BS inlets and outlets.

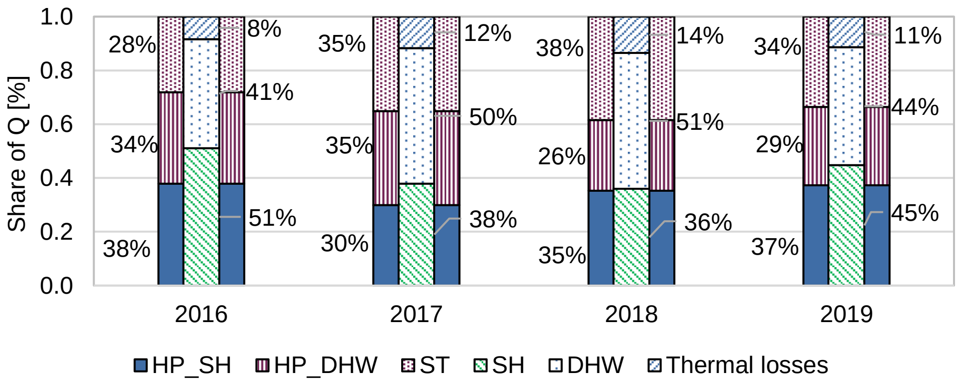


Figure 35: Thermal energy balance of the buffer storage.

In Figure 35 the thermal energy balance of the buffer storage for the four monitoring years is presented. Noteworthy, the thermal energy delivered by the HP at low temperature (HP_SH) is lower than the required for SH. This difference is covered by the heat delivered at high temperature from either the HP in DHW mode or the ST collectors.

Figure 36 shows the daily load duration curve of the charging (left) and discharging (right) powers of the BS in 2018. The DHW daily average power is 8 kW, which slightly reduces in the non-heating season. ST contributes mainly during the non-heating season and it can cover the DHW demand almost entirely. During the heating season, ST peak load is slightly higher than the DHW and losses only for a few days, thus ST hardly contributes to DHW.

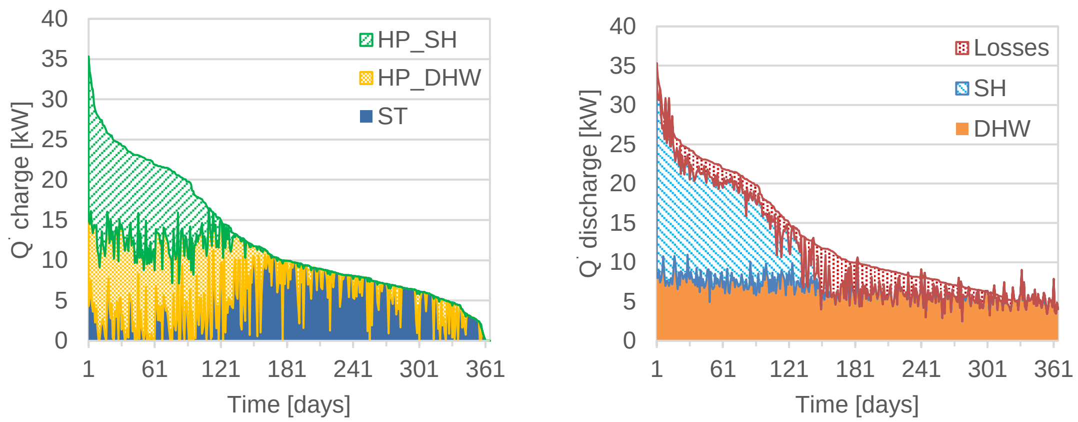


Figure 36: Daily load duration curve of charging (left) and discharging (right) of the buffer storage in 2018. Remark: Only the positive losses are included i.e. there were days with "negative" losses (the daily heat for charging was lower than the daily heat for discharging). For example, a day with no charging at all (e.g. day 365) in which the buffer storage was fully charged by ST in the previous day.

Note that the charging peak load is 35 kW, which rapidly falls to 30 kW, whereas the HP rated heating capacity is almost double, i.e. 58 kW (W10/W35).

2.4.4.2 Heat Pump Monitoring

The share of the supplied heat by each component as well as the SPF of the HP is presented in Figure 37 for 2018. These are divided into SH and DHW mode and in stage 1 and stage 2. In SH mode, the supplied heat was mainly in 'stage I' (34%), with 'stage II' covering only 8%. Despite the scope of the DSH being the simultaneous preparation of DHW while in SH mode, in 2018 there was no evidence of this behaviour. In DHW mode, the HP operated only in 'stage II', with the DSH contributing to the supplied heat by the 16%.

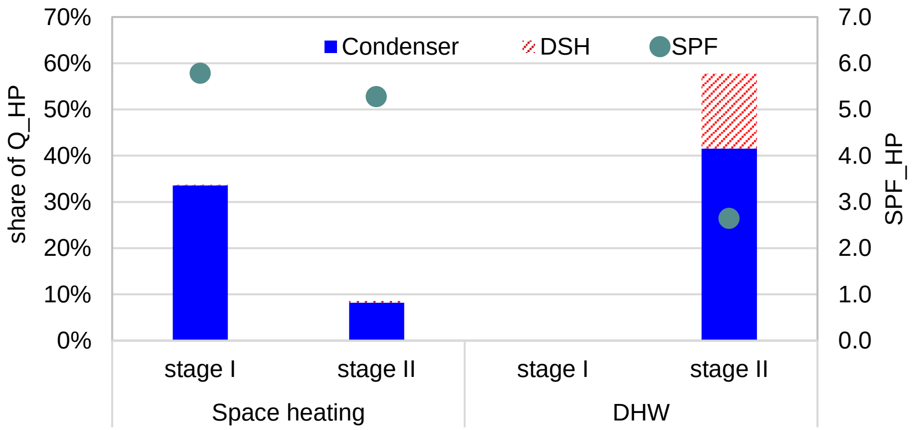


Figure 37: Share of supply heat by the heat pump in different modes (heating/DHW, stage 1 or 2, and condenser/ desuperheater), and the corresponding SPF of the heat pump in 2018.

The SPF of the HP in SH mode in 'stage II' was 5.3, slightly lower than 5.8 in 'stage I'. In DHW mode, the SPF was significantly lower with a value of 2.6.

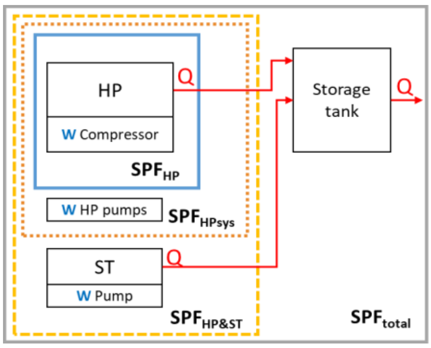


Figure 38: Boundaries for SPFs calculation.

The SPF could be computed also considering different boundaries, as presented in Figure 38. The SPF_{HP} accounts for the performance of the HP not including the electricity consumption by its auxiliaries (i.e. pumps), which are included in SPF_{HPsys}. $SPF_{HP\&ST}$ provides the performance of the system including the contribution of ST. Therefore, it is significantly higher than the two SPFs previously introduced. SPF_{total} encompasses the performance of the system as a whole, thus including also the storage losses.

In Figure 39 the SPFs for the monitoring years are presented. The maximum SPF_HP is 4.58 in 2019, which drops to 3.19 if the auxiliaries are included. The corresponding SPF_{total} is 4.19, very close to the maximum (SPF_{total} = 4.22) reached in 2018. If storage losses are excluded, the SPF raised to 4.87 in 2018.

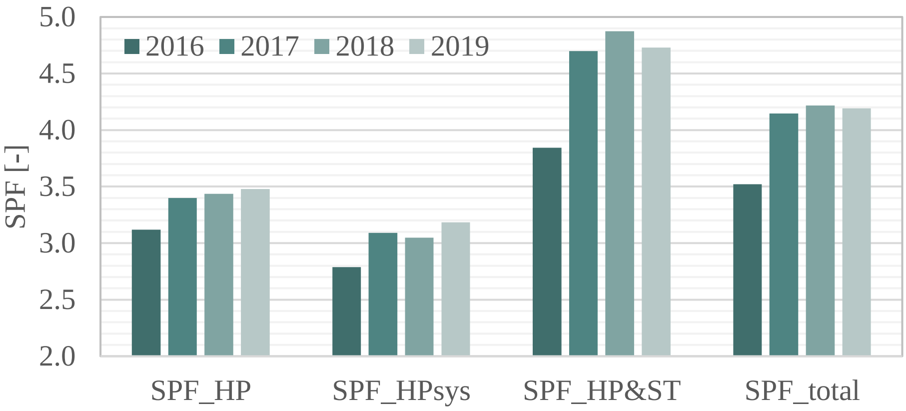


Figure 39: SPFs computed considering different boundaries (see Figure 38) for the monitoring years.

2.4.4.3 Distribution System

As previously mentioned, the distribution system was designed to work with relatively low temperature to limit distribution losses. The following figure reports the cumulative distribution function (CDF) of the hourly averaged monitored flow and return temperatures in 2018 of the SH and DHW distribution loops.

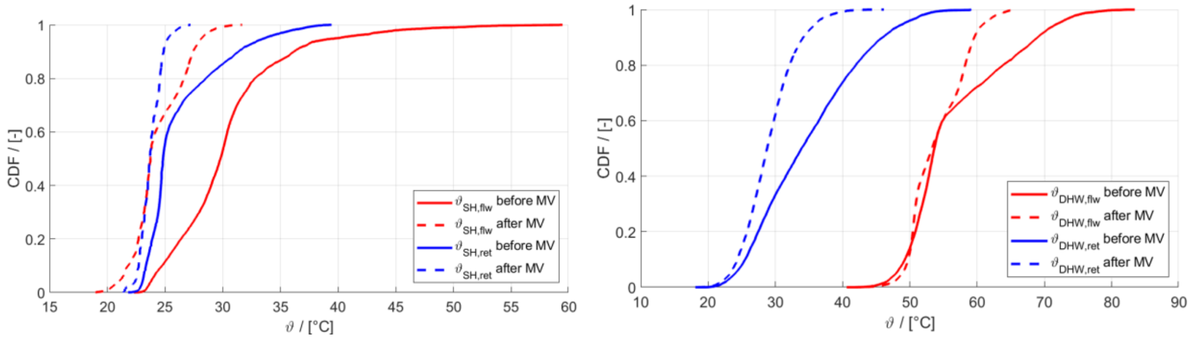


Figure 40: Cumulative distribution function (CDF) of the heating loop (left) and of the DHW loop in 2018 (right). The dashed lines represent the temperature measured after the mixing valve (MV)

Figure 40 left shows the CDF for the SH loop before and after the mixing valve (MV). The temperature of the water delivered to the flats is below 30 °C most of the time, thus the SH system is indeed a low distribution system. The flow temperature before the mixing valve reaches very high temperatures because of the natural circulation of storage water heated by ST. Similarly, Figure 40 right shows the CDF of the DHW loop. The low-temperature distribution system was also achieved for this case, as the return temperatures highlight. Most of the time the return temperature is below 40 °C, whereas for obvious reasons the flow temperature must be above 50 °C. The mixing valve on the DHW loop is installed to avoid flow temperatures higher than 65 °C during the non-heating season because of ST, which is proven to properly work as the flow temperature after the MV does not surpass 65 °C.

2.4.4.4 On-site Renewable

As discussed in section 2.4.4.1, ST collectors contribute mainly during the non-heating season, covering almost entirely the DHW demand. In the heating season, ST contributes only slightly, and it barely compensates for the storage losses. As can be seen in Figure 41 the SPF considering both the HP and the ST contributions, but excluding the storage losses during the heating season is higher than the SPF of the HP. However, when also including storage losses in the computation of the performance, the total SPF results negligibly higher than the SPF of the HP, showing the little contribution of ST during the coldest months. This depends on storage losses (both thermal and electric storage) and similar behaviour is expected, if PV is considered.

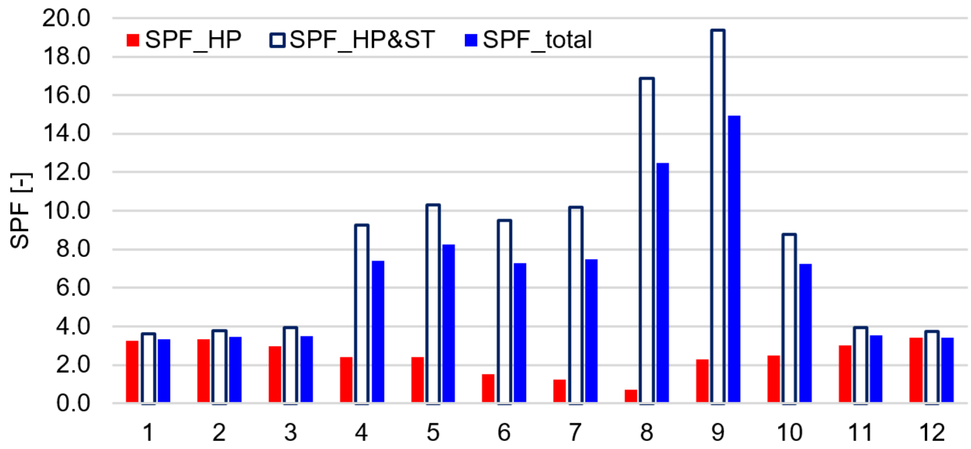


Figure 41: Monthly seasonal performance factors (SPFs) in 2018 for the boundaries defined in Figure12

The on-site annual electric energy generation by PV is shown in Figure 44 of the following section. The PV generation during 2018 is influenced by a failure of the inverter during June. Figure 42 shows the comparison of the annual thermal energy yield by ST collectors and the equivalent thermal energy yield by PV, which is computed as

$$Q_{\mathrm{PV\&HP}} = \sum_{i=1}^{12} W_{PV\_i} \cdot SPF_{HPsys\_i}$$

While ST energy yield remained almost constant during the monitored years, with slight variations, the PV generation is presenting a decreasing trend, as it is also highlighted by the increasing trend of the difference between ST and PV energy generation. As previously mentioned, the larger difference in 2018 is due to the failure in the inverter system. The annual ST output is always larger than PV, however, for a complete comparison storage losses and ST pumps electricity consumption should be included.

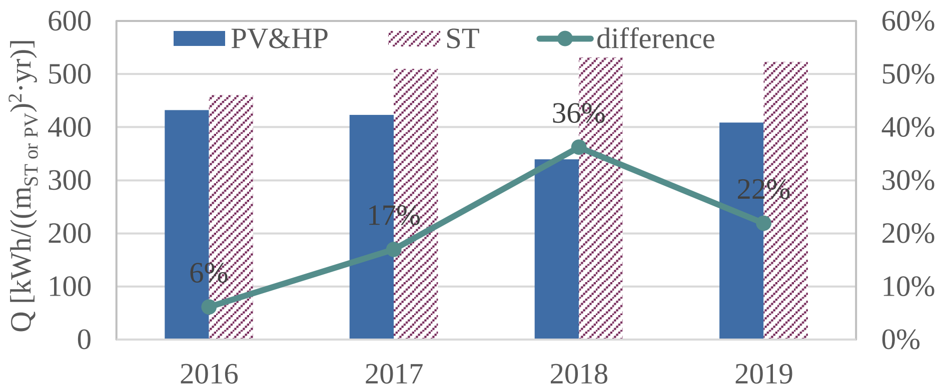


Figure 42: Comparison of specific heat supplied by ST and the combination of PV and HP during four years of monitoring (in 2018 there was a failure of the inverter). Note that storage losses are not considered.

2.4.4.5 Photovoltaic panels supply and load cover factors

The supply (SCF) and load cover factors (LCF) provide an indication of the direct utilization of the on-site electricity generation. The SCF is the ratio of self-consumed (SC) energy to the on-site generated energy, therefore representing the percentage of supplied energy directly consumed on-site. The LCF represents the fraction of the total consumed energy that is directly provided by the on-site generators being defined as the ratio of the SC energy to the total energy consumption.

The SCF and LCF for the heating and non-heating season of 2019 and the estimated SCF and LCF of 2018 are reported in Table 13. The total energy consumption is considered for the calculation SCF and LCF. This includes the electric energy needed by the HVAC (from monitoring) and the energy used for the household appliances, which was not monitored and had to be estimated. An optimistic annual consumption of 1500 kWh/yr per flat, evenly distri-buted throughout the year (constant power) is assumed for sake of simplicity.

SCF and LCF can be evaluated from the monitoring data for 2019, while data gaps in the monitoring in 2017 and 2018 do not allow for a complete calculation of the actual self-consumption.
However, for 2018 it is possible to estimate the self-consumption by simulating the power profile of the PVs. Therefore, a model of the PVs was realized in Simulink using the CARNOT library, and parametrized to the monitoring data of 2019, leading to a relative error between the predicted and measured energy of 6%, with the simulation model slightly overestimating the on-site generation. The measured and simulated PV energy yield relative error in 2018 is 8%. Being the estimated energy generation overestimated, the resulting factors for 2018 might be slightly overestimated, too. The comparison between monitored and estimated SCF and LCF for 2019, showed an overestimation of 2% on average. The LCF is between 19% and 24% (lower in 2019 because of the higher overall consumption) on annual basis, but is only 7% to 13% in the heating season. The SCF is on average 67% on annual basis and slightly lower in the heating season.

Table 13: Load (LCF) and supply cover factor (SCF) in 2019 for the heating and non-heating season and annual

	Heating season		Non-heating season		Annual	
	SCF	**LCF**	**SCF**	**LCF**	**SCF**	**LCF**
2018	81%	13%	64%	36%	68%	24%
2019	83%	7%	63%	32%	66%	19%

2.4.4.6 Electricity Balance

The monitored electricity demand includes all the HVAC system-related consumption and excludes the household's consumption.
The monitoring system logs the total auxiliary energy consumption and measures separately only the consumption of source (SRC) pumps (well and EVP), and ST pumps. Consequently, only an estimation of the remaining auxiliaries' consumption is possible, which are: sink (SNK) pumps (CND and DSH), ventilation system, SH and DHW circulation pumps, and monitoring system sensors. The SRC pump consumption is given by the product of the HP operational time times the rated power of the pumps. Ventilation related electric consumption is computed knowing the specific fan power (SFP) and the minimum ventilation required.

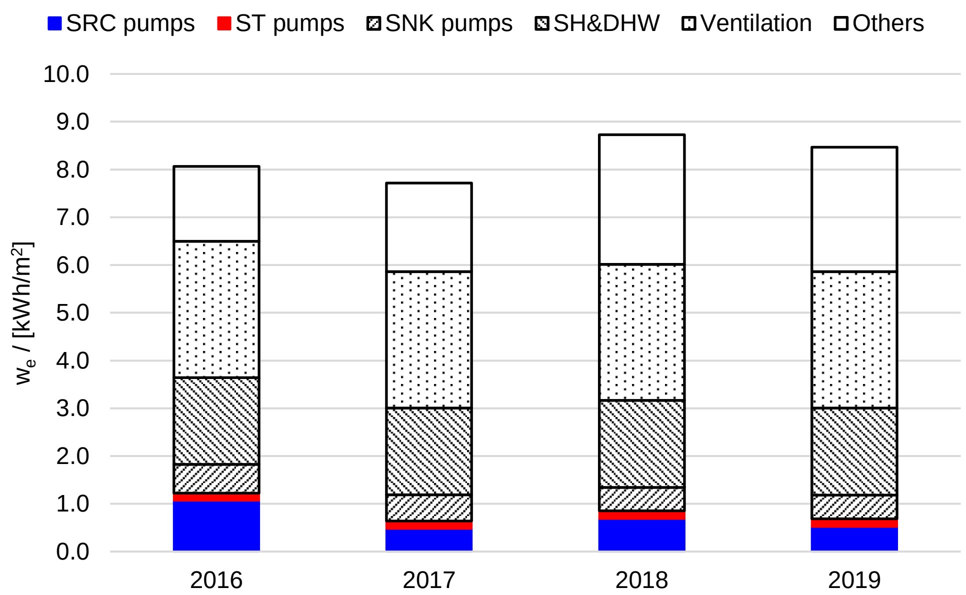


Figure 43: Annual auxiliaries' consumption. The shares filled with a pattern represent an estimated consumption. "SRC pumps" (source) includes well and EVP pumps, "SNK pumps" (sink) includes CND and DSH pumps, "Others" includes remaining unknown consumption and the estimation error.

The SH pump is used also for cooling – so far only in 2018 – and remains active for the whole heating season. This pump should modulate to adjust the flow rate based on the heating demand; however, from the monitoring analysis, it seems that the SH pump is operated at a

constant speed. Therefore, its consumption is estimated as the product of the heating season hours times its rated power (536 W).
The DHW pump works the whole year keeping a minimum flow to maintain the distribution system heated, thus ensuring a rapid response when DHW is required. Its consumption can be computed multiplying power of 135 W – which is a good representation of the average power consumption of the pump – by the hours in a year. The remaining energy consumption represents the consumption of the monitoring system and other unknown sources of consumption. Being this fraction the result of the subtraction of estimated consumption from the total, it also includes the estimation error.

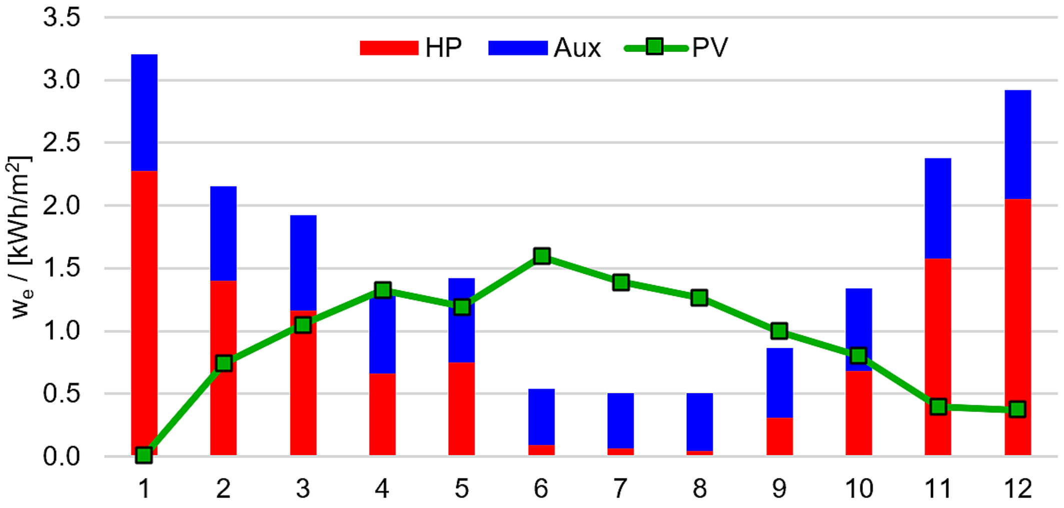


Figure 44: Monthly electricity consumption by the HP and the auxiliaries, and PV electricity yield in 2019. For the annual electricity yield refer to Figure 45

Figure 43 shows the annual auxiliaries' energy consumption highlighting the share of each component. In 2016, as previously presented, the heating demand of the building was significantly larger due to the concrete reaction. Moreover, the well pump was set to too large volume flow, thus the significantly higher energy consumption of SRC pumps with respect to the following years. As 2018 was the only year so far that required cooling, there was a slight increase in SRC pumps energy consumption in that year.
In Figure 44 the monthly electric energy consumption and generation for 2019 are shown. During the heating season, the PV yield is barely able to cover the auxiliary energy consumption, whereas in the non-heating season there is a large electricity surplus.

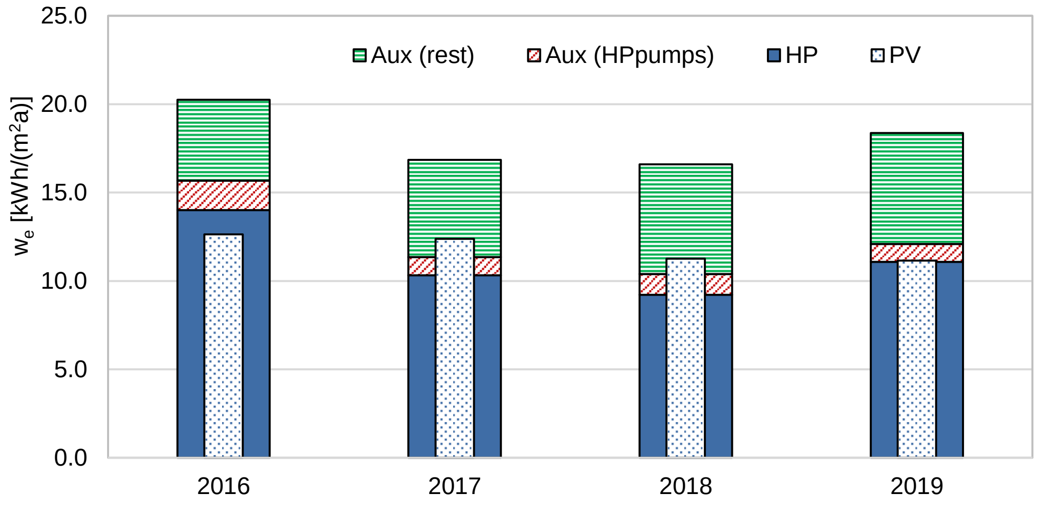


Figure 45: Electricity consumption of the HP, circulation pumps of the HP, and the remaining auxiliaries (consisting of DHW and SH circulation pumps, ventilation systems) and electricity generation by PV for the monitoring years. Note that in 2018 there was a failure of the PV inverter resulting in reduced energy yielded by PV.

Despite that, in none of the monitored years, the on-site generation was sufficient to cover the energy consumption of the HVAC system, thus failing to achieve the design goal of net-zero annual energy balance, as can be seen in Figure 44.

2.4.5 Planning vs. Monitoring

In this section, the monitoring results are compared to the predicted behaviour during the design. Figure 46 shows the comparison of the predicted to the monitored HDs. “PHPP adapted” represents the predicted HD by the PHPP when it is modified to account for the monitored monthly average indoor temperatures and the monitored climates. “PHPP calibrated” is the “PHPP adapted” whose infiltration rate (n_{50}) has been modified to match the predicted annual heating demand to the monitored in 2018.

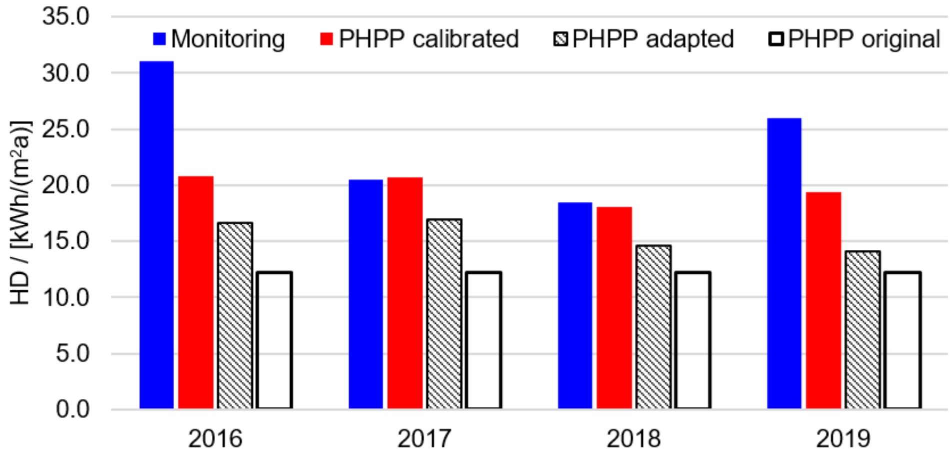


Figure 46: Comparison of annual heating demand (HD) monitored and predicted by the design PHPP, by the PHPP adapted with monitored indoor temperatures and climate, and by the PHPP calibrated to the annual HD of 2018 by adjusting the infiltration rate.

The mismatch between the “PHPP calibrated” and the monitored HD can be justified by the user behaviour, which for example likely increases the ventilation losses by opening windows.

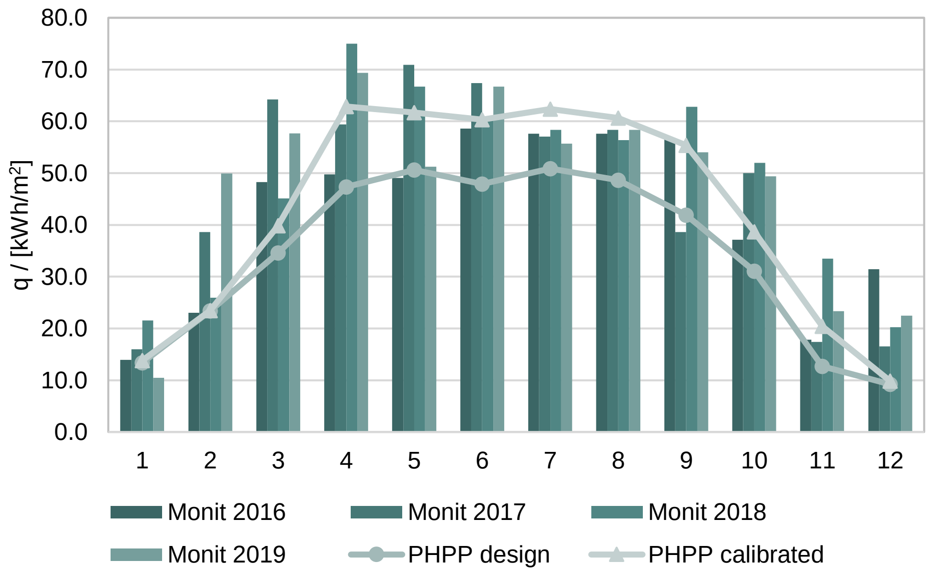


Figure 47: Comparison of predicted (PHPP design) to monitored monthly delivered ST energy. “PHPP calibrated” represents the ST energy supply predicted by the PHPP calibrated to the climate of 2018 and the monitored SH and DHW demand.

The “PHPP calibrated” attempts to account for the user behaviour for the ventilation of the building, leading to a good match in 2017 and 2018. The mismatch in 2016 is explained by the ongoing reaction of the concrete, whereas in 2019 the mismatch must be explained by user behaviour, probably increased ventilation rates with respect to the previous years.

It is interesting to notice the accuracy in the prediction of the annual HD by the PHPP when modified to account for the in-operation conditions of the building.

In Figure 46 the comparison of the predicted and monitored ST supplied energy is shown. The predicted ST energy supply underestimates, on average, the monitored output in each month, with a larger mismatch during the non-heating season.

In addition to the predicted and monitored ST energy generation, Figure 47 shows also the predicted energy supply obtained by calibrating the PHPP to the monitored heating and DHW demand in 2018 and considering the climate of that year.

The PHPP underestimates also the PV energy generation, as can be seen in Figure 48. Although the PHPP was modified to account for the monitored climate in 2019, the predicted PV yield does not vary much with respect to the design value, however, it correctly represents the monitored trend. Note that during the monitoring years 2017 and 2018 a failure in the monitoring system – that was solved after the failure of the inverter in June 2018 – did not allow the correct measurement of the PV energy generation in those years.

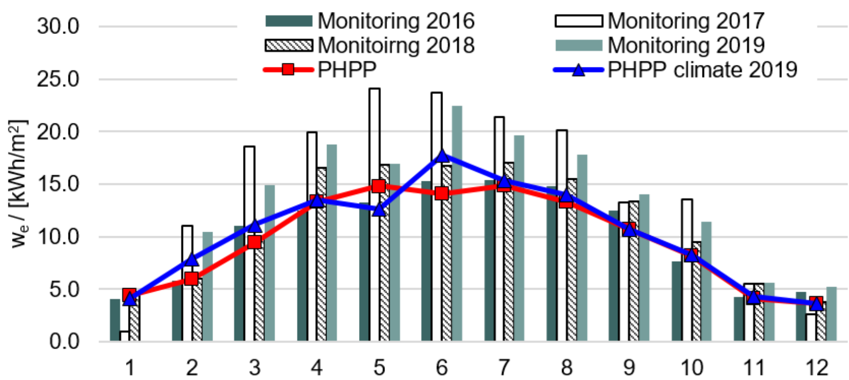


Figure 48: Comparison of predicted by the PHPP and monitored monthly PV energy supply. "PHPP climate 2019" is adapted to account for the monitored climate of 2019.

2.5 Multi-family building Riedberg, Germany

In a district of Frankfurt, the housing company Nassauische Heimstätte has built an Efficiency House Plus with 17 two-to-four-room apartments on a total area of 1,600 m² on four floors plus an attic floor.
By a high-quality building envelope and the optimal use of renewable energies, the Efficiency House Plus standard can be achieved in an apartment building and thus showing that achieving an energy surplus in the annual balance is not limited to buildings of few residential units. The focus is on activating surfaces suitable for the production of solar power. Not only the south-facing roof, but also the south facade itself is used to produce electricity.
The five-storey multi-family residential building is located on a triangular plot in the north of Frankfurt. In August 2015 the building was initially commissioned. The pentagonal building form is based on the form of the property and the integration into two urban grids.
On the inside, the apartments are arranged around a central, bright circulation core (stairs and elevator) with sizes of about 45 to 125 m². From the entrance hall, both the circulation core and a ground floor bicycle storage room, as well as the basement and underground garage can be accessed.
The apartments are divided into four types, each with slightly different floor plan design and sizes. Each apartment has its own loggia.
The shape, compactness and orientation of the building ensure optimal use of daylight, natural ventilation and solar radiation.


Figure 49: South-side view of MFB Riedberg [HHS PLANER+ARCHITEKTEN AG | Constantin Meyer Photographie]

2.5.1 Energy concept

A photovoltaic system with an installed capacity of 99 kW_p (84 + 15 kW_p) was installed on the roof and the south façade, respectively. The PV surplus electricity can be used to charge a lithium-iron phosphate battery with a nominal capacity of 60 kWh. The coverage of the additional electricity demand for household and technical equipment is guaranteed by a connection to the public grid.
The use of solar energy is supplemented by a solar thermal system in the form of solar air absorbers with an area of 85 m², which is installed under the PV modules. The provision of heat for the low-temperature floor heating system and domestic hot water preparation (apartment transfer stations per apartment) is carried out by a brine-to-water heat pump. An ice storage (98 m³) and the solar air absorber on the roof serve as source for the heat pump. Depending on the temperature level and availability, the heat source is the solar thermal absorber on the roof or alternatively the cylindrical ice storage tank (diameter 6 m, height 4 m). The regeneration of the ice storage takes place by the absorber and free-cooling in the summer.
There are two networks for the heat distribution in the building, a low-temperature network for the floor heating and a high-temperature net with a storage tank of 1,000 l. The high temperature net supplies the domestic hot water preheaters in the apartment transfer stations, the bathroom radiators and the heating register of the ventilation system.

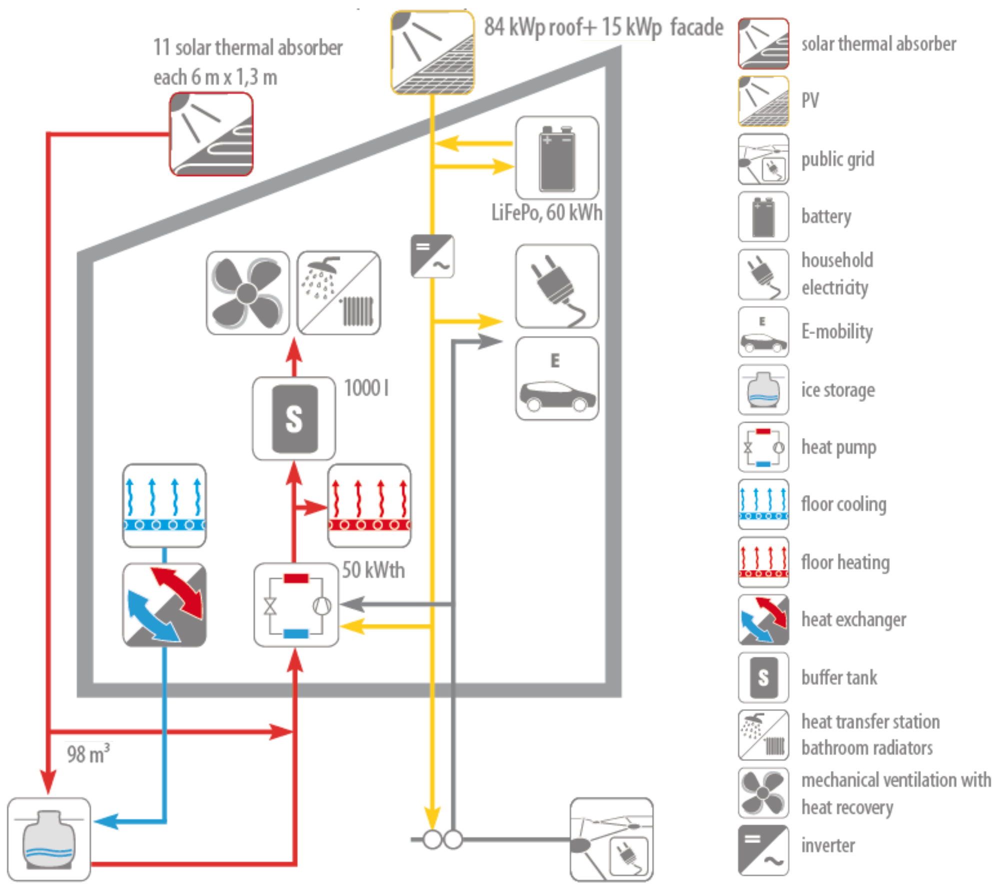


Figure 50: Energy concept multi-family house Riedberg

Occurring ventilation heat losses in winter are to be reduced by a central mechanical ventilation system with heat recovery and the living comfort is to be increased by the system. The possibility of natural ventilation is always available.

Table 14: Technical data building technology

	System technology	Performance/Area/Volume-flow
Heating	Brine-to-water heat pump with ice storage (98 m³) and solar absorbers (11 pcs each 6 m x 1,3 m)	max. 11 kW_{el} and 50 kW_{th} thermal storage 1000 l
Cooling	Free cooling by the ice storage	
Electricity	Roof and façade integrated photovoltaic	roof 84 kW_p and façade 15 kW_p, total area PV 553 m² electrical storage 60 kWh
Ventilation	Controlled supply/exhaust air system with heat recovery	max. 1,600 m³/h heat recovery 84 %

2.5.2 Building envelope

The polygonal building has five façades, four of which are made up of curtain walls covered in fiber cement boards. The fiber cement board grid is adapted to the scattered arrangement of the floor to ceiling glazing. The south-facing façade has been designed as a pure glass façade with customized glass / glass PV modules.

Table 15: Characteristics of building envelope

	U-Value [W/(m²K)]
Exterior wall / Roof / underground car park	0.12 / 0.13 / 0.12
Window	0.8 (g-value 0.53)

The exterior walls, made of reinforced concrete with thermal insulation and a curtain wall made of fiber cement panels on the outside, reach a U-value of 0.12 W/(m²K). The pent roof with a slope of 10°, has a 30 cm thick thermal insulation, thereby reaching a U-value of 0.13 W/(m²K). The windows with triple glazing achieve a U-value of 0.80 W/(m²K). The floor slab of the apartments above the underground car park is designed as a reinforced concrete floor with floating screed and 24 cm thick insulation on the bottom reaching a U-value of 0.12 W/(m²K).

2.5.3 Comparison with design data

In the design phase, an annual heating demand of 8.24 kWh/(m^2_{AN}a) was calculated for the apartment building. The annual primary energy demand according to EnEV 2014 adds up to 7.02 kWh/(m^2_{AN}a) (including offsetting the use of own electricity). During the planning phase an annual PV yield of 36 kWh/(m^2_{AN}a) was calculated, so that a balanced surplus of electricity of 24,500 kWh/a was achieved.

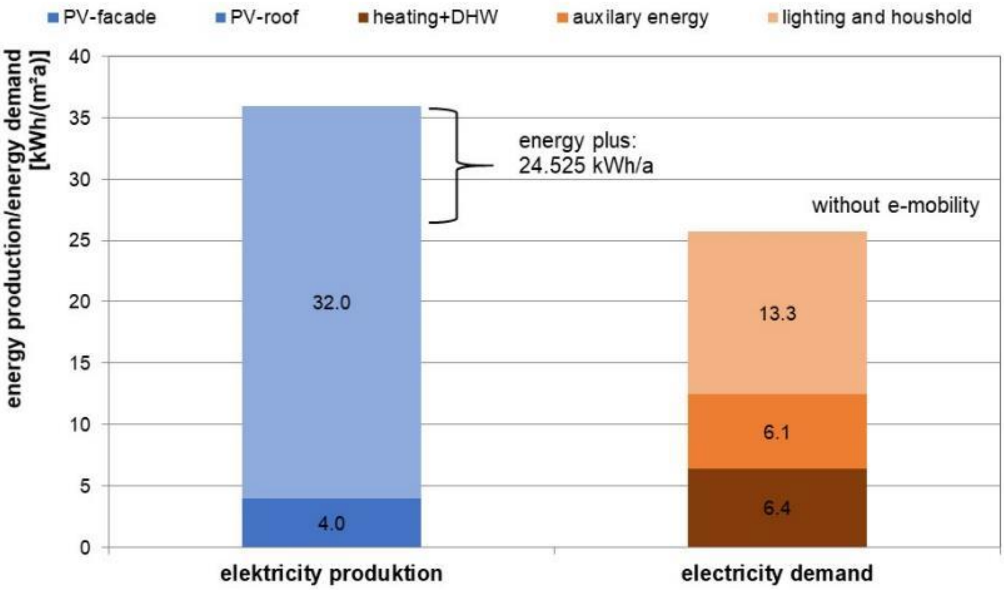


Figure 51: Calculated delivered energy demand in planning for the multi-family house Riedberg

Table 16 shows a comparison of the electrical monitoring to the design data. In comparison to the design data the monitoring data have quite high deviations. The electricity consumption for space heating and domestic hot water is up to 180% higher than calculated. The total monitored value of the electricity use of 50.6 kWh/(m²a) including the building technology and household is also significantly higher than the estimated value in planning phase of 25.8 kWh/(m²a). The PV yield delivered about 11% more electrical energy than calculated. The cause for the higher electricity consumption is the building technology, as users only consumed 10% more household electricity than previously assumed.

Table 16: Comparison of the design data with the results of the monitoring

	Calculation	Monitoring	Deviation
Space heating + DHW	6.4 $kWh_{el.}/(m^2a)$	18.1 $kWh_{el.}/(m^2a)$	+180 %
Total electricity consumption	25.8 $kWh_{el.}/(m^2a)$	50.6 $kWh_{el.}/(m^2a)$	+96 %
Electricity production PV	36.0 $kWh_{el.}/(m^2a)$	40.0 $kWh_{el.}/(m^2a)$	+11 %
SPF of heat pump	4.5	2.2	

2.5.4 Monitoring concept

For the evaluation of the building performance and for energy monitoring, an infrastructure for measuring electricity and heat consumption has been installed. The readings of heat and electricity meters are automatically recorded and forwarded for monitoring purposes. Battery charge and discharge are also recorded and the sum of PV direct yield (without intermediate storage in the battery) and battery discharge is measured to record the total yield of renewable electricity.

The interface to the public grid (power purchase and power feed-in) is also recorded. For the analysis of the heat supply, the heat quantity of the solar absorber (to ice storage for regeneration and to heat pump), as well as the heat quantity from the ice storage to the heat pump and the total heat produced by the heat pump are recorded. On the consumption side, the total heat energy quantity provided from the storage tank in the high-temperature net and the total heat quantity consumed in the low-temperature net are measured. In the high-temperature net, the consumption within the residential units is recorded for domestic hot water and the bathroom radiators that are supplied by the high-temperature net. Since August 2017, the heat quantity of the heating register of the ventilation unit has also been measured. In the low-temperature net, the heat consumption of the underfloor heating system is also measured in each residential unit. The measurement of cooling energy via free cooling is carried out only centrally.

M-Bus meters are used, which are read at 15-minute intervals. The meter reading and the momentary power are read out in each case. In the case of heat meters, the flow and return temperatures and the flow rate are also recorded.

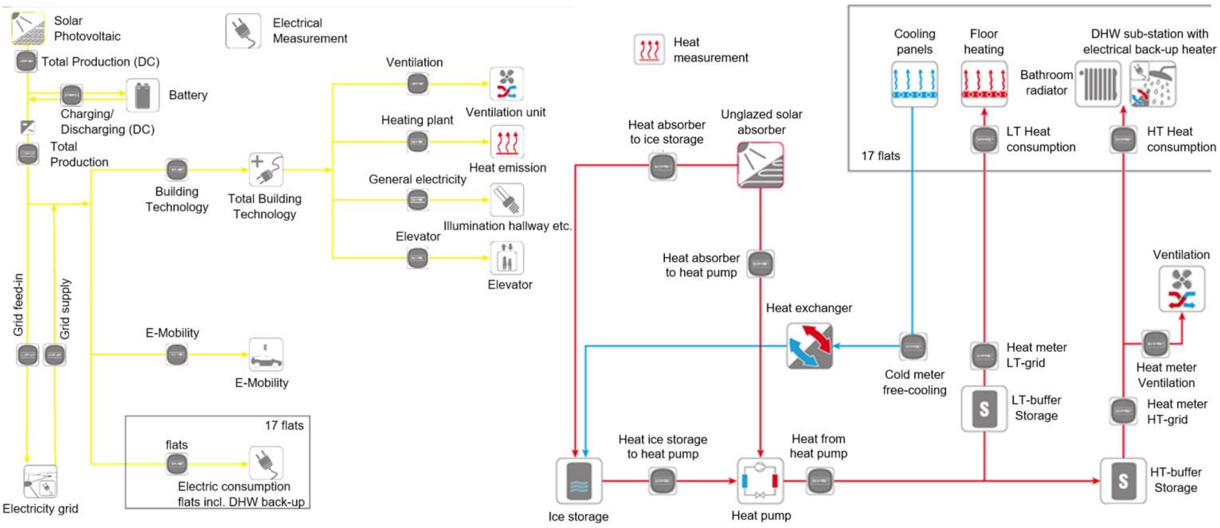


Figure 52: Meter overview electricity (left) and heating/cooling (right)

2.5.5 Monitoring results

As part of the renovation of the heating system from January to April 2016, an oil-powered mobile heating unit ("hotmobile") was used to heat the building. The delivered and primary energy consumption by using heating oil is included and listed in the energy balances.

2.5.5.1 PV yield and own electricity use

The building technology primarily envisages the direct use of solar yields from photovoltaics. Only surpluses that cannot be stored will be fed into the public grid. The balanced annual surplus energy calculated from the measured data exceeds the planning values. Compared to the calculated electricity yield of 86,400 kWh/a from the PV system, approx. 99,500 kWh/a were delivered, around 15% more than assumed in the planning. In the last four years of operation, the PV system has delivered around 386 MWh of solar energy in total. This results in a mean installed capacity of approx. 975 kWh/kW$_p$. For the multi-family house no energy plus according to planning can be proven. The average annual electricity deficit is about 25,600 kWh/a (about 20% of the electricity consumption). Over the period under consideration (2016 -2019), about 53% of solar electricity was used in the building itself, the rest being fed into the public grid. The load cover factor varies between 39 % and 45 % over the years, reaching an average of 42% over the four years. In the monthly view the SCF runs from 36% to 97% and the LCF from 7% to 80%. The opposite trend is clearly visible. (Figure 54 and Figure 55). Failure to achieve EnergyPLUS can be explained by two major factors: On the one hand there was an increased consumption of heating energy as well as increased distribution losses compared to the planning. In the high-temperature network, the heat losses are in the range of 40%.

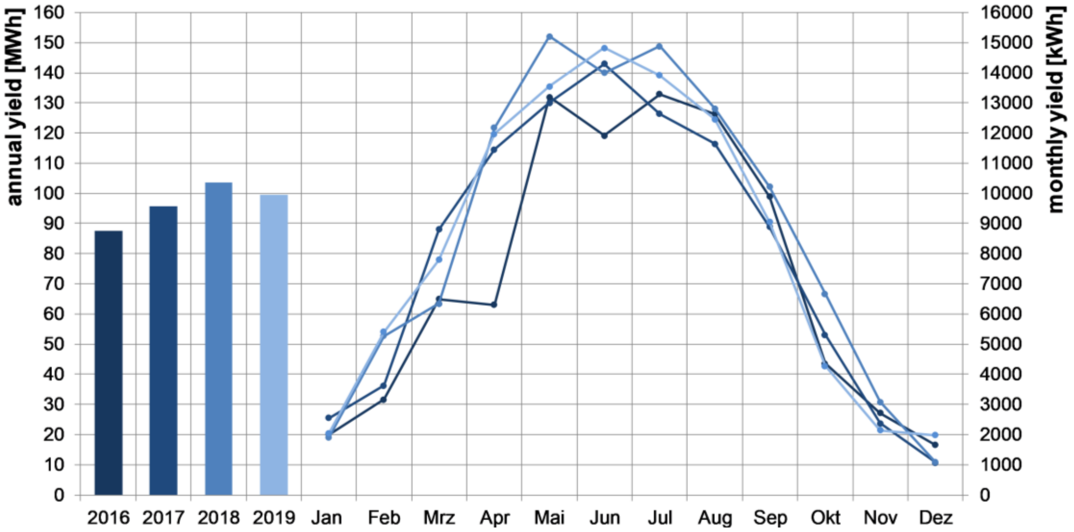


Figure 53: Annual and monthly electric yield of the PV collectors, 2016 - 2019

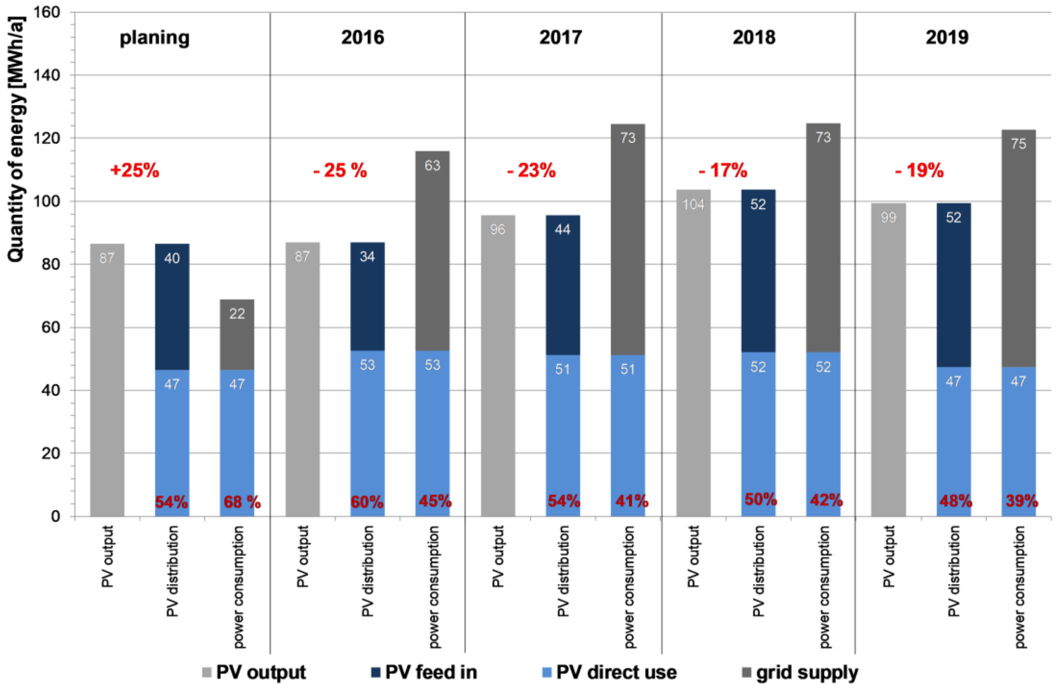


Figure 54: Annual balance of total energy, 2016 – 2019 (red = fraction)

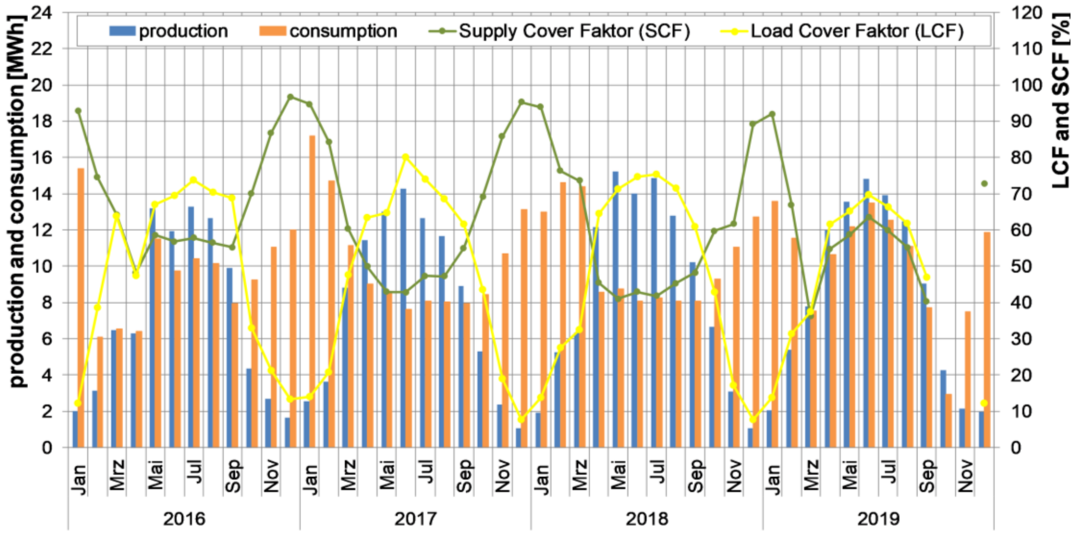


Figure 55: Monthly load/supply cover factor, 2016 - 2019

2.5.5.2 Delivered and primary energy and CO_2-emissions

The annual balance of delivered and primary energy for the years 2016 to 2019 is shown in Figure 56 In accordance with the German standards DIN V 18599-1 and DIN 4701-10 / A1, a primary energy factor of 2.8 is applied to the electricity feed-in and a primary energy factor of 1.8 to the electricity purchase.

From 2016 to 2019, a primary energy deficit of ~ 12.7 MWh/a was achieved in the first years. 2018 and 2019 a primary energy surplus of 12 MWh/a was reached. With regards to the delivered energy deficit, values between 21.2 MWh/a and 29.0 MWh/a could be generated.

For CO_2-emissions, CO_2-equivalents of 527 g/kWh are used for both electricity savings and grid purchases. This results in CO_2 deficit of 11 to 15 t/a.

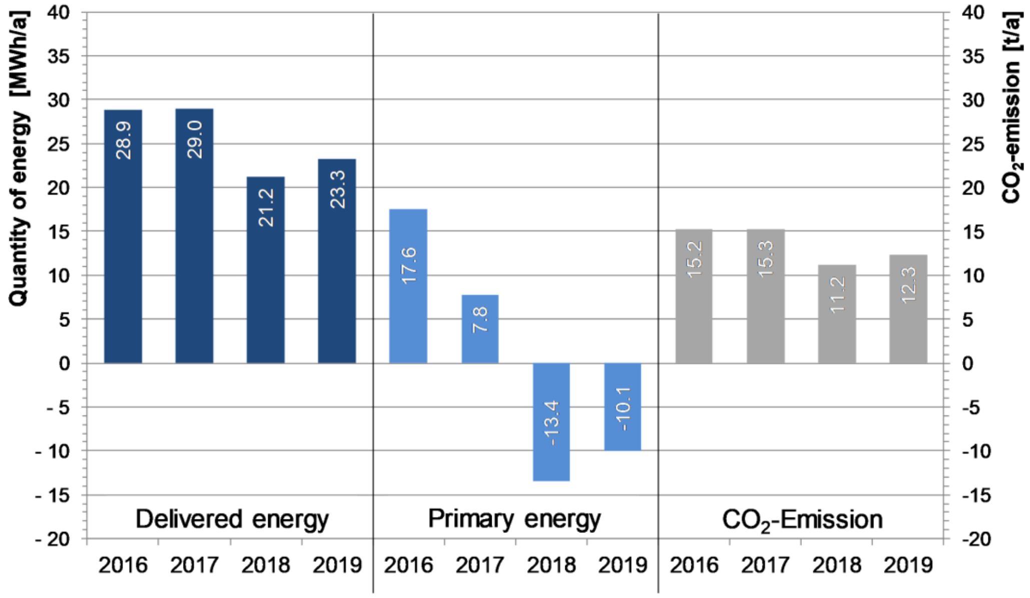


Figure 56: Final energy, primary energy and CO_2-emission (2016 to 2019)

2.5.5.3 Electricity balance

Due to measurement data failures of almost all individual meters in the building, the individual consumers can only be estimated on the basis of monthly values. It turned out that in this building the electricity for the heat supply accounts for about one third of the total electricity consumption. The heat pump flow is about as high as the user flow.

Figure 57 shows the shares of electricity for the heat pump and household. The total annual electricity consumption is about 50.6 kWh/(m²a) (122,200 kWh/a) The heat pump accounts for approx. 36 %, household for approx. 64 % of the annual energy consumption.

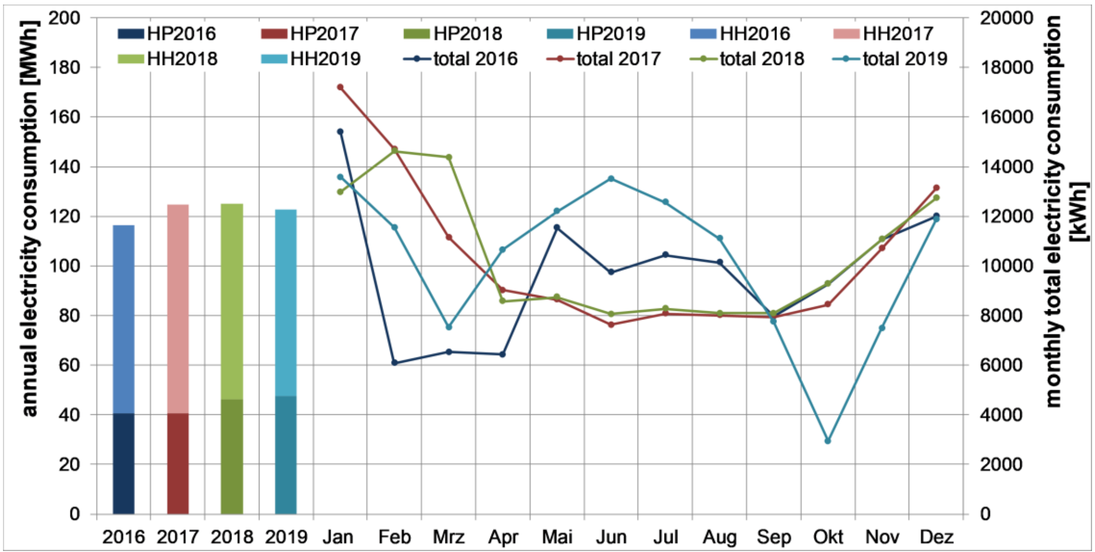


Figure 57: Monthly and annual electricity consumption by category – heat pump and household, 2016 – 2019

2.5.5.4 Thermal balance

Figure 58 shows the shares for heating and domestic hot water for the four years of operation. The proportions are broken down into heat transfer for space heating and domestic hot water. The annual energy consumption (heating, DHW) is about 63.4 kWh/(m^{2}a) (153,300 kWh/a) The space heating accounts for approx. 69%, DHW, storage and distribution losses for approx. 31% of the annual energy consumption. The area-related total heat energy consumption in the operating years of 2016 to 2019 ranges from 60 to 65 kWh/(m^{2}a). Between 145 and 158 MWh/a of heat is generated.

Therefore, the share for domestic hot water production (20.6 kWh/(m²a)) is significantly higher than the standard energy efficiency requirement of 12.5 kWh/(m$^2_{NGF}$a) required by the EnEV.

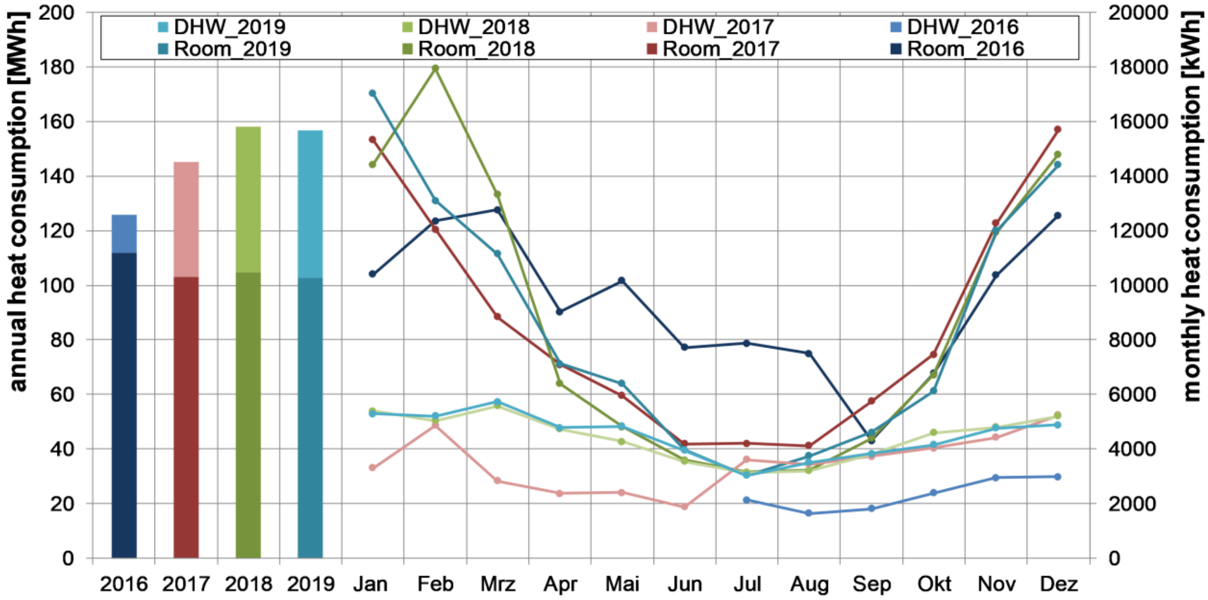


Figure 58: Monthly and annual heat balance, 2016 to 2019

2.5.5.5 Seasonal Performance Factor

The faulty implementation is reflected firstly by the solar absorber, since flows were not completely guaranteed and heat generated was not available to the calculated extent. Furthermore, there were problems during the four years of operation with regard to ventilation and hydraulics. Excessively high return temperatures resulted in unfavourable heat pump cycles, resulting in suboptimal temperature levels around the condenser, leading in a monthly seasonal performance factor of only 1.7 - 2.6, see Figure 59.

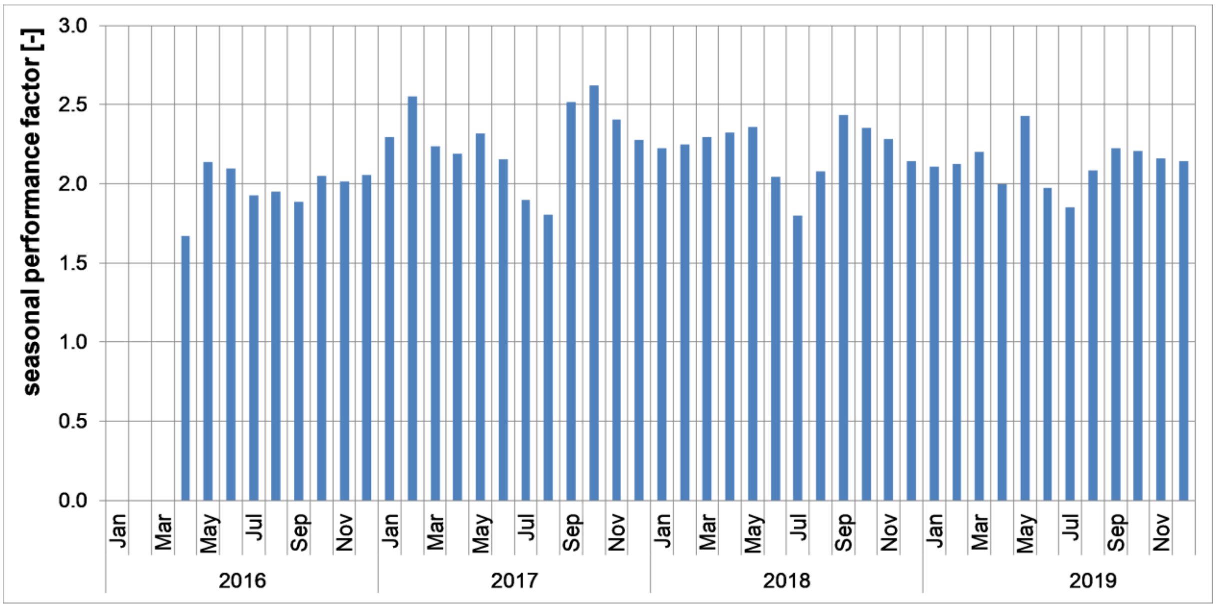


Figure 59: Monthly seasonal performance factor 2016 to 2019

2.5.6 Building envelope integrated heat source and PV

Implementing the requirements of the EPBD from 2019 onwards to build only nZEBs is not only a financial challenge. While in the area of single-family houses the requirements can be met by clever choice of energy supply technology in combination with an adapted building envelope, this is more difficult in the case of multi-family houses. Balancing the energy requirements by using renewable energy supplies can be limited by the available space. From certain consumption values, which are also linked to the number of occupants, the roof area of a building may no longer be sufficient to cover the necessary parts of the energy demand using renewable energy. It is irrelevant whether solar thermal, photovoltaic or a combination of both is used. Technically, however, there are various possibilities to increase the amount of space available. Surrounding roof areas of garages or carports, but also neighbouring buildings are conceivable. If necessary, the roof area efficiency can be increased with PV/T collectors. The facades of a building offer an additional potential of space. From an energy point of view, a façade-integrated photovoltaic system is not ideal as can be seen in Figure 53. When using the south facade, only about 70% of the maximum possible yield is achieved. However, the use of a facade can make sense due to unfavourable roof shapes, poor building or roof orientation and to maximize the solar-active building area.

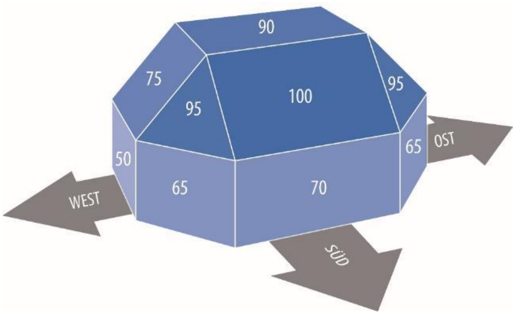


Figure 60: Maximum PV yields in percent based on module orientation

Just like the eastern or western orientation of PV systems, the integration of solar thermal energy in the façade area, i.e. at positions that initially appear unfavourable, can offer energetic and technical advantages. Especially in the case of solar thermal combi-systems, which serve to support space heating in addition to domestic hot water, façade-integrated collectors can offer system engineering advantages and increase the solar yield by reducing stagnation times in summer and providing favourable irradiation angles for solar radiation in the transitional period and in the winter half-year to support heating.

In contrast to a standard photovoltaic module, the building-integrated photovoltaic system can also function as a shading, weather, visual and sound protection in addition to generating electricity. By using insulating glass, building integrated photovoltaics (GiPV (BIPV)) can also provide thermal insulation.

The possibility of integrating a PV system is not limited to new buildings; there are also options for existing buildings. The choice of photovoltaic systems for the façade is just as varied as for roof-mounted systems. Opaque cold PV facades or (semi)transparent warm facades, which additionally take into account the use of daylight as design elements, can be implemented. There are coloured and also flexible modules, the latter are offered as thin-film modules. In addition to the façade itself, BIPV can also be used on parapets, skylights or sun protection systems. Combinations with switchable glasses can be used for sun protection or to increase passive solar gains in winter. Due to the generally required embedding of photovoltaics in safety glass, BIPV can also take on additional mechanical protection functions.

In the field of mounting systems, aluminium profiles are mainly used, similar to the roof-top systems. However, depending on aesthetic requirements or wishes, rope constructions or special solutions can also be implemented for fastening.

In general, the construction materials for fastening BIPV are more expensive than mounting systems for roof integration or on-roof mounting - and the modules for a façade also cost more. In addition to the higher investment costs, the lower yields of façade-integrated photovoltaics have to be taken into account when considering the economic efficiency.

With the help of a high-quality building envelope and optimal use of renewable energies, the Riedberg multi-family house is to achieve the Efficiency House Plus standard, thus demonstrating that achieving an energy surplus in the annual balance is not limited to buildings with only a few residential units. The concept focuses on solar power generation. In order to achieve a surplus of PV electricity, it is usually not sufficient for multi-family houses that only the roof surfaces are covered with PV modules. In the Riedberg MFH, therefore, not only the south-facing roof, but also the south façade itself is used to generate electricity.

The south-facing façade is designed as a pure glass façade with custom-made glass/glass PV modules. For optical reasons, dummy modules are used both on the roof and in the façade in some places where PV modules cannot be arranged.

2.5.7 Discussion and conclusion

A system optimization could only be achieved to a limited extent. The first step involved the integration of a buffer tank as a hydraulic diverter in the low-temperature network. This was done to avoid cyclic operation of the heat pump due to the very high number of heat pump cycles.

Furthermore, the set point temperature for switching between solar absorbers and ice storage has been optimized, as well as adjusting pump delivery heads to increase the volume flows and thus increase the temperature level on the source side.

Due to findings that the performance of the solar absorbs were insufficient too early in the course of the year for operation as a heat source and the ice storage was used as a source, there was a temporary support to the heat supply by electric instantaneous water heaters in the heating period 2016/2017.

In the course of 2017, three instantaneous water heaters were permanently installed in the high-temperature network with a capacity of 9 kW each. Furthermore, dummy modules were removed from the roof to ensure a better flow around the solar absorber.

Due to control errors and deficiencies in implementation, the supply system with the two heat sources, solar absorber and ice storage could not function optimally. By switching to the ice storage too soon, it was not possible to carry out planning-compliant operation in which about 75% of the heat would be provided by the solar absorbers. In addition, there were problems with the heat pump efficiency and thus increased energy consumption.

This building shows that the application of complex systems with multiple heat sources and the operation should be monitored in order to achieve a regular operation. The same applies to the construction in order to avoid implementation errors and to ensure scheduled operation.

It was to be examined how the solar absorbers could be integrated more efficiently into the heat supply system. For this purpose, the switching temperature between the two heat sources can be optimized. On the other hand, the heat transfer from the outside air to the heat transfer medium can be optimised. For this purpose there is the option of improving the flow around the absorbers and thus the convective heat transfer. Due to the installation underneath the PV modules, an increase in absorber performance through higher radiation gains cannot be realised.

2.6 Multi-family building Sonnenpark Plus, Wetzikon, Switzerland

The multi-family building SonnenparkPlus in Wetzikon, Switzerland, is a five story building with 10 flats on an energy reference area of 1706 m^2. The objective of the building energy concept was to reach a plus energy balance including surplus for electric mobility. Therefore, both on the roof and in the façade PV systems are integrated, as shown in Figure 61 left for the PV balustrade at the balconies of the single flats and in Figure 61 right for the roof top integrated PV system. The building has been commissioned in spring 2018 and monitored from the beginning. For the evaluation the measurement period of the whole year 2019 was selected.

Figure 61: Back-view of the building Sonnenpark Plus with façade integrated PV in the balcony (left) and air-view with roof integrated PV-system

2.6.1 Building envelope concept

The building is certified according to the Swiss passive house standard MINERGIE-P®, which implies efficient building envelope components with respectively low U-values. Table 17 summarises the characteristics of the building envelope. U-values of the building components are in the range of 0.10-0.18 W/(m^2K). The windows are triple-glazed with a U-value of the glass of 0.6 W/(m^2K) and in the range of 0.8 W/(m^2K) for the entire windows, which are typical values of passive house components. Consequently, the calculated space heating demand is 17 kWh/(m^2a), which almost meet the limit of 15 kWh/(m^2a) for passive houses.

Table 17: Characteristics of building envelope

	U-Value [W/(m²K)]
Exterior wall / Roof / underground car park / Window	0.10 / 0.12 / 0.18
Window	0.8 (g-value 0.53)

2.6.2 Building system technology

Figure 62 shows a hydraulic sketch of the building technology system. The core component is a two-stage ground-coupled heat pump of max. 22.9 (11.9) kW_{th} capacity / COP 4.6 (4.9) at B0/W35. The heat pump is connected to the ground heat source of two 40 mm vertical Duplex ground probes of 230 m depth each. The ground is also used for free-cooling in summertime. The central mechanical ventilation systems with nominal heat recovery efficiency of 85% supplies the flats with a maximum total volume flow rate of 1350 m^3/h.
For the DHW operation a 1800 l DHW storage is integrated. In order to guarantee the legionella protection despite the temperature limit of 55 °C for the heat pump operation, an electrical back up heat heat up the storage to 60 °C.
A 300 l heating buffer storage is also integrated. The heat is emitted by wall heating in the flats. The design temperature of the wall heating system are 35/28 °C. The buffer storage is loaded to 40 °C and is also connected to a ventilation air reheater with the same design temperatures as the wall heating, so that space heating can additionally be provided by the ventilation air. In summertime, the free cooling energy from the ground is also emitted by the wall heating.

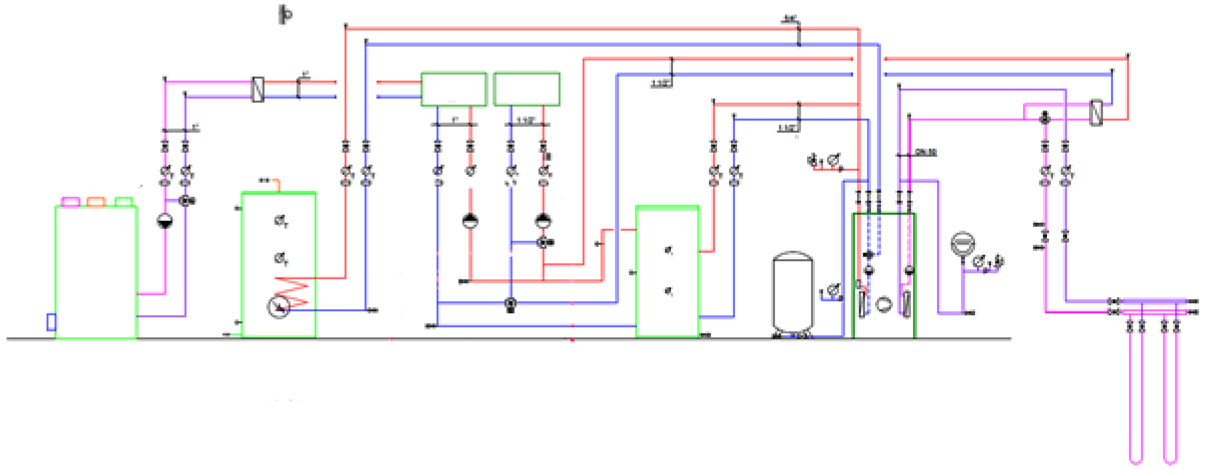


Figure 62: Hydraulic sketch of the building technology system

In order to reach a plus energy balance, a solar PV system is installed, which is composed of 44.55 kW_p on the roof, in south-west and north-east direction, and 36.1 kW_p façade-integrated, of which 21.1 kW_p are integrated in the south-east façade, and 15 kW_p integrated in the south-west façade. Additionally, an electric battery of a 78 kWh capacity serves as electric storage. Moreover, a shared electric car for the tenants is parked in the underground car park, which is integrated under the building. A charging station is installed near the parking space of the electric car with a charging power of 22 kW.
In order to optimise the on-site PV electricity consumption, all electric components of the building technology are connected to a smart energy management, by which the self-consumption shall be optimised.

2.6.3 Monitoring system

By the smart energy manager the electrical power can be balanced quite detailed, since most electrical consumers are connected to it.
For the thermal measurement energy meters are installed for the single flats in order to accomplish the billing of heating costs.
The produced energy by the heat pump was to be evaluated by the heat pump internal measurements of the produced condenser heat. However, due to a measurement error the produced heat of heat pump could not be evaluated, but just the electric energy was available by the smart energy manager. Thus, the SPF_{HP} could not be evaluated by the monitoring values, but just the SPF_{sys} of the used energy of the system based on the measurements in the flat. Nevertheless, in order to depict the entire system in an energy flow diagram, see Figure 72, the heat pump SPF was estimated by on the source and sink temperature levels, the electric consumption and the HP performance map. Since this is affect by insecurities, though, detailed measurement are planned for the next heating period.
The measurements were taken since the commission of the building in May 2018, and the evaluation was started in March 2020 after the contact of the building owner to the university. As evaluation period, the year 2019 was chosen, which is the first heating period and the first year where year-round data are available.

2.6.4 Comfort evaluation

In one of the flats, sensors for measuring the indoor environment parameters of the room temperatures, the relative humidity and CO_2-measurements have been temporarily installed.
Figure 63 show hourly averaged values of the room air temperature as an indicator for the operative temperature. Due to the high performance building envelope, the indoor surface temperature have high temperature in the range of the room air temperature, so the air temperature corresponds in good agreement to the operative temperature.

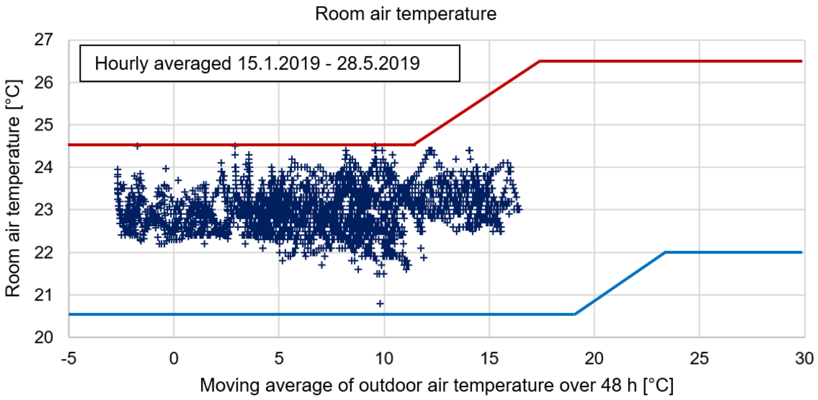


Figure 63: Measurement results for room air temperature depicted in the comfort range according to SIA 180:2014

The temperatures are well in the middle of the comfort range according the SIA 180:2014. All temperature are inside the comfort range. As observed in many field monitoring, indoor air temperatures are rather in the range of 22-24 °C than in the range of 20-21 °C as used in many calculation method of the space heating demand.
Figure 64 show respective 5 min average values of the relative humidity and CO_2 concentration. The relative humidity is mainly in the comfort range between 30 and 60%. However, in wintertime the minimum values go down to 20%, thus, there is a slight tendency of too dry air in winter. However, most of the time the relative humidity is above 25%, so the times of too dry air is limited. Due to the CO_2-demand controlled ventilation, also the indoor air quality is well below 1000 ppm.

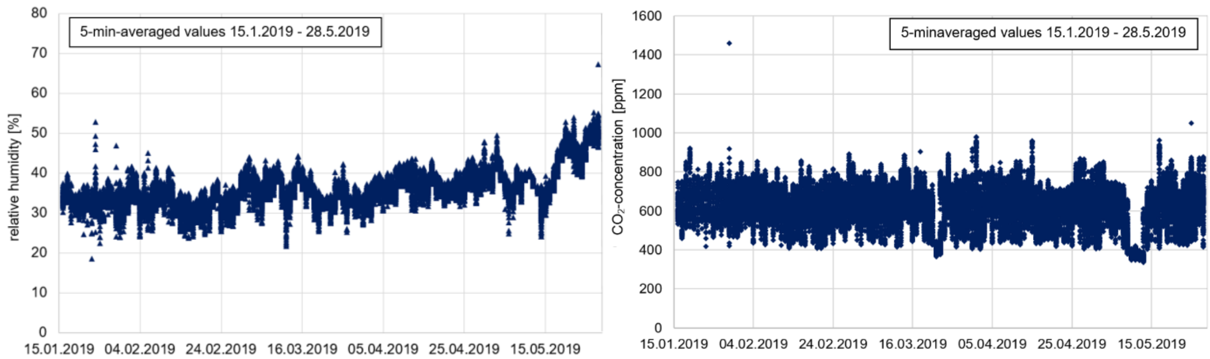


Figure 64: Measurement results for indoor environment parameter relative humidity and CO_2-concentration

2.6.5 Energy consumption

The annual used heat and a breakdown of the electricity are given Figure 87.
The total space heating demand is 28004 kWh or 16.4 kWh/(m²a), which corresponds well to the planning value of 17 kWh/(m²a). Despite the certified building envelope according to MINERGIE-P® the share of space heating energy is about 75% of the total heat demand of the building, while the DHW operation only accounts for 25%. The DHW demand of only 9419 kWh or 5.52 kWh/(m²a) is thereby notably lower than the standard value of 19.8 kWh/(m²a). Table 18 summarises the heat balance of the building, which also includes the planning values.

Table 18: Monitored space heating and DHW energy compared to planning values

	Monitoring [kWh/a]	Monitoring specific [kWh/(m²a)]	Planning [kWh/(m²a)]	Deviation [%]
Space heating	28,004	16.4	17	-3.4
DHW	9,419	5.5	19.8	-72.1
Total	37,423	21.9	36.8	-40.5

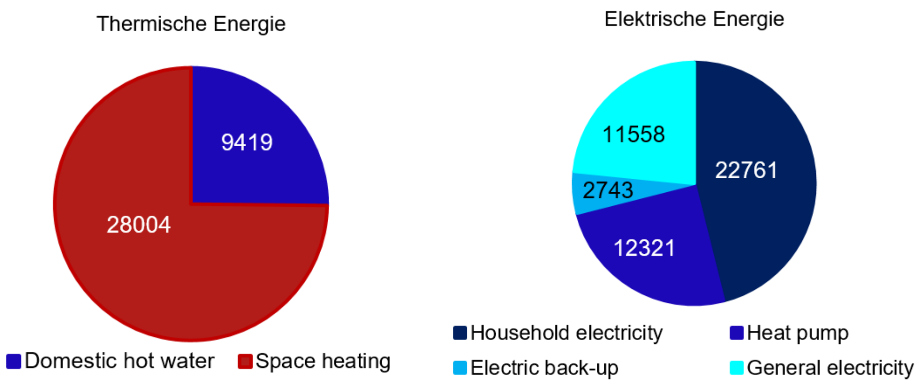


Figure 65: Measured used heat for space heating and DHW (left) and electricity breakdown to the electric consumers (only living, without e-mobility)

One reason for the low DHW energy consumption may be a specific user behaviour. However, another reason is that the building is relative weakly occupied for a multi-family house based on the energy reference area. In the multi-family standard use according to SIA 2024 (2015), the specific area per persons is 30 m^2/person, which would lead to a nominal occupancy in the range of 56 persons. Currently, on 26 persons are living in the building, which is only about 50% of the standard use and rather corresponds to single family use. Thus, the nominal DHW use would double and thus reach about 50% of the total heat consumption, which is the in the range to be expected in passive house.

Figure 65 left shows the breakdown of the measured electricity consumption for the living and building operation without e-mobility, which adds 3500 kWh to the consumption. The total consumption including e-mobility adds up to 52882 kWh, of which the household electricity of appliances, plug load and illumination in the flats make up the largest fraction with 42% or 22761 kWh. For space heating and DHW, the heat pump and the electric back-up consume a fraction of 17% or 15064 kWh, whereby the direct electric heating has a relatively high fraction of 18% or 2743 kWh, despite it is only used for the DHW legionella protection. General electricity for the building outside the flat is responsible for 11558 kWh or about 23%.

2.6.6 PV-yield and annual energy balance

The objective of the building concept was a plus energy balance, which can also cover the need of an electric vehicle for the tenants. Moreover, by the smart energy manager, most of the PV yield shall be used to cover the energy needs of the building by PV self-consumption. The total DC yield of the PV system is about 67,100 kWh/a, of which 64,100 kWh/a are used as AC electricity after the inverter, leading to an inverter efficiency of 96%. The overall specific yield of the PV system is thus 795 kWh/kW_p installed capacity. Thereby, the roof top system reaches 1,005 kWh/kW_p, while the façade reaches with 535 kWh/kW_p only 53% of the roof system. The yield of the façade is lower than the theoretical value in the range of 65% for south-east or south-west facades according to Figure 52. One explanation for the reduced output is that the facades are partly shaded due to trees and surrounding buildings. Table 19 summarises the PV yield of the roof and façade system.

Table 19: Monitored values of the PV system

	Installed capacity [kW_p]	Specific yield [kWh/kW_p]	Absolute yield [kWh/a]	Fraction [%]
PV Roof	44.55	1005.4	44789.7	70
PV SW façade	14.97	5404.91	7573.5	11.8
PV SE facade	21.12	554.9	11718.9	18.2
Total PV yield	80.64	792.7	64082.1	

Figure 66 shows the balance between on-site PV electricity production and consumption as specific values. The surplus of the annual balance in absolute values is 10211 kWh, so the intended plus energy balance is reached. The shared car with a consumption of 3500 kWh can be also covered by the PV surplus in the annual balance.

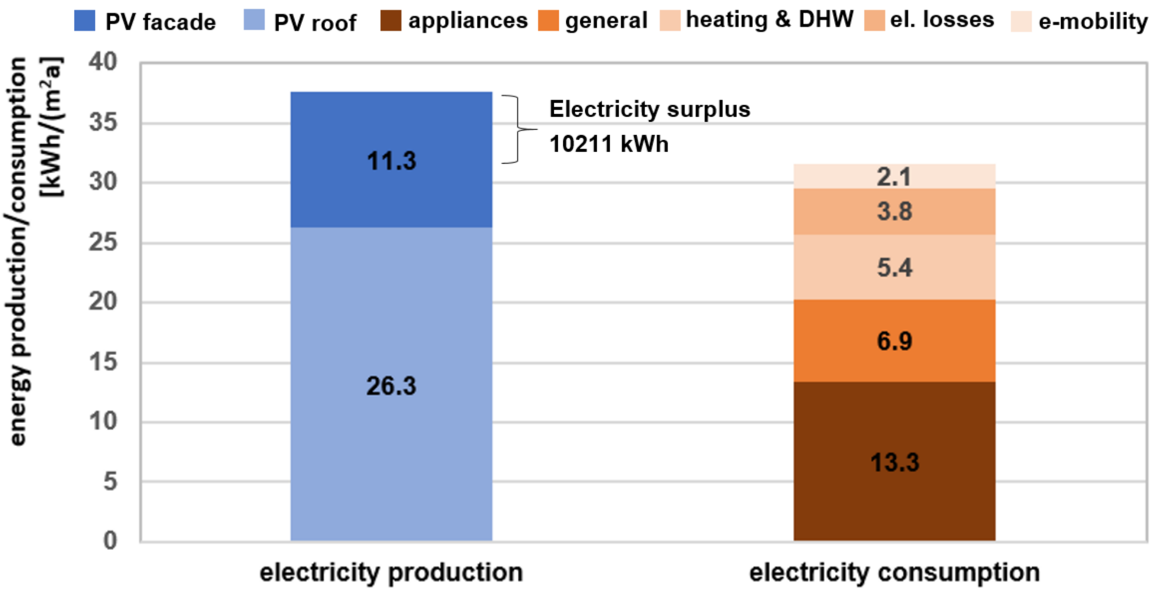


Figure 66: Measured used heat for space heating and DHW (left) and electricity breakdown to the main consumers

Even though the consumption of the e-mobility is quite low due to limited use of the electric car by the tenants, there is still some reserve in the annual surplus for future more frequent use of the electric car. The losses depicted in the balance of the energy consumption refer to the inverter and the battery losses, which make up about 12% of the consumption. It also becomes clear in the balance, that without the façade yield, the plus energy balance could not be reached. Thus, in the case of multi-story multi-family buildings, it is very hard to reach a plus energy balance with PV only installed on the roof.

2.6.6.1 Seasonal analysis of PV yield and PV self-consumption

A more detail analysis of the seasonal PV yield on monthly basis split-up into the roof and façade system in depicted in Figure 67. The fraction of the façade yield is 19292 kWh or 30% of the total PV production of 64082 AC production despite the installed capacity in the façade is with 37 kW_p only 7.5 kW_p lower than the installed capacity on the roof with 44.5 kW_p. Regarding the seasonal distribution of the PV electricity, 72.3% is produced in the six summer month from April to September, whereby the roof system yields about 75% of the production. Even in the winter month of October to March, the façade only yields a fraction of 40%, so even with lower sun position, the roof production is higher than façade production. Only in the month of January, the façade production surpasses the roof production with a fraction of 62%. Thus, despite a similar installed capacity, the roof is also dominating the production in wintertime, and the peak in the summer month is still quite pronounced. Thus, based on these monitoring data, a shift by the façade to a more even production by a shift from summer production to the transitional or even winter production is not particular distinctive.

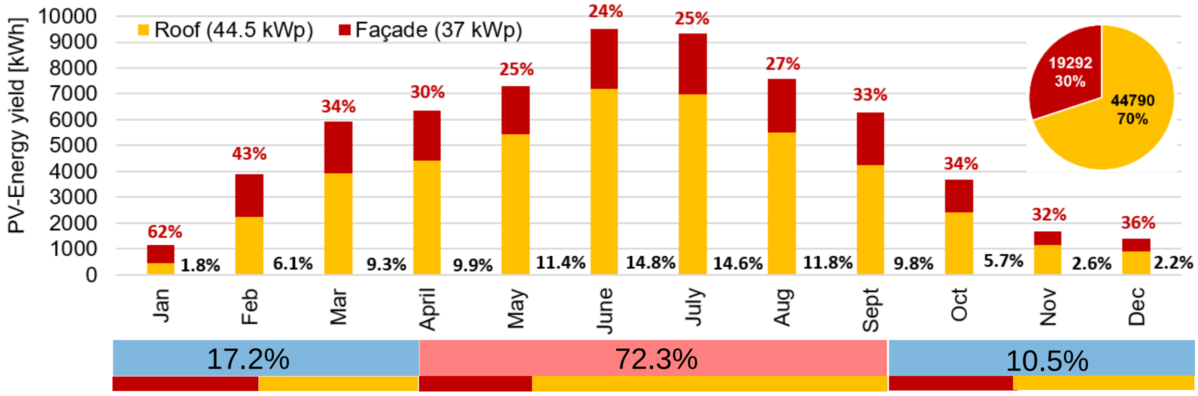


Figure 67: Seasonal distribution of PV-yield of roof and façade

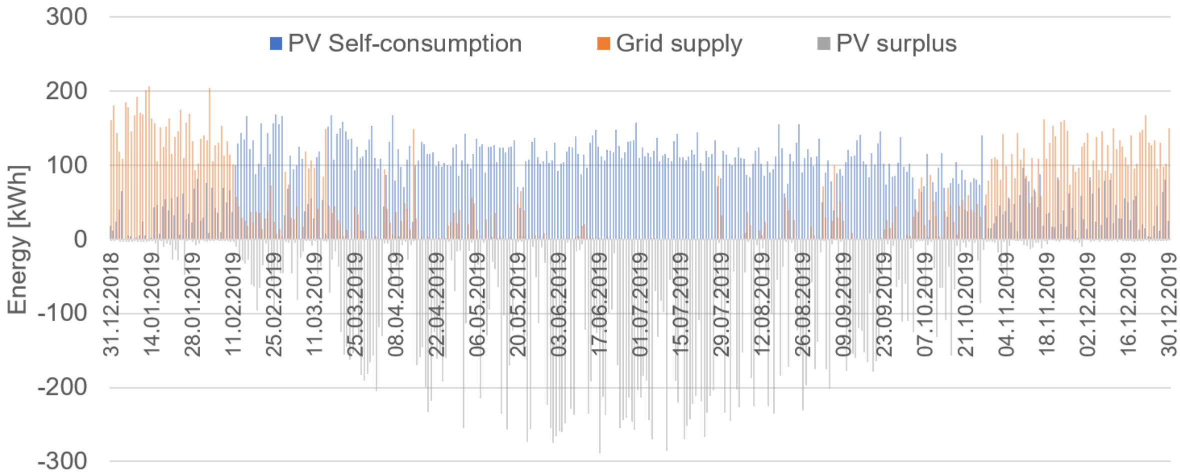
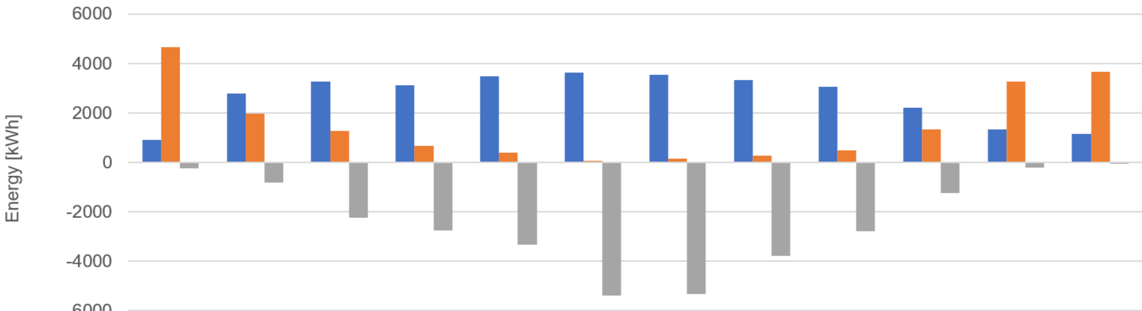


Figure 68: Daily electricity balance of PV yield, grid supply and PV self-consumption

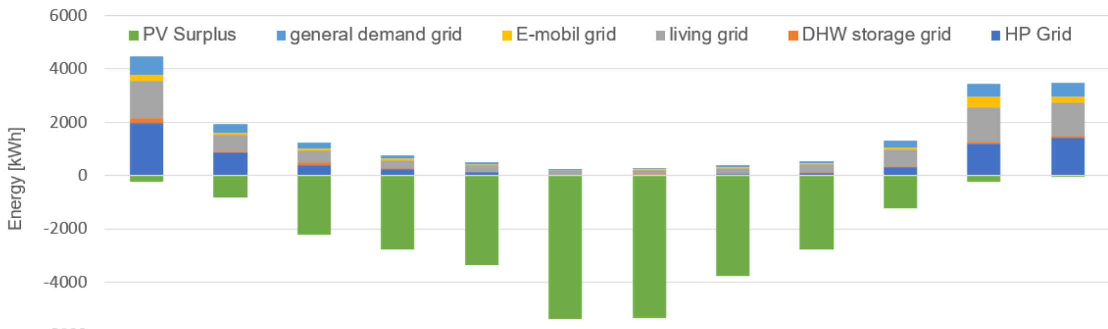
Figure 68 shows the daily and Figure 69 the monthly balance of PV self-consumption and PV surplus (depicted negative as grid export) as well as grid supply (depicted positive as grid import). Also in these figure, the pronounced summer production is clearly visible. However, from March to October, already significant PV surplus exists and main grid supply is limited to the core winter month of November to February. In total, 40% or 22600 kWh of the total PV production is export is exported to the grid, with surpasses annual grid supply with about 18550 kWh.



	Jan	Feb	March	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec
PV Self-consumption	899	2778	3253	3129	3478	3637	3537	3332	3067	2202	1325	1157
Grid supply	4663	1968	1278	670	395	72	144	273	479	1332	3263	3658
PV Surplus	-246	-807	-2235	-2761	-3343	-5393	-5331	-3778	-2786	-1239	-228	-65

Figure 69: Monthly electricity balance of PV yield, grid supply and PV self-consumption

Figure 70 completes the picture of the monthly PV balance with the electric consumers covered by PV self-consumption and grid supply.



	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
PV Surplus	-246	-807	-2235	-2761	-3343	-5393	-5331	-3778	-2786	-1239	-228	-65
general demand grid	702	310	222	116	70	16	22	59	97	274	502	507
E-mobil grid	209	71	73	56	32	1	19	22	39	74	371	228
living grid	1402	650	472	300	245	182	160	225	295	629	1320	1252
DHW storage grid	165	43	76	27	1	1	20	0	14	12	75	71
HP Grid	1980	857	409	261	148	17	29	72	112	332	1184	1424

Figure 70: Monthly electricity balance of PV yield, grid supply and PV self-consumption

Due to the well-insulated building envelope and due to the higher share of space heating demand, the main operation of the heat pump is concentrated to the four winter month November to February. In the summer month the grid import is almost negligible and almost the entire consumption is cover by on-site PV production. Notably, also the PV surplus reaches very high values in the summer month, which affects the grid interaction during the summer month.

Figure 71 depicts the month PV yield, the monthly consumption and the monthly self-consumption as well as the load cover factor (LCF) and supply cover factor (SCF) based on hourly measurement values. The curves of the load and supply cover factor correspond to the typical form with an increasing load cover factor in summer an increasing supply cover factor in the winter operation, see chap. 1 for definition and explanation of the characteristic. As annual values, a load cover factor or autarky of 64% is reached, while the supply cover factor or the PV self-consumption is 53.6%, which are quite high values regarding the occupancy of the buildings, which rather correspond to the single family use.

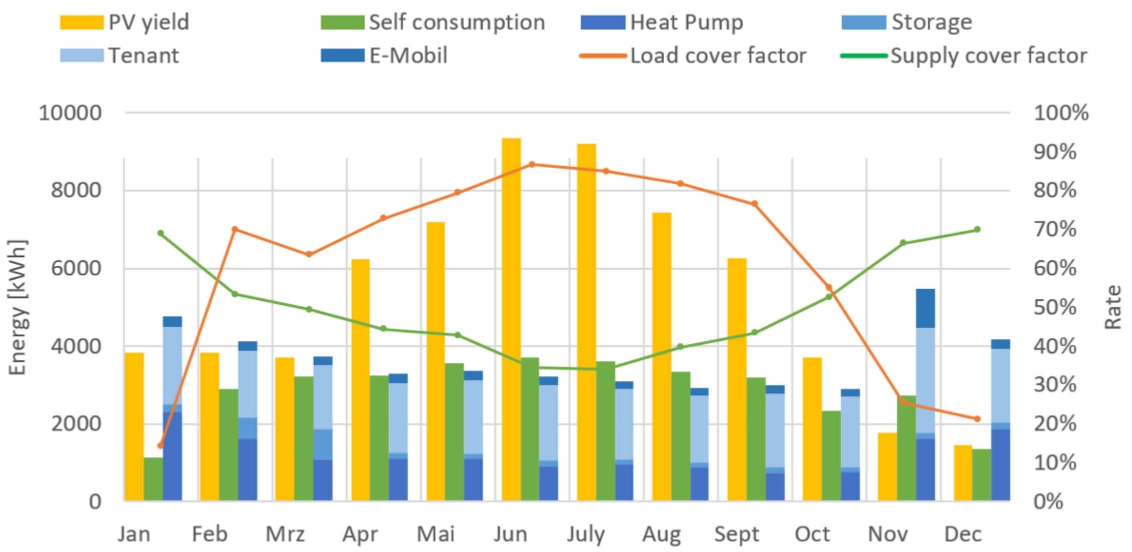


Figure 71: Monthly load cover factor and supply cover factor based on hourly measurement data electricity balance of PV yield, grid supply and PV self-consumption

2.6.7 Energy balance

The complete energy balance from the monitoring data of 2019 in depicted as Sankey diagram in Figure 72. The upper part of the diagram depicts the electric balance, while the lower part with the light blue and purple energy balance shows the thermal energy balance of the space heating and DHW operation. As mentioned before the produced thermal energy and the performance factor of the heat pump could not be evaluated from the monitoring and is amended as calculated value, which is depicted by the light blue background. Also the storage losses of the heating buffer storage and the DHW storage had to be estimated based on maximum allowed storage losses based on the storage size from the Swiss energy law. The total energy balance also includes the source energy extracted from the heat source as well as the operation of the electric battery.

2.6.8 Primary energy balance and avoided CO_2-emissions

Figure 86 illustrates the PV surplus in terms of delivered energy, primary energy and avoided CO_2-emissions. The primary energy and the avoided CO_2-emissions have been calculated based on the Swiss consumer mix, which has a total primary energy factor of 3.08 and total CO_2-emissions of 102 g/kWh, which explains the relatively small CO_2-emission savings. The Swiss consumer mix, though, also considers imported and exported electricity. Since most electricity is imported from French nuclear power plants, the discrepancy between the rather high primary energy factor of 3.08 and the rather low CO_2-emissions can be explained, since the nuclear power has very limited CO_2-emissions for the operation. The Swiss production mix has for the internal balance has a lower primary energy factors.

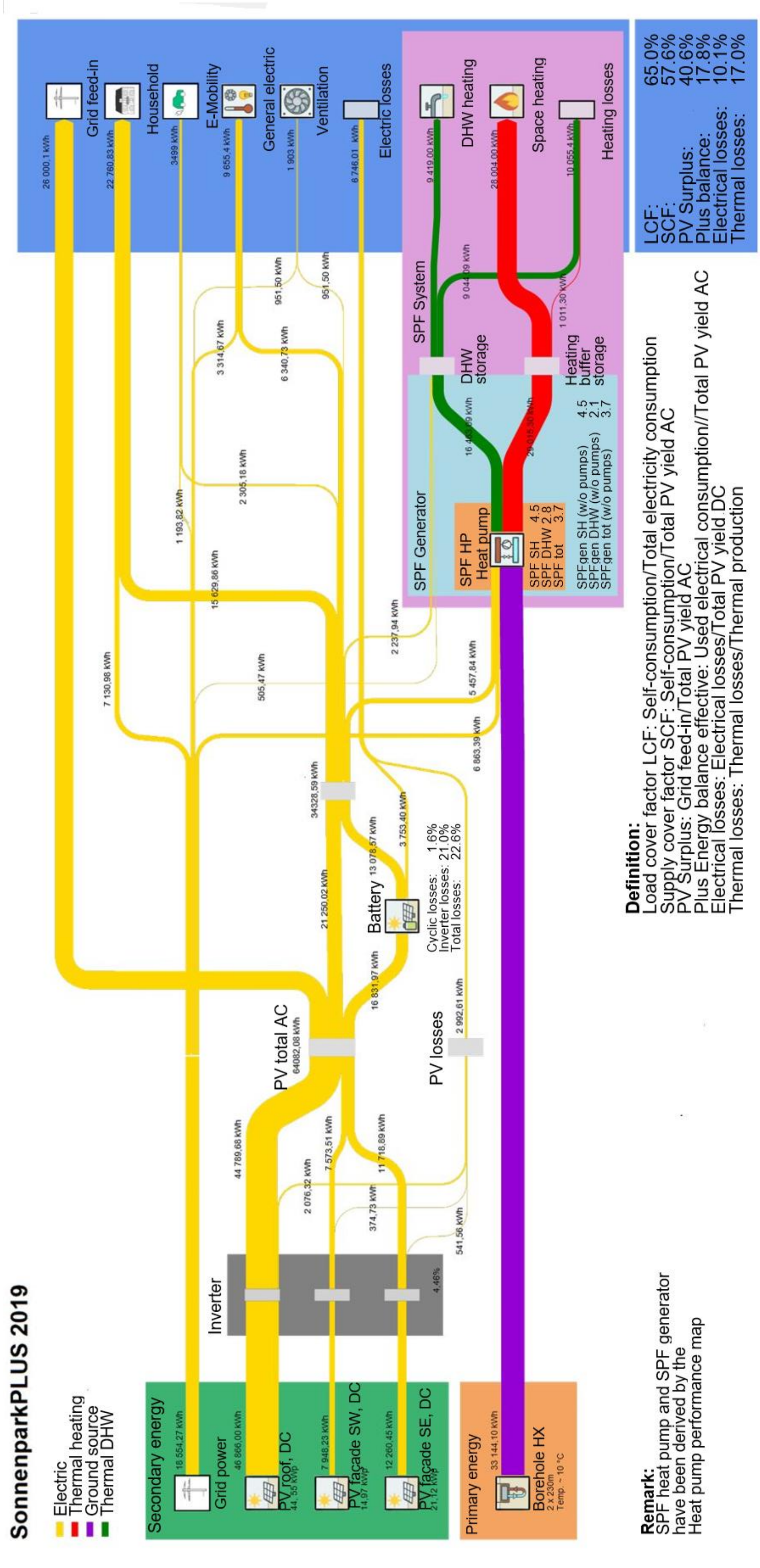


Figure 72: Sankey diagram of the energy flows of the SonnenparkPLUS for the measurement year 2019

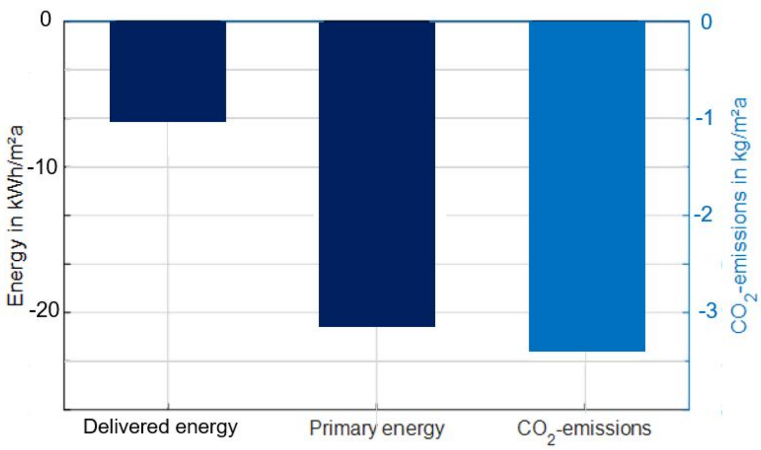


Figure 73: Primary energy and avoided CO_2-emissions for the measurement year 2019

2.6.9 Conclusion

In conclusion the building reaches both the MINERGIE-P label for the Swiss passive houses and the MINERGIE-A label for the Swiss NZEB and even a PV surplus of 20% compared to the consumption and 40% compared to the production. However, the plus balance also depends on the use of the building. The occupancy is with 26 persons rather low, and the break even point for the plus energy balance would be 35 inhabitants with standard residential multi-family use, which is still below the standard occupancy. This consideration underlines the challenge to reach a plus energy balance in multi-story multi-family buildings, which always requires a PV installation in the façade.

2.7 Multi-family plus energy building Allmendholz

2.7.1 Introduction

A sustainable, future-proof form of living was a focus of the Allmendholz multi-family building with four flats, which was built in 2017 in Horgen (ZH). The wooden element construction, mostly made of local wood, was built as a replacement of an older single-family house and thus realises an inner densification in the neighbourhood. Figure 74 shows different views of the multi-family house.
The building fits into the topography of the hillside. A complete basement was deliberately omitted in favour of a small excavation volume. A natural cellar (outside the insulation perimeter) is available for storing the harvest of the connected garden.
The project was not scientifically accompanied as a research project, but only examined in more detail after commissioning by the inhabitant of the building. A focus of the energy balance is the performance of the low temperature lift heat pump of the Swiss company BS2 AG, which was developed by one of the inhabitants, so that the building could be used as a test case and support an adapted planning of the system technology in the future.

Figure 74: Street View (left) and bird's eye view of the multi-family house in Horgen with four flats

2.7.2 Building envelope

The building consists of two storeys with four flats on a total energy reference area of 500 m^2. It is located in Horgen, ZH, on a hillside close to the lake Zuerich. The building envelope was based on the requirements of the Swiss MINERGIE®-label, but the building has not been certified. Table 20 summarises the U-values of the building envelope components. Despite the low U-values of the building envelope, the calculated space heating demand is 40 kWh/(m^{2}yr), which is due to the fact, that a mechanical ventilation system was deliberately avoided, as the building is located in a quiet residential area, so window airing does not increase the noise inside the flats for the air exchange. Thus, no heat recovery is installed for recovering the ventilation losses.

Table 20: Characteristics of building envelope

	U-Value [W/(m²K)]
Exterior wall / Roof / ground floor	0.18 / 0.13 / 0.12
Windows	1

2.7.3 Energy concept of the building system technology

The building technology was implemented according to the principle of "simple but efficient". Figure 75 gives an overview of the system configuration. The heat pump system corresponds to the current standard, but with an optimized design. The two geothermal probes were drilled around 30% longer than required by Swiss design standard SIA 384/6 (2010), with the aim of operating the probes at high temperatures in order to avoid the use of antifreeze fluids.

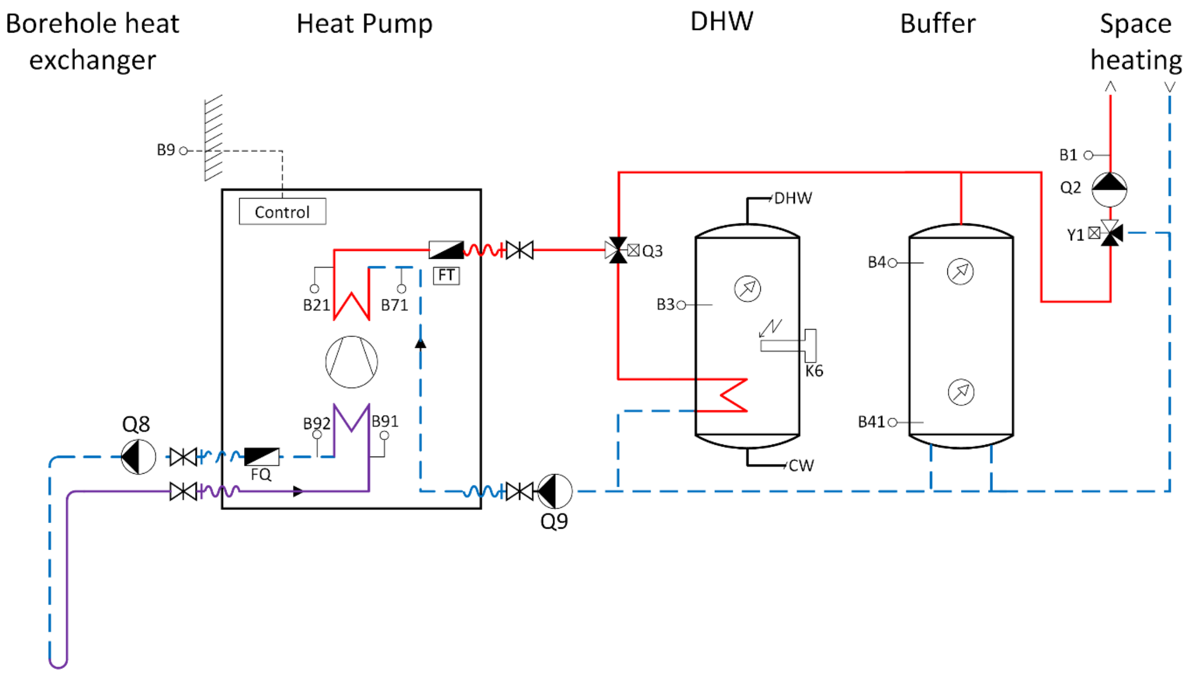


Figure 75: Hydraulic sketch of the heating system

The capacity-controlled heat pump was especially developed for systems with high source temperatures and low temperature lift, i.e. the refrigerant cycle is optimized for systems with high source and low sink temperatures.
The complete system control for the two geothermal probes of each 225 m, including a solar circuit control for the regeneration (not installed in this system) is integrated. Moreover, it has an integrated monitoring, which simplifies the optimization of operations.
In addition, all measured values can be recorded and analyzed with a "Cockpit", see chap. 2.7.4. Flow sensors are installed in both the source and the sink circuit. These do not only provide valuable information, but also protect the primary circuit from freezing since no antifreeze protection is used.
Although not absolutely necessary with a capacity-controlled heat pump, a heating buffer storage of 1000 L is installed in this system. Reasons are on the one hand the relatively low thermal mass of the wooden structure and the wall heating, and on the other hand, it was intended to increase the self-consumption from the on-site generated PV-electricity. The 13.3 kW_p solar PV system on the roof is optimized for high yield with a south-east orientation and 7° of inclination. In order to optimize self-consumption, the hot water preparation is primarily triggered by the heat pump when there is enough solar power. Second, the heating storage is overloaded to a predetermined level of higher temperatures than the supply temperature.
An 800 L DHW storage is integrated for the domestic hot water operation. The installed heat pump heats the DHW to the temperature level of 55 °C in the hot water storage. Additionally, a direct electric heating element is installed in the DHW storage in order to provide a temperature level of 60 °C two times a week for legionella protection.
Moreover, each apartment has a small wood stove, which creates a cozy atmosphere in winter. The heat input from the wood stoves is taken into account in the evaluation using the estimated wood consumption.

2.7.4 Measurement concept and monitoring system

With the exception of the electricity meter for the direct electric heating element, which was also installed as part of the SFOE project "Managing domestic hot water energy consumption" (Hässig et al, 2019), it was possible to rely on existing measuring devices:

- Internally measured and calculated values from the heat pump
- Heat meters, hot and cold water meters in the individual apartments
- Electricity meter for the individual apartments and general electricity use
- PV inverter with Smart Meter

The energy monitoring is evaluated every six months by the recording of incidental cost. The information on self-consumption is determined by the PV inverter and is based on 5 min values. The values were recorded for the entire building and not broken down to the individual apartments or building technology fractions.
The heat pump records detailed data (temperatures, states, pressures, etc.) at intervals of 1-2 minutes. This data is only saved for 48 hours and then overwritten again. However, they allow certain situations to be analyzed in detail in real time. It is possible to read out and save this data via ethernet, but it was not necessary for this evaluation.
Monitoring started in July 2018 and continues to date. The evaluation period was chosen from July 2018 to June 2019. The total of heating degree days (location: City of Zurich) for this period is 3140 heating degree days, just below the average of the last ten years of 3198 heating degree days, so the monitoring period reflects an average winter period of the region. In view of the increasingly warmer winters, fewer heating degree days can be expected in the future.
The "Cockpit" depicted in Figure 86 is integrated in the heat pump as monitoring interface and enables simple evaluation and access to all of the heat pump's recorded data.

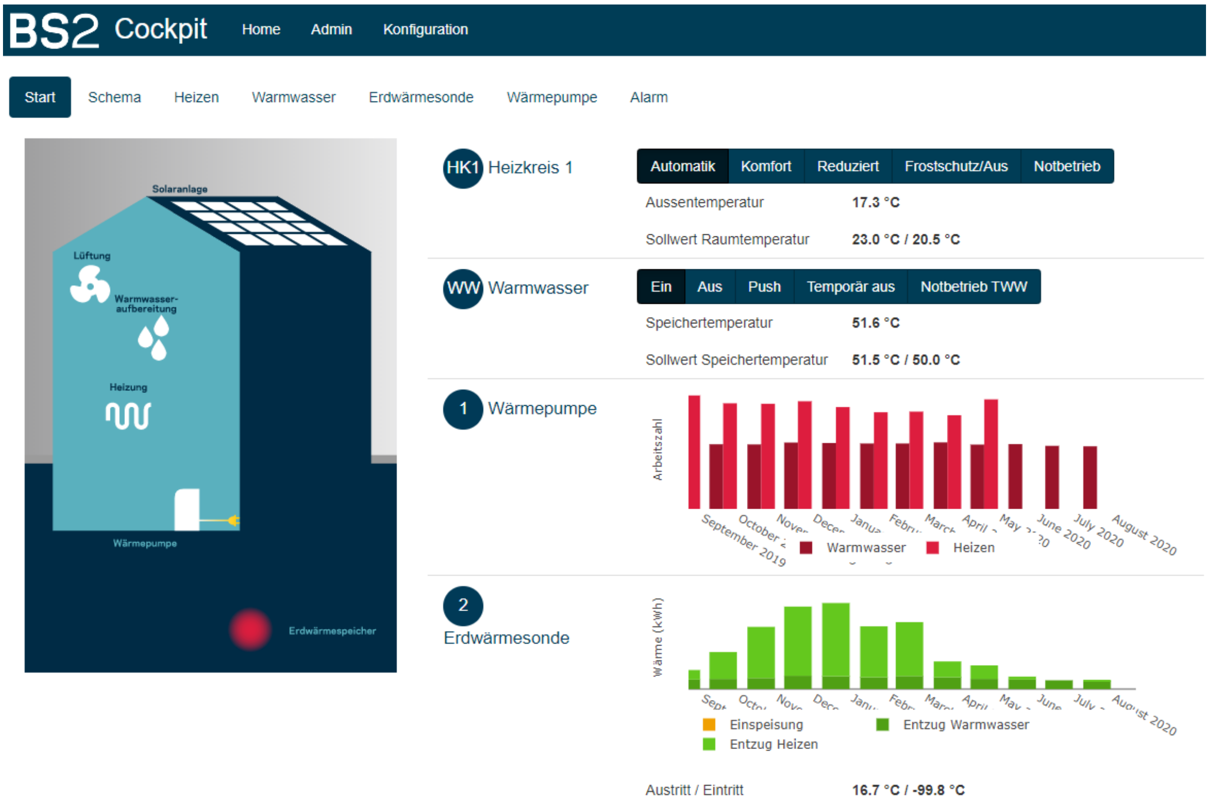


Figure 76: Main page of the interface of the "BS2 Cockpit" energy monitoring system

2.7.5 Monitoring results

In the annual balance, around 40% more electricity is generated on the roof than required for the building use, i.e. a clear plus energy balance has been reached in the monitoring period. Figure 87 shows the overall electricity balance of the building. Regarding the electricity consumers, the heat pump makes up about 40% of the total electricity consumption and is the main consumer besides the household appliances. The PV system yield an energy surplus of 12.4 kWh/(m^{2}yr), which is 43% of the total PV yield of 29 kWh/(m^{2}yr) or 14788 kWh as absolute value.
Figure 78 shows a detailed breakdown of the thermal and electrical energy. Despite an efficient building envelope on MINERGIE® level, the DHW fraction is only 27% while the major part is the thermal energy for space heating. Regarding the electrical energy space heating operation of the heat pump is almost on the same level as the DHW fraction, since the SPF in space heating is significantly higher than the DHW operation, see chap. 2.7.5.1.

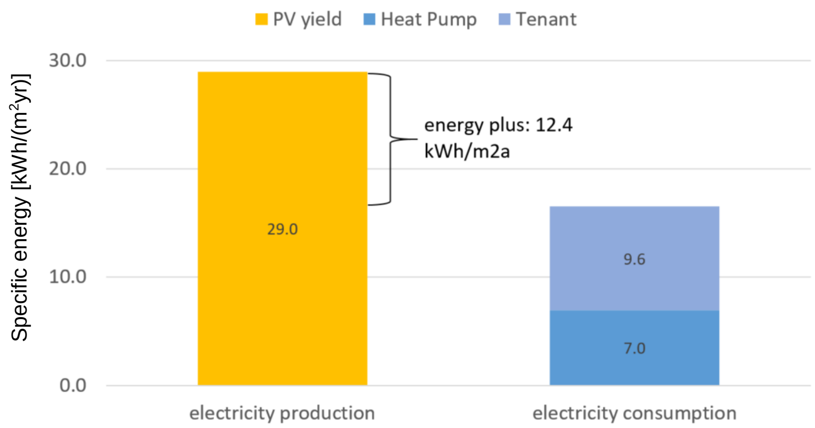


Figure 77: Calculated final energy demand and PV production in the monitoring

Space heating and DHW electrical energy constitutes a share of 41% and are in the same range as the residential use with a share of 43%. The rest is spent on general use, i.e. the non-heating electricity use dominates with 59%.

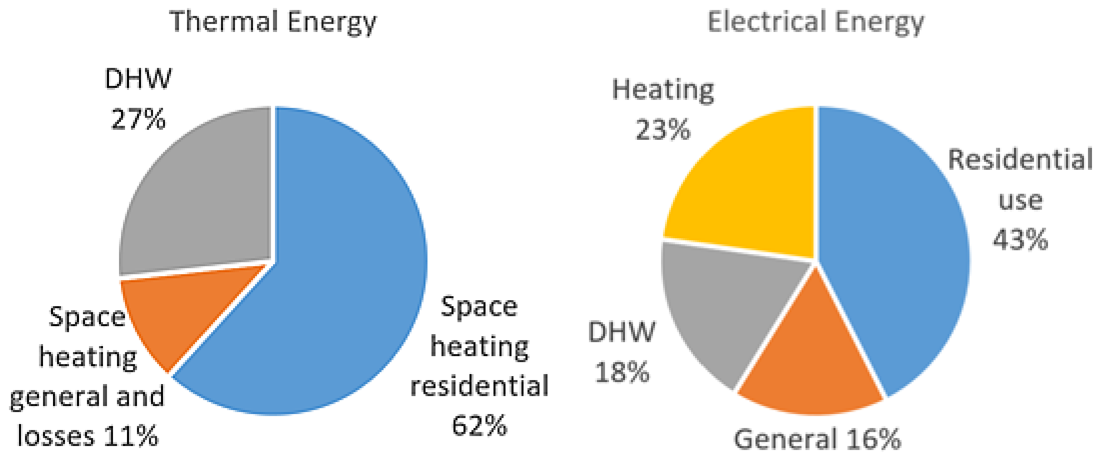


Figure 78: Thermal and electric energy fractions

Figure 79 depicts the overall energy balance and flows as Sankey-diagram. The heat pump reaches an overall SPF for space heating and DHW of 5.3.

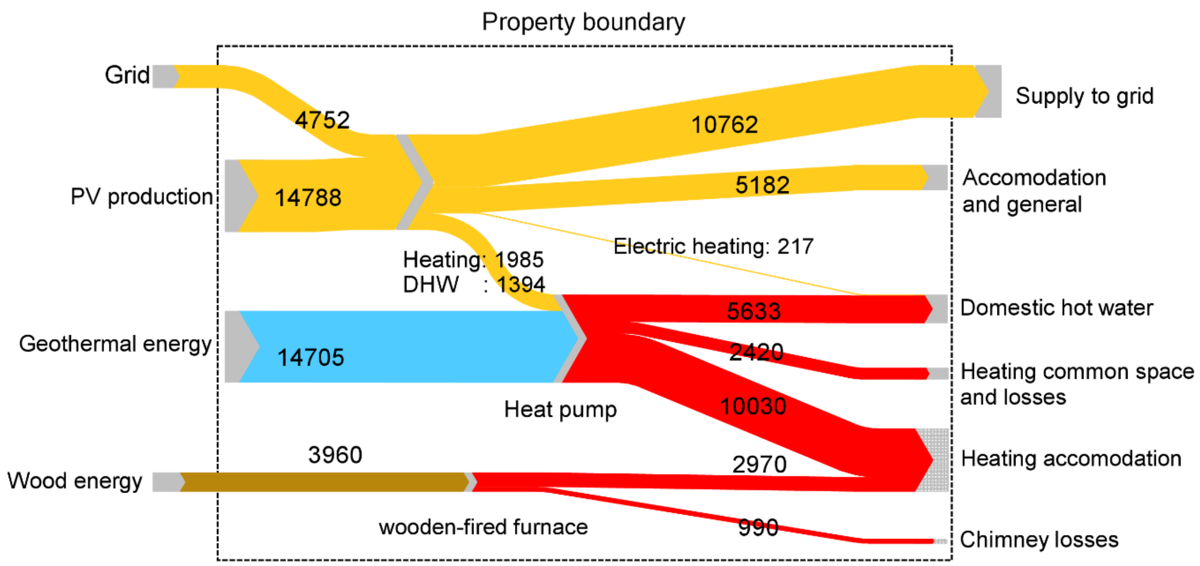


Figure 79: Sankey-diagram of the energy flows in the multi-family house Allmendholz

The good performance can also be concluded by the ratio between the geothermal energy and the HP electricity. The fraction of the electrical back-up heater for legionella protection adds up to only 3.8% of the DHW heating. The efficiency of the wood furnaces are in the range of 0.75, which is a typical value for smaller wood furnaces. Regarding the PV production, the on-site production makes up about 70% of the electricity entering the balance. The supply cover factor is 27% which corresponds to the fraction of generated PV electricity that is consumed on-site. The remaining 73% are fed into the grid. However, despite the annual surplus of 40%, the load cover factor, i.e. the fraction of the load covered by on-site generated PV, is only 45%. Details on the monthly distribution of the load and supply cover factor are given in chap. 2.7.5.2.

2.7.5.1 Seasonal Performance Factor (SPF)

Figure 90 shows the monthly averaged performance factor (PF). For hot water production, this is fairly constant throughout the year, slightly higher in summer as a result of the higher source temperature. In heating mode very high values up to a PF of 7 are reached. However, as can be seen, it is lower in the transition period which is a consequence of the increased self-consumption, which is further discussed in chap. 2.7.7.2.

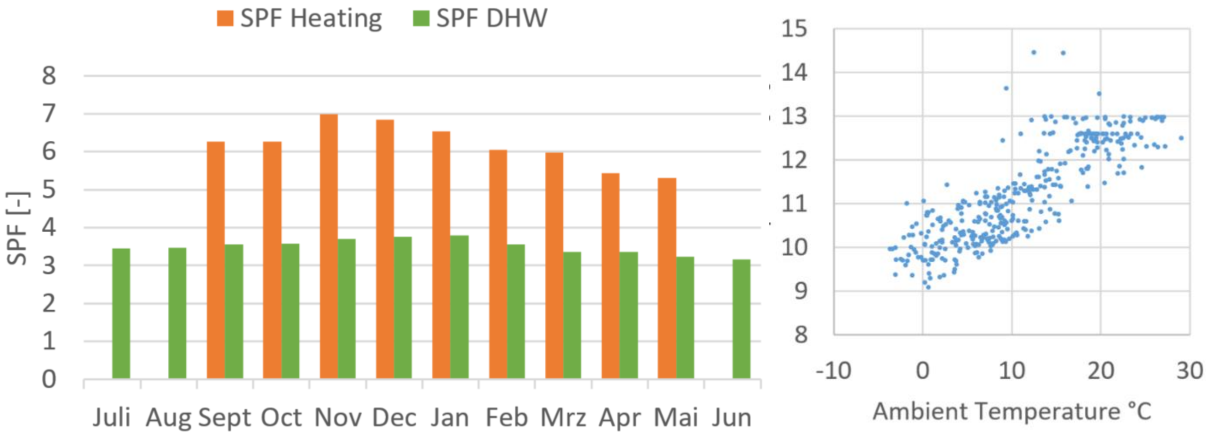


Figure 80: Monthly performance factor of the heat pump for SH and DHW (left) and borehole outlet temperature vs. ambient air temperature

The reasons for the very high performance factors in space heating mode is the low-temperature-lift heat pump, which optimally uses the high source temperatures of the larger design of the water-filled ground probes. The operation of the ground probes with water is environmentally leakage safe, and the water has a lower viscosity, which reduces pumping energy of the source pumps. Moreover, the water has a higher specific heat capacity, which reduces the volume flow of the source. Thanks to the "oversized" geothermal probes, the source temperature is constantly high. Figure 80 right depicts the evaporator inlet temperature vs. the outdoor air temperature. Even at cold outdoor air temperatures, the inlet temperature hardly falls below 10 °C, reaching the lowest values of 9 °C. The nonetheless existing dependency on the outside temperature is due to the extraction of heat and the resulting reduced outlet temperature of the ground probes. The power requirement increases as the outside temperature drops. This reduces the outlet temperature. The primary circulation pump is set to a temperature spread of 3 K.

2.7.5.2 PV production and self-consumption

Figure 81 depicts the monthly distribution of the PV yield and the electrical consumption split up into the household electricity of the tenants and the heat pump consumption as main consumer of the building system technology. Moreover, the monthly load and supply cover factors are depicted, which have been evaluated based on 5-minute averaged values. Notably, even in summer where the PV yield exceeds the electrical consumption by a factor of 6, still not the entire load is covered by the PV electricity due to daytime and night-time mismatch. This could be overcome the integration of an electric battery, which would significantly increase the load cover factor, which is with 27% rather low.

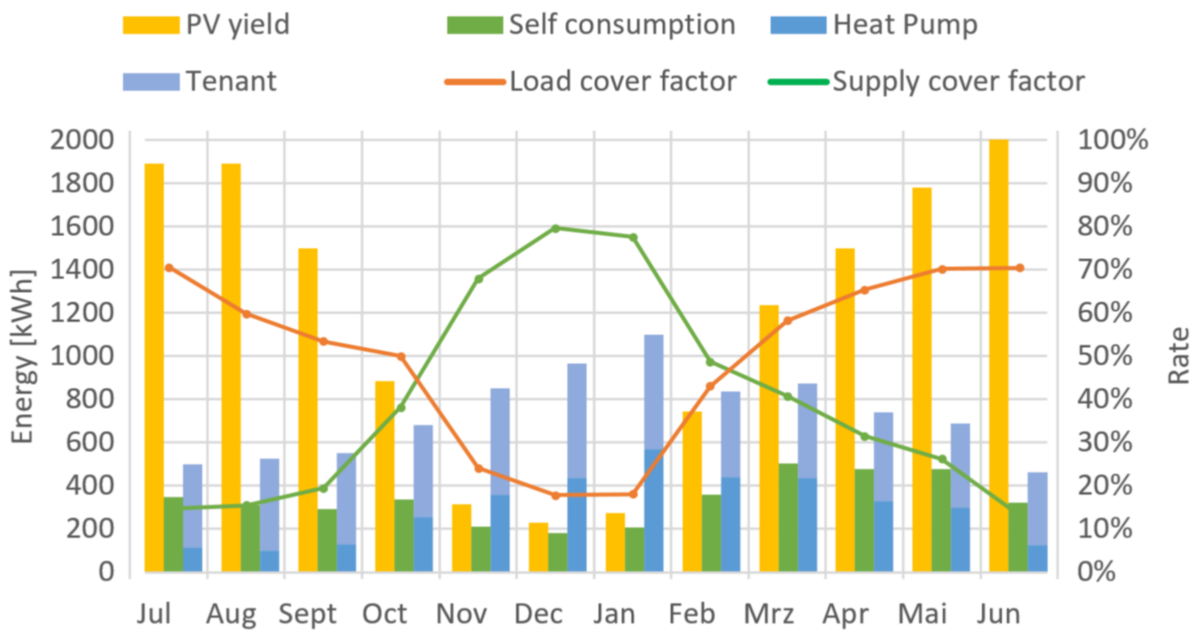


Figure 81: Monthly PV yield and electric use as well as monthly load and supply cover factor based on 5-minute evaluation

The typical annual evolution is clearly visible. The PV yield in summer is high and the loads are lower, thus, the supply cover factor is low, since only a small fraction of the total PV yield is consumed on-site, but the load cover factor is high, since most of the lower loads in summer can be covered by on-site PV yield. In winter, though, the characteristic is the other way round, since loads are higher and PV yield decreases, which leads to higher supply cover factors and lower load cover factors. In total, 75% of the PV yield is produced in the summer season, while only 25% in the six winter month from October to March. In the core winter the PV yield decreases to only about 15% of the maximum in the summer month. The sum of the winter month December to February is less than half to the yield in June. A comparison between the yellow and the blue bars depicts impressively the load mismatch, which results in the 40% surplus and explains the large fraction of grid export, which has already been discussed for the Sankey-diagram.

2.7.6 Comparison with design data

In Table 21 a comparison between the design data and the monitoring data is shown.

Table 21: Comparison of the design data with the results of the monitoring

	Calculation	Monitoring	Deviation
Space heating	40 $kWh_{th.}/(m^2yr)$ 6.1 $kWh_{el.}/(m^2yr)$	30 $kWh_{th.}/(m^2yr)$ incl. 7.9 $kWh_{wood.}/(m^2yr)$ 4.0 $kWh_{el.}/(m^2yr)$	-25 % -34 %
DHW	19.8 $kWh_{th.}/(m^2yr)$ 5.4 $kWh_{el.}/(m^2yr)$	11.3 $kWh_{el.}/(m^2yr)$ 3.2 $kWh_{el.}/(m^2yr)$	-43 % -40 %
Total electricity consumption		17.5 $kWh_{el.}/(m^2yr)$	
Electricity production PV **Load cover factor** **Supply cover factor**	26.6 $kWh_{el.}/(m^2yr)$	29.6 $kWh_{el.}/(m^2yr)$ 45% 27%	+11 %
SPF of heat pump **Heating (W10/W35, 10.5 kW)** **DHW (W10/W55, 10.5 kW)**	 6.5 3.7	5.3 6.3 4.0	 -3 % -5 %

Both the heating and hot water requirements deviate strongly from the calculated standard values. This is mainly caused by the sufficient user behavior. The 34% reduction in electricity required to generate heat is explained on the one hand by the low heating requirement and on the other hand by the generation of heat using the wood stoves, which was not taken into account in the design, since the wood stoves were mainly built for comfort reasons. However, since the residents use the stove quite frequently, about 20% of the space heating energy was generated with the stoves. In one of the four apartments the proportion was even about 50%. The heat pump therefore had to deliver significantly less heat as planned. According to the planning values, the heat pump had an output at full load that was approx. 30% too high, but still had enough lower output reserves to be operated at part load. Due to the significantly lower heat requirement, the power reserve has been increased so that the capacity control by the inverter can hardly be used. The PV yield is 11% higher than the calculated values, and reaches a particularly high specific yield of 1112 kWh/kW$_p$. As design value for Switzerland, values around 950-1000 kWh/kW$_p$ are used.

2.7.7 Discussion and improvements of the existing system

High performance figures are achieved in heating mode, but it could be even better. The following effects reduce the COP and performance factors, respectively.

2.7.7.1 Oversized heat pump

As already described in section 2.7.6, the heat pump is oversized. This shifts the design point to the left to lower heating capacities in Figure 82. The heat pump is only within the performance range at the coldest outside temperatures and will soon start to cycle. However, the range of the best COP is at higher speeds at 50-70% heating capacity. Furthermore, the figure shows the dependence of the COP on the heating capacity, which is roughly proportional to the compressor speed, i.e. for the operating point W10/W35, the range of maximum efficiency is around 9-13 kW. The figure also shows the power requirement (h/year) according to the SCOP calculation according to EN 14825.

The maximum running time was reached on 7th and 8th February 2019 with 39.8 h, i.e. an average of almost 20 hours per day including hot water preparation. This took 1.8 hours over the two days, i.e. 37 hours were spent on heating. During this time an amount of heat energy of 221 kWh was produced, which results in an average output of 6 kW in heating mode. Taking into account the water heating and the heat generated by the wood stoves, a design output of 8.7 kW would have been sufficient.

The average temperature on the two days was around 2 °C and was therefore not the coldest day of this winter. It should be noted, however, that the wood stoves are often in operation in winter and thus support the heat pump.

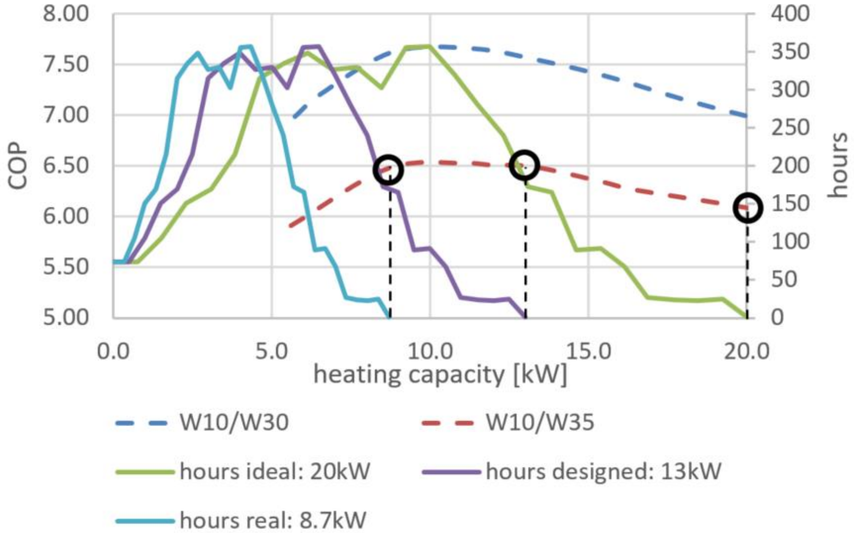


Figure 82: Application range of the heat pump. The dashed lines show the COP for a sink temperature of 30 °C and 35 °C. The solid lines show the number of hours. Due to the oversizing, the application range shifts to the lower COPs and higher part load COP by inverter control cannot be used.

The heat pump usually runs at the lowest speeds at which the COP is lower. There is the option of setting the heat pump so that it operates at higher speeds and thus better COP. The excess power produced is stored in the heating storage. With a fixed storage volume, however, the amount of heat that can be stored depends on the hysteresis of the storage tank charging. A large hysteresis, in turn, reduces efficiency. If the selected hysteresis is too small, the running times are reduced and the number of compressor starts increases, which reduces the compressor lifetime.
However, if the speed is too low over a long period of time, this can also have negative effects on the lifetime of the compressor, as the compressor cooling with the low refrigerant flow is not ideal.

2.7.7.2 Reduction in efficiency through increased self-consumption

Another cause of the non-optimal seasonal performance factor is the increased self-consumption. If the grid feed-in power of 2.3 kW is exceeded, the solar inverter sends a signal to the heat pump (SG-Ready).

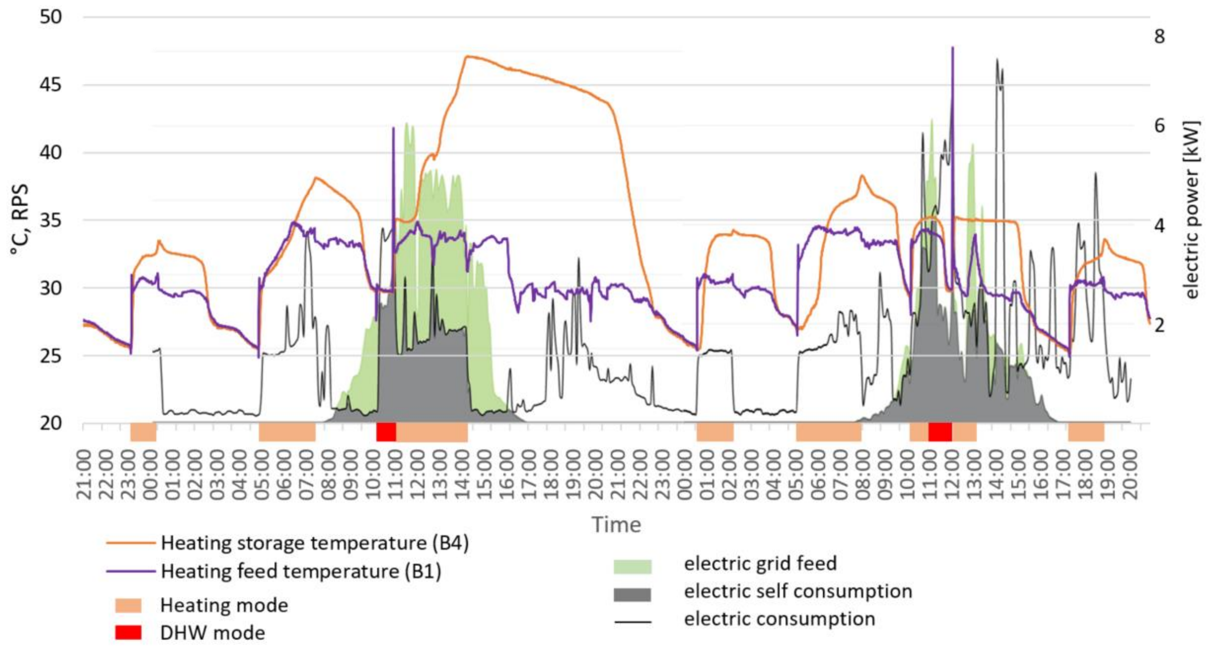


Figure 83: The temperature curve in the storage tank and the output of the PV system over 48 hours shows how the self-consumption optimisation works

The heat pump starts the compressor and charges the hot water storage tank in a first step. It then switches to heating mode and charges the heating storage up to a predefined temperature. The COP decreases as the temperature in the storage tank increases. The signal is deactivated again when a grid consumption of 500 W is exceeded. Figure 83 shows measurement data for self-consumption optimization over two days (12th to 13th November 2019). The heating storage tank is charged from 5 a.m. to 7 a.m. because the temperature level is too low. At 10 o'clock the inverter activates the SG-Ready signal. The heat pump charges the domestic hot water storage tank until 11 a.m. and then switches over to the heating storage tank, which is charged to the preset target value of 47 °C by 2 p.m. Then the compressor switches-off and the building is heated from the storage tank. It is only at 0.30 a.m. that the storage tank has cooled down enough to require a new charge.
On the second day the PV yield is insufficient to overcharge the storage. However, thanks to the SG Ready signal, the hot water preparation is shifted backward to 11 a.m., normally it would not have been triggered until 1 p.m.
With increasing outside temperatures, less energy from the storage tank is used at night. During the day, the storage tank is charged to 50 °C with solar power.
However, it is not completely discharged at night and in the morning, when the first excess electricity comes from the PV, it can still be over 40 °C. The heat pump immediately starts charging the storage tank again.

This means that it remains at a relatively high temperature level for a long time. This reduces the COP on the one hand and on the other it increases the storage losses.
The increased self-consumption was deactivated for winter 2020/2021 in order to obtain a comparative value.

2.7.7.3 Hot water preparation

The hot water preparation is conventionally produced by the heat pump with an integrated DHW storage. For legionella protection, the storage tank is first heated up to 53 °C twice a week with the heat pump (operating limit of the heat pump at 60 °C, 7 K temperature difference of the internal heat exchanger in the storage), and then up to 60 °C with a direct electric back-up heating element. The circulation is controlled by a timer. It is open daily from 6-8 a.m. and from 6.30 p.m. to 9.30 p.m. In addition, it is switched on for 45 minutes during the legionella prevention (Wednesday and Sunday) at the time when a temperature of 60 °C is reached in the storage tank. The heating element remains active while the circulation pump is in operation and maintains the temperature above 60 °C. This means that the pipes are also flown through with hot water. With these settings, an optimum between hygienic requirements, comfort and energy consumption is achieved.
The water heating was examined in detail as part of the SFOE project documented in Hässig et al. (2019).
The daily hot water consumption is between 150 and 200 liters for the whole house with 8 residents. This means that the 650 liter storage tank is significantly too large. The low consumption is mainly due to the sufficient user behaviour, e.g. bathtubs are installed only in two of the four apartments (at the request of residents).
For hot water preparation, the heat pump must be operated at a higher speed and thus a higher output than in heating mode. This is necessary because of a limitation of the compressor. With a lower output, with the same temperature spread on the secondary side, the gradient in the storage-internal heat exchanger could be reduced and thus also the condensation temperature could be reduced. That would lead to a higher COP.

2.7.7.4 Challenges of the inverter

The speed-controlled heat pump has many advantages, in particular the larger tolerance to differences between the design output and the actual output. The variable speed as a further parameter, however, results in a large number of possible operating points. The following difficulties have arisen in connection with the speed control in this system:

- Resonances: In addition to the natural frequencies (blocked in the factory), at which the heat pump starts to oscillate, there was a natural frequency with the room, but only when the door is closed. With the door open, as was the case during commissioning, no response could be detected.
- There are restrictions on the permissible compressor speed for various areas in the envelope of the compressor. This leads, e.g. in hot water preparation, to unfavorable speeds and requires proper coordination during commissioning. In the event of rapid changes in the operating conditions or the speed (e.g. when changing from hot water preparation to heating mode), there is a risk that the operating point will shift to an unfavorable area of the envelope and thus trigger a malfunction. With a fixed-speed compressor, however, it is not possible to adjust the speed at all.

2.7.7.5 Installation errors

Several installation errors were discovered during commissioning.

- Swapped primary and secondary circulators. This error would have led to a suboptimal operating range of the pumps, but the effect on the system efficiency would be negligible.
- Secondary circulation pump was installed the wrong way round. This has led to the condenser as well as the heating tank and the heat exchanger in the hot water tank being flowed through from the wrong side. The condensation temperature rises slightly in the condenser, no stratification can be built up in the heating storage tank, and in the hot water storage tank there is a higher degree of temperature and thus a higher condensation temperature. In principle, the system worked with the incorrectly installed pump, but the efficiency is noticeably limited. It was discovered because of the cooling of the inverter.

This is cooled by the heating return water, which came directly from the condenser due to the reversal of direction and was therefore warmer. During the hot water preparation, the cooling capacity was not sufficient and the heat pump reported a fault.

- The direct electric immersion heater for legionella prevention was not connected according to the electrical diagram of the heat pump, but switched on every night via the remote control of the utility. As a result, the DHW storage is mainly heated by the direct electric heating. The cause of the error was insufficient communication between those involved.
- Further errors occurred during the installation of the M-Bus devices (heating and water meters), which is why the data acquisition was only fully available from June 2018.

The errors in the installation of the heating system listed here would have reduced the system performance significantly. Errors of this type may be found in many installations, but are often not discovered.

2.7.8 Conclusion

Despite the two effects described above, which reduce the SPF in heating mode, good efficiency is achieved. Reasons for this are:

- Thanks to the available data, operations could be constantly monitored and optimized.
- Constantly high source temperatures around 10 °C

It bears no relation to the monetary savings from the optimization. It should also be noted that, despite the simple system, there are many complex dependencies, e.g. the application range of the heat pump is limited, i.e. certain operation conditions (source/sink temperatures) cannot be approached at all speeds.

With the knowledge gained from the monitoring, the heat pump could have been dimensioned smaller and the heating storage tank could probably have been saved. The wood stoves provide a 100% backup, which significantly relieves the heat pump in very cold periods, even when it is only partly in use.

2.8 Conclusions of monitoring results in residential buildings

In IEA HPT Annex 49 the focus of the monitored buildings contributed by the participating countries was on larger buildings, where the achievement of the nZE balance is much more challenging than in single family houses, since the building surface for on-site energy generation is much more restricted in relation to the building loads.

As result of the investigated single family house Berghalde, it is shown, the with maximum PV roof installation a significant plus energy balance can be achieved. However, the occupancy of the building is not so high, so loads are rather restricted. Moreover, in new built residential buildings with good building envelope performance and low temperature emissions systems, very high performance of the heat pump can be expected, in particular with good heat source of the ground. While reaching the balance may thus not be the dominating aspect for single family buildings, a research issues may rather be the management of surplus by large PV installations regarding optimised self-consumption and grid supportive operation. Evaluation on the load management and demand response by storage integration and controls are treated on the example of the single family house Berghalde is treated in the Task 2 report of the Annex 49.

In larger multi-family buildings with 4 storey and more, reaching the balance can still be challenging. Thus, an evaluation performed in the monitoring and accompanying simulation has been dedicated to the characterisation of system performance requirements and optimisation potentials to reach the nZE-balance. As result of the monitorings, see also in next chapter of buildings with mixed office and multi-family use, the nearly zero energy balance for the boundary building technology is reachable with only the roof area covered with PV. However, if the net zero balance incl. household appliances and plug load is to be reached, the roof area is scarce and the façade has to be used for on-site renewable energy generation. Simulation studies for the Vögelebichl buildings confirm that the net ZE-balance can be fulfilled, if the façade is used for PV generation as well, at the same performance values of the building technology.

However, the monitoring results of the multi-family building Riedberg show that a plus balance can also be challenging including the façade. However, heat pump performance was with performance factor of 3 rather low due to a new integration option, which needed higher commissioning expenditure and continuous optimisation in the first years. A better performance of the heat pump can contributed to reach a plus energy balance.

The five storey multi-family building Sonnenpark Plus in Switzerland confirms that also a significant surplus is possible, but as limiting factor of the monitoring results are the low number of inhabitants. If the occupancy is extrapolated to standard areas per person, the DHW demand is significantly increase and surpluses melt away.

Regarding the heat pump performance, all of the larger residential buildings use ground coupled heat pumps. Therefore, the performance in the monitoring project reach high overall seasonal performance values. The limiting operation is the DHW fraction, with is increasing with good building envelopes and multi-family use,

With respect to optimisation potentials the field monitoring show positive results. Most of the systems reach high performance factors. However, as shown in the example of Vögelebichl, in-depth analysis by accompanying simulation can further increase the performance. Another results of this project is, that storage losses and auxiliary energy can have a significant effect on the nZE-balance, so optimisation shall also focus on auxiliary components and system losses.

New and complex system integrations like the absorber heat source with the ice storage combinations show, that monitoring can give more insight into the system operation and is a prerequisite for fault diagnosis and detection in order to derive as-planned system operation. Thus, as general recommendation a monitoring should be provided by larger high performance buildings, in particular in the case of new system integrations, as it is also a trend in some building certification programmes and labels.

3 Monitoring results of office buildings

In this chapter the monitoring results of office buildings contributed to IEA HPT Annex 49 are summarised.

3.1 Overview

The **office building in Uster (ZH), Switzerland** is a building with mixed office and residential use on a total energy reference area 1206 m^2 of which 7 flats in the upper floors of 839 m^2 have multi-family residential use and the ground floor on 367 m^2 is reserved for office use. The building has been commissioned in 2014 as first building certified according to the MINERGIE-A® label requirements for office use, an monitoring carried out for two year in 2015 and 2016 had the objective to verify the MINERGIE-A®-label requirements for office use as well as the investigation of on-site self-consumption for the combination of office and residential use. The building is equipped with a high performance building envelope with U-values of 0.15-0.18 and an average U-value for the windows of 1.0 W/(m^2K), which are in the range of the new built requirement from 2020 on. A ground coupled heat pump supplies the building with space heating and DHW energy and is also used for free-cooling in summer. For the nZE balance a 128 m^2 (23.1 kW_p) PV system is integrated in the roof, and also a smaller PV/T collector of 7.1 m^2 is used for DHW preheating. Furthermore, a shared electric car is integrated for load management reasons.

The **Black & White in Pfäffikon (SZ), Switzerland** is a building with office and commercial use on the lower floors with an energy reference area of each 616 m^2 and multi-family residential use on 1,521 m^2 on the upper floors. The building is equipped with a ground-source heat pump for space heating, domestic hot water as well as ground-coupled free-cooling and active back-up cooling by the heat pump. Since the design envisaged a net-zero energy balance, a 74 kW_p solar PV-system is installed with 26 kW_p on the roof and with 48 kW_p façade-integrated. Since the building is integrated in a central location and due to higher loads for office and commercial use, as well as for the large façade integrated fraction of the PV system, the objectives for the monitoring were the achievement of the nearly energy balance as well as the seasonal distribution of the PV electricity generation in an urban surrounding. In this context the mixed use of office/commercial use on the one hand and residential use on the other hand can create internal synergies for load balancing on the electric side and waste heat recovery on the thermal side between the different loads. In that sense, also an advance cooling concept with focus on freecooling and waste heat recovery from the active cooling mode is an interesting aspects of the building technology, which also use ground regeneration for the recooling.

The **Post am Rochus in Vienna, Austria** is the new head quarter of the Austrian Post. The office building use on an gross (useful) area of 49,300 (42,449) m² with retail use on the ground floor is refurbished to a high performance building envelope with U-values of 0.09-0.15/0.11/0.3 W/(m^2K) of new and refurbished outer walls, roof and ground floor and triple glassed windows of 0.77 (1.70) W/(m^2K) for new (refurbished) windows.

A focus of the project was the integral planning in a complex multi-stakeholder process to improve time, cost- and energy-efficiency for the implementation of complex nZEB requirements in larger office buildings. Thus, evaluations of the planning process both on the organisation and communication among the different stakeholders as well as software supported project management and technical commissioning were investigated in details and conclusions are drawn regarding critical points and success factors from the overall experiences in the building process.

3.2 nZEB with mixed office and residential use in Uster, ZH

3.2.1 Introduction

The newly constructed building with mixed residential and office use located in the centre of the Swiss town Uster in Eastern Switzerland is the first building in canton Zurich with office use certified to the MINERGIE-A® label, which is an implementation of a Swiss nZEB. The building has been commissioned in February 2014 and has an energy reference area of 1206 m^2 divided into 367 m^2 office and 839 m^2 residential multi-family use. The office part provides space for 20 workplaces. The calculated space heating demand is 33.8 kWh/(m^{2}yr) and thereby less than the legal requirement of 43.9 kWh/(m^{2}yr). The design value for the MINERGIE-A® index of weighted energy consumption yields with -5.0 kWh/(m^{2}yr) a slight surplus. Table 22 shows the building and summarizes the building envelope characteristics.

Table 22: Building envelope characteristics of the monitored building in the Swiss town Uster

Living space	**U-Value (W/m^2/K)**
Floor	0.18
Roof	0.18
Outside Walls	0.15
Windows (ø of all)	1.00
Office space	
Basement	0.13
Walls, cellar	0.16
Outside walls	0.15
Windows (ø of all)	0.97

3.2.2 Technical concept of the building

The technical concept of the building technology as shown in Figure 84 (Hässig et al, 2015). The building is designed as an “all-electric building” with a heat pump and a PV-system as core components, i.e. only electricity is used as delivered energy. The ground source brine-to-water heat pump covers the space heating and domestic hot water (DHW) energy. A ground heat exchanger of 11 boreholes with a length of about 80 m each are used as a source for the heat pump. The shallow layout of the boreholes is due to restriction in the area for drilling deeper borehole. The heating capacity/COP of the heat pump are 33.1 kW$_{th}$/4.6 at B0/W35 and 30.5 kW$_{th}$/3.0 at B0/W50, respectively. The heat emission to the room is accomplished with a floor heating, which is also used for ground-coupled free-cooling in summer operation. For the space heating operation, an 800 l buffer storage is integrated in parallel to the floor heating system.

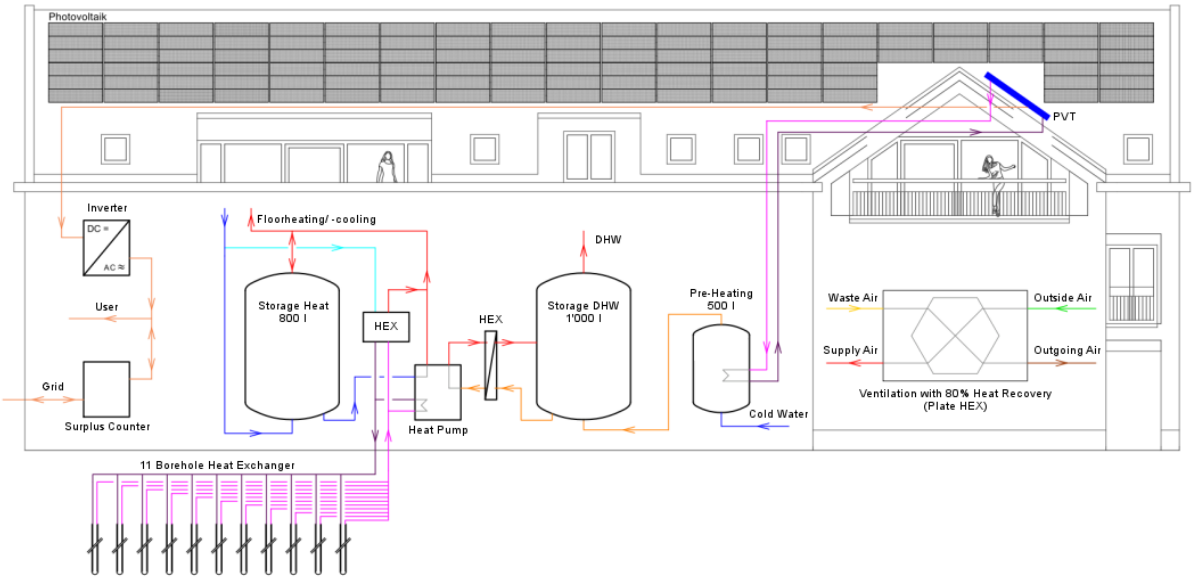
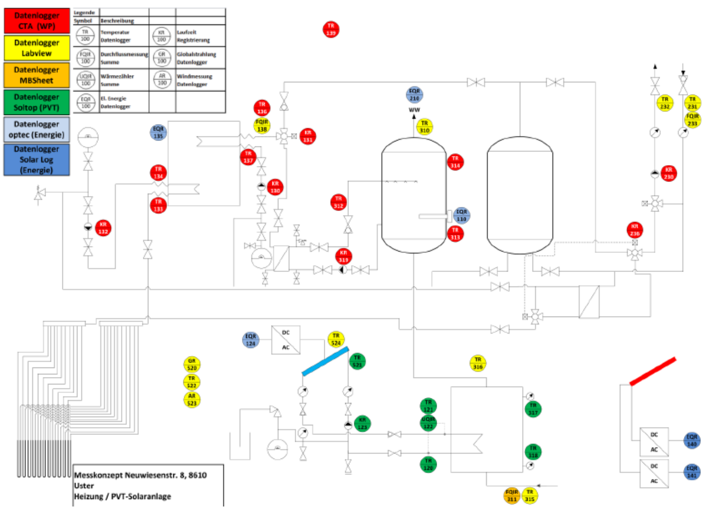


Figure 84: Overview of the building technology of the nZEB (Hässig et al., 2015)

An accompanying electrical tube heating (heat tape) is installed to fulfil the Swiss standard SIA 385/1 (2011) for DHW tapping comfort. The system has a power of 1 kW and allows supplying tab water at 40 °C in 10 s at any time of the day. A DHW preheating of a 500 l DHW tank is realized by a PV/T-collector of 5 modules with a total area of 7.1 m^2 and electrical and thermal peak power 1 kW$_{pel.}$ and 2.3 kW$_{pth}$, respectively. The PV/T-collectors are installed on the south-oriented roof oriented. The DHW is reheated by the heat pump in a 1000 l storage to a temperature of about 53 °C. For legionella protection a direct heating element is installed to reach temperatures of 60 °C due to the upper operation limit of the heat pump. The 23.7 kW$_p$ PV-system installed on the SSW oriented roof has and inclination of 35°. The calculated electrical energy generation for the PV-system is 1,007 kWh/kW$_p$ or about 24,000 kWh/a. Furthermore, the building is equipped with a mechanical ventilation system with heat recovery. Moreover, in order to enhance the local use of PV electricity and reduce grid interaction a publicly rentable electric car is used as local electricity storage of PV electricity.

3.2.3 Monitoring concept

The building has been commissioned in February 2014 and has been measured during a two year period. The first measuring period covers from May 2014 till April 2015 characterises the first year of operation and serves to identify optimisation measures. During the second measuring period of May 2015 till April 2016 the assessment shall be refined for the second year of operation including the evaluation of applied optimisation measures. The monitoring of the PV/T-collector, the PV-generator, the heat pump and electrical energy comprises around 70 measuring points and is depicted in Figure 85.



Sensor	Symbol	Unit	Description
EQR 110	Electric heating element	kWh (Btu)	Electrical energy heating element
TR 120	TPVT-S	°C (°F)	Supply temperature to PV/T collector
TR 121	TPVT-R	°C (°F)	Return temperature to PV/T collector
UQIR 122	QPVT	kWh (Btu)	Heat energy PV/T collector
KR 123	tL-PVT-UWP	h	Status pump PV/T collector
EQR 124	EPVT	kWh (Btu)	Electrical energy PV/T collector
KR 130	tWP-UWP-WW	h	Status HP DHW pump
KR 131	tST-WP-H/WW	h	Status HP SH pump
KR 132	tWP-UWP-ground	h	Status HP source pump
TR 133	Tground-probe-VL	°C (°F)	Supply temperature borehole
TR 134	Tground-probe-RL	°C (°F)	Return temperature borehole
EQIR 135	EWP	kWh (Btu)	Electrical energy heat pump
TR 136	TWP-VL	°C (°F)	Supply temperature heat pump
TR 137	TWP-RL	°C (°F)	Return temperature heat pump
FQIR 138	VWP-circulation	L	Volume flow heat pump condenser
TR 139	T outdoor	°C (°F)	Outdoor air temperature
EQR 140	EPV_140	kWh (Btu)	Electrical energy solar PV field 1
EQR 141	EPV_141	kWh (Btu)	Electrical energy solar PV field 2
EQR 210	E_element	kWh (Btu)	Electrical energy heating element
KR 230	tWP-UWP-H	H	Status distribution pump
TR 231	TWP-VL-H	°C (°F)	Supply temperature heating
TR 232	TWP-RL-H	°C (°F)	Return temperature heating
FQIR 233	VWP-H	L	Volume flow heat pump heating
KR 236	tST-WP-H/C	H	Status heat pump heating/cooling
TR 310	TWW-outlet	°C (°F)	Temperature DHW outlet
FQIR 311	Vcold-water	L	Volume flow cold water
TR 312	TWW-storage-VL	°C (°F)	DHW storage supply temperature
TR 313	TWW-storage-bottom	°C (°F)	DHW storage temperature bottom
TR 314	TWW-Speicher-top	°C (°F)	DHW storage temperature top
TR 315	Tcold-water	°C (°F)	Temperature cold water inlet
TR 316	T outlet preheating	°C (°F)	Temperature outlet DHW preheating
TR 317	Tpreheating-top	°C (°F)	Temperature DHW preheating top
TR 318	Tpreheating-bottom	°C (°F)	Temperature DHW preheating bottom
KR 319	tWW-UWP	h	Status storage loading pump
GR 520	Global irradiation	W/m2 (Btu/ft^{2}h)	Global solar irradiation
TR 521	Tcollector	°C (°F)	Surface temperature PV/T collector
TR 522	Troof	°C (°F)	Temperature on the roof below tiles
AR 523	Wind speed	m/s (ft/s)	Wind speed

Figure 85: Overview of the building technology of the nZEB

The objective of the monitoring were

- Evaluation of relevant key metrics like the MINERGIE-A® index (nZE balance), SPF of the heat pump, yield of solar components and electrical behaviour like the supply cover factor
- Feedback on requirements for office use to the MINERGIE-A® labelling
- Optimisation of the current operation and increase the efficiency of the installed building technologies
- Investigations to self-consumption in buildings with mixed residential and office use

3.2.4 Monitoring results

3.2.4.1 Energy flow

Figure 86 shows the energy flow of the MINERGIE-A® relevant consuming and producing building technologies for the second year of operation in order to approve the nZE-balance. Furthermore, the energy flow diagram shows the renewably supplied energy (geothermal and solar energy) to the building. Moreover, the ground-coupled free-cooling operation of the office space is illustrated.

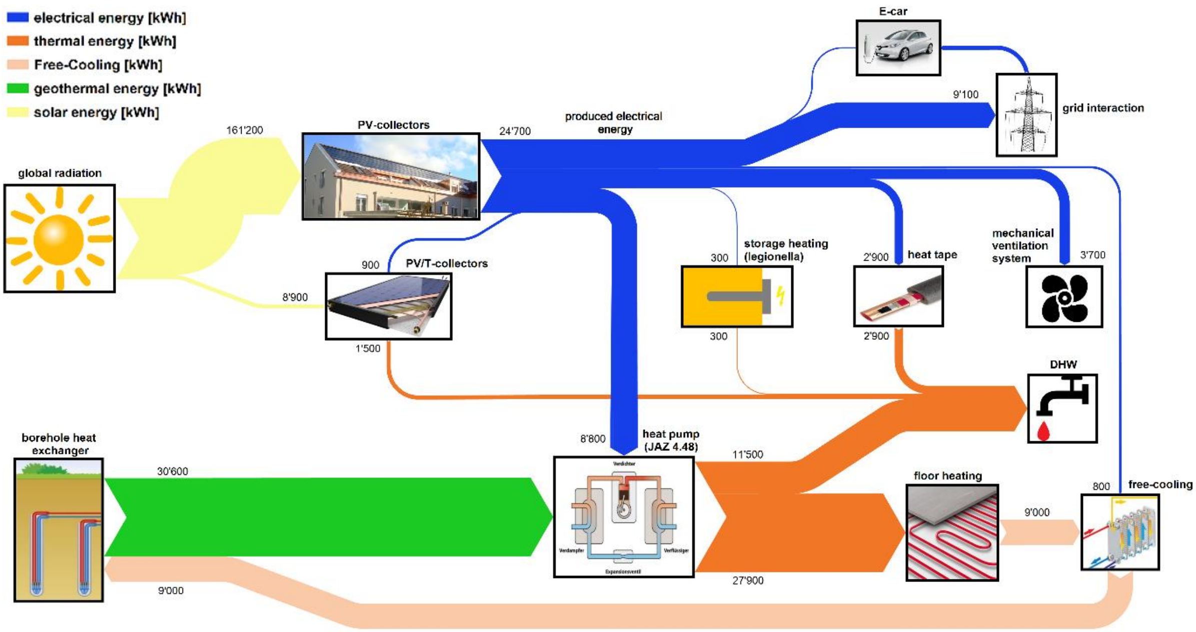


Figure 86: Energy flow diagram of the building for the period May 2015 – April 2016

The MINERGIE-A® index is a weighted balance of the energy use and on-site production according the equation

$$Minergie - A^{®} - index = \frac{2}{1206\ m^2}(E_{Ven} + E_{HP} + E_{HR} + E_{Sol} - E_{PVT} - E_{PV}) \qquad (1)$$

E_{Ven}:	Energy consumption ventilation	E_{Sol}:	Energy consumption circulation pump
E_{HP}:	Energy consumption heat pump	E_{PVT}:	Energy production PV/T-generator
E_{HR}:	Energy consumption heating element	E_{PV}:	Energy production PV-generator

For all electric building, all delivered energies are electricity with a weighting factor is 2 equal to the cantonal building directive MuKEn. According to the MINERGIE-A®-guideline, geothermal and solar energy is weighted with a factor of 0, which means no compensation is required for the source energy.

3.2.4.2 nZE balance in terms of MINERGIE-A® Index

Figure 87 shows the electrical consumption of the installed building technologies and the on-site electricity production by the PV and PV/T-collectors both operation years.

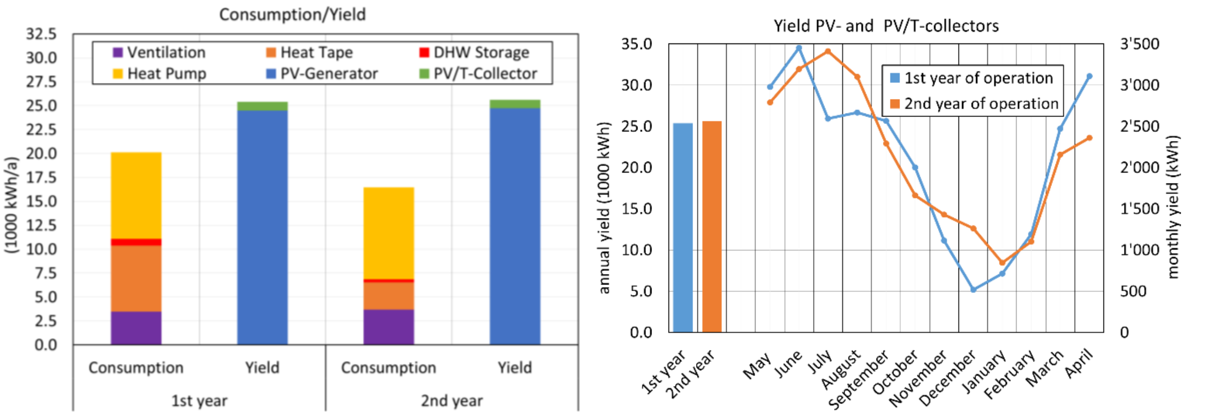


Figure 87: Production and consumption of the MINERGIE-A® relevant building technologies (left) and electricity production of the PV- and PV/T-collectors (right)

Compared to the first year, the consumption of the additional heating systems (heat tape and DHW storage legionella protection) is significantly reduced due to the implemented optimization in the second year as further described in chapter 3.2.4.5. The electrical production by the PV and PV/T-collectors are similar in both years. The seasonal fluctuations are shown Figure 87 right. During the summer months the production is 3-4 times higher than in the winter months. The PV-system reaches a specific yield of around 1,030 kWh/kW$_p$ in both years.

Additionally, the PV/T-collector generates an electrical energy of about 900 kWh_{el}/a. Considering only the building technology, the heat pump is with 45% responsible for the largest share of the electrical consumption in the first year of operation. Due to optimizations after the first year regarding the additional heating systems the proportion of the heat pump increases in the second year to about 60%, while the total consumption is reduced by 15%.
Figure 88 shows the nZE balance in terms of the MINERGIE-A® index on monthly and annual basis for both years of operation.

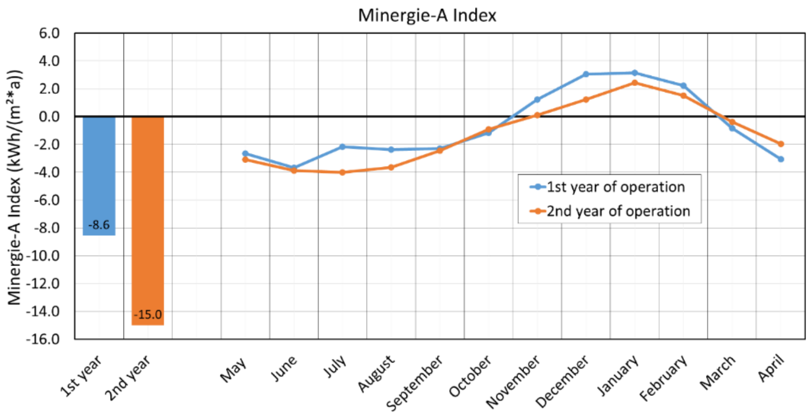


Figure 88: MINERGIE-A®-index for both years of operation

3.2.4.3 Heat pump

For both years, the seasonal performance factor (SPF) for heating and DHW operation as well as the overall seasonal performance factor including the entire source pumping energy have been determined. The SPF_H in space heating mode reaches with 4.6 in the first and 4.9 in the second year a high value, and also the SPF_{DHW} in DHW mode is high for the evaluated period with a value around 3.5 for both years. This leads with a DHW fraction of about 30% to an overall SPF of 4.24 and 4.48, respectively. The increase of the SPF in the second year can be explained by the following reasons:

- A longer running time for the heat pump was implemented through a wider temperature range in the controller setting of the DHW storage
- The heat pump operation time throughout the working days was slightly switched from 00:00 to 05:00 in order to reduce the storage losses

The operation time for the legionella protection (electrical heating element in the DHW storage) takes place directly after the DHW operation of the heat pump. The temperature difference of the buffer storage has increased from ± 2 to ± 3 °C. The minimal operation time for the space heating has increased from 30 to 60 min. Another factor for the high SPF in the monitored period is the source temperature for the heat pump, which allows the heat pump to operate at low temperature lifts and thereby high performance level.

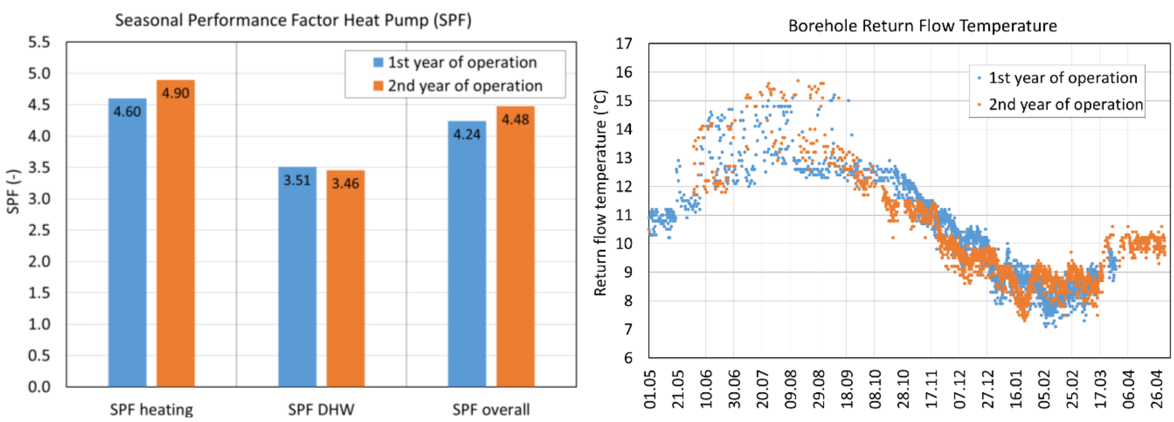


Figure 89: Seasonal performance factor of the heat pump for DHW and space heating mode and overall (left) and heat pump source temperature for both years of operation (right)

Figure 89 right shows the return flow temperature of the boreholes (2 min before stopping the circulation pump). The source temperatures are constantly high. Especially in the late summer months the heat pump source temperatures reaches high values of 12-16 °C. An explanation for the high source temperatures is the ground-coupled free-cooling operation which takes place in the summer month and regenerates the borehole field.

3.2.4.4 Free-cooling

During the summer months the office spaces in the basement are cooled with a ground-coupled free-cooling. In cooling operation, the system efficiency can be described as the ratio of the heat removed from the building and the electricity consumed by the borehole- and the floor-heating circuit auxiliary pumps. The system performance factor for cooling operation (SPF_C) reaches in the monitored summer months a value of 17, which is comparable with other cooling systems, which reach values in the range of 10 to 30. A positive side effect of the ground-coupled cooling mode is the regeneration effect of the boreholes as mentioned above. The higher source temperatures of the heat pump lead to an increase of 5% for the SPF_{DHW}. The minimum temperature of the heat pump inlet never falls below 7 °C, which is also a reason for the high overall SPF of the heat pump described in the previous chapter.

3.2.4.5 Heat tape and legionella protection

The two additional DHW heating systems – heat tape for DHW tapping comfort by reduced wait time for hot water at the tap and direct electric heating element for legionella protection in the DHW storage – are responsible for 38% of the entire energy consumption of the building technology in the first year. Through stepwise improvements, the electricity consumption could be reduced by 60%, which leads to reduction of 4,450 kWh each year, as shown in Figure 90.

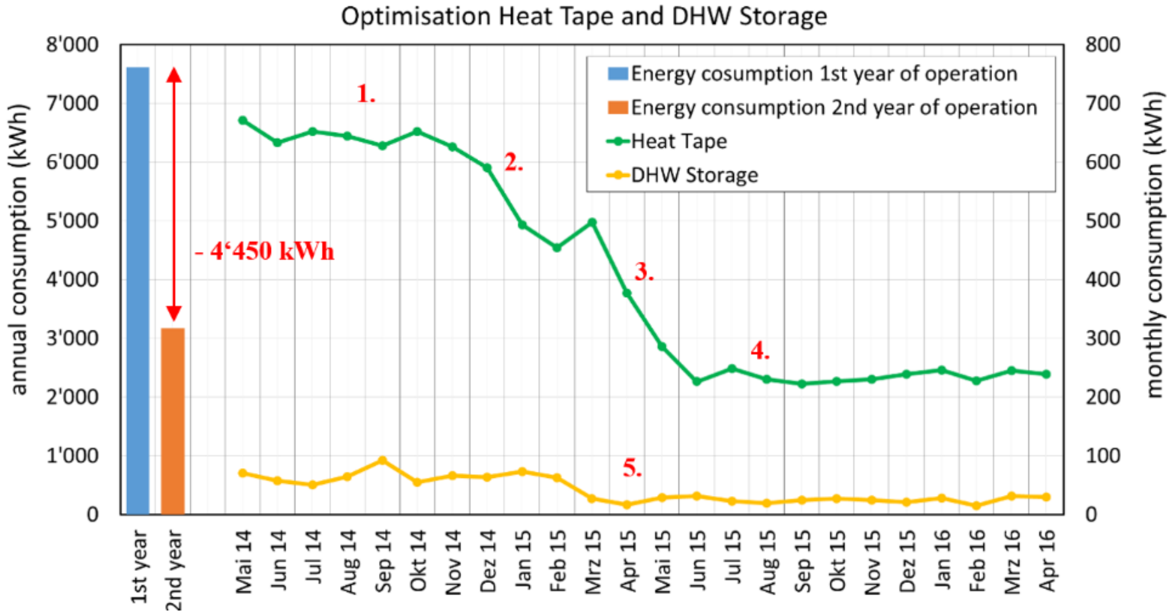


Figure 90: Optimisation of the heat tape for DHW comfort and the electric heating element for legionella protection

Effectively, this means a decrease of the MINERGIE-A® index by about -6.4 kWh/(m^2·a) for the second year. The improvement steps, indicated in Figure 90, are the following:

1. Permanent operation of the heat tape leads to a temperature in the DHW pipes of 55 °C and a high energy consumption
2. By adding of a controller, the DHW pipe temperature is reduced from 55 °C to 40 °C
3. The heat tape operation time has been restricted to times with low DHW needs (during high DHW needs, no additional pipe heating is provided to meet the comfort requirements).
4. Heat tape operation is restricted to 22:00 – 06:00 and 10:00 – 20:00. By simulations the operating time of the heat tape the consumption is investigated and afterwards adapted to the user behaviour. Subsequently, the heat tape operation was reduced to 00:00 – 06:00 and 14:00 – 20:00

5. The operating time of the legionella protection was also adapted. Before the adaption, the legionella protection was conducted two times a week on following days.
   After improvement, the legionella protection is operated just once a week and directly after the preheating of the heat pump.

3.2.4.6 PV/T-collector

The performance of the PV/T-collectors is in both years similar with a production of 900 kWh_{el} and 1,300-1,400 kWh_{th}. After substracting the energy need for the solar circulation pump of about 100 kWh, a yield of 280 kWh/m^2_{col} is gained.

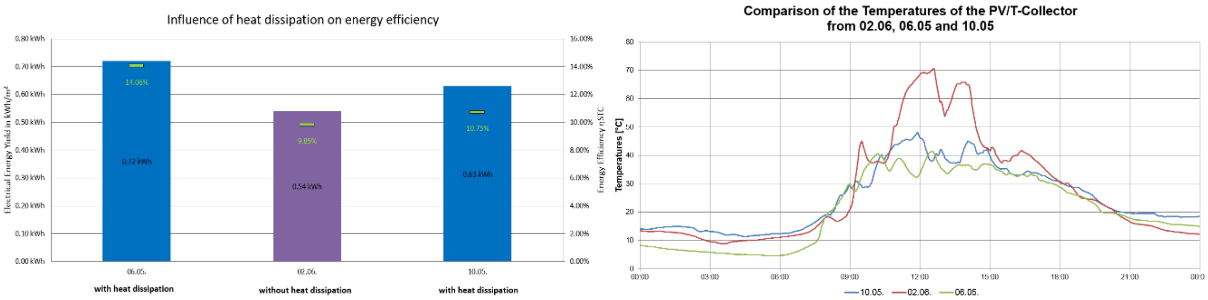


Figure 91: Effect of higher efficiency due to lower collector temperature

In both years the collector performance factor, which is calculated by the annual yield divided by the solar irradiation, is in the range of 0.27. Based on the monitoring of the PV/T-collectors, the effect of higher efficiency due to lower collector temperatures could be approved, as shown in Figure 91 left. For the duration of a day (June 2) the solar circulation pump was switched-off and compared with a day (May 6) when the solar circulation pump was running. Without heat removal, the electrical efficiency of the PV/T-collectors decreases from 14.1% to 9.9%. Figure 91 right indicates a 30 K higher collector temperature without the heat removal.
The overall seasonal performance factor SPF_{gen} includes the whole source systems, i.e. also the heat and electricity produced by the solar PV/T-collectors and the heating element in the DHW storage. The electrical yield of the PV/T-collectors is subtracted from the electrical energy. Additionally, the heat tape can be included. Figure 92 shows the SPF_{gen} for both years with and without the heat tape. Due to a measurement interruption, the results from April 2015 to July 2015 are missing. Without the heat tape an SPF_{gen} of 4.5 for the first and 4.8 for the second year was measured. The SPF_{gen} is significantly less affected by the heat tape in the second year due to the implemented optimization.

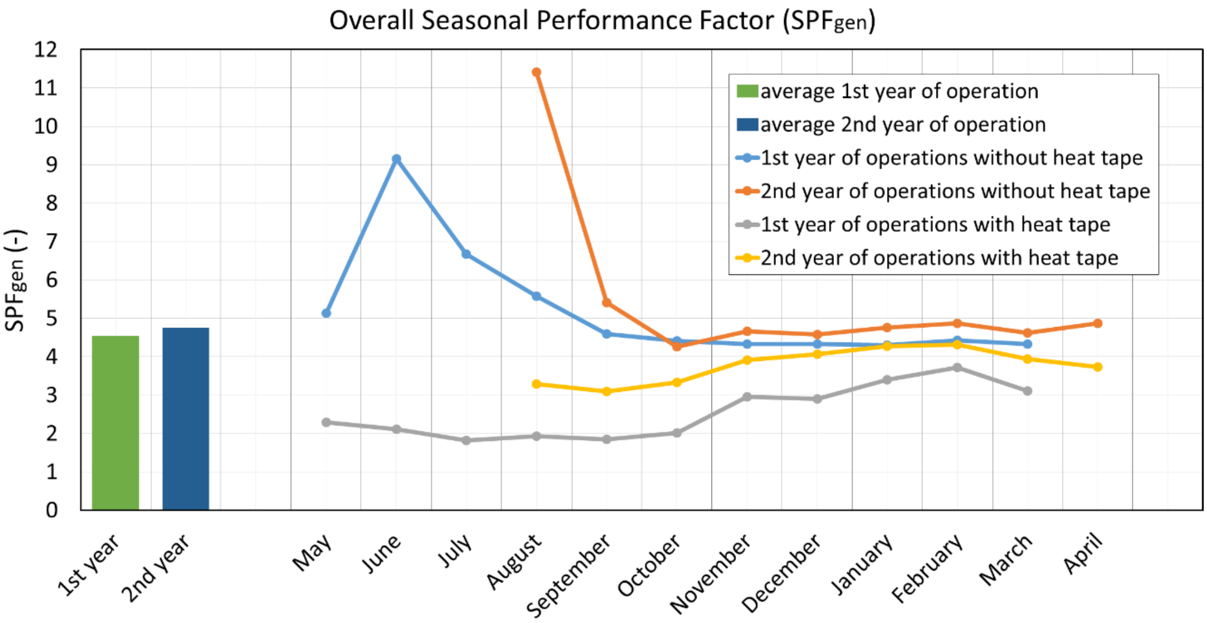


Figure 92: Overall seasonal performance factor (SPF_{gen})

3.2.4.7 Indoor-environment

Temporary measurements of the indoor environment have been performed in the beginning of the measuring period in May 2014. Figure 93 depicts the room temperature and the respective limits of comfortable room temperature according to the Swiss standard SIA 382/1 (2007) and the CO_2-concentration in the offices. Due to good insulation levels and thereby high internal surface temperatures close to the room air temperature, the room air temperature is a good indicator and thereby significant to assess the global thermal comfort. All monitored temperatures are in the comfortable temperature range and to 90% in the range of 23-24 °C. The relative humidity was during the measuring period in about 80% of the time in the comfortable range of 45-50%. The CO_2-concentration in the office is an indicator for the indoor air quality.

The limit value of 1,350 ppm (average air quality, comfort class B) was never exceeded and the value for high air quality of 950 ppm was achieved in most of the time during the measurements. The CO_2 concentration was in 95% of the time in the range of 400 to 900 ppm and in 55% between 400 to 500 ppm, which is comparable with outdoor air. During the summer time in 2015, also a survey was performed with the users regarding the indoor environment. A positive feedback was given by all participants regarding the room temperature and the indoor air quality by the mechanical ventilation.

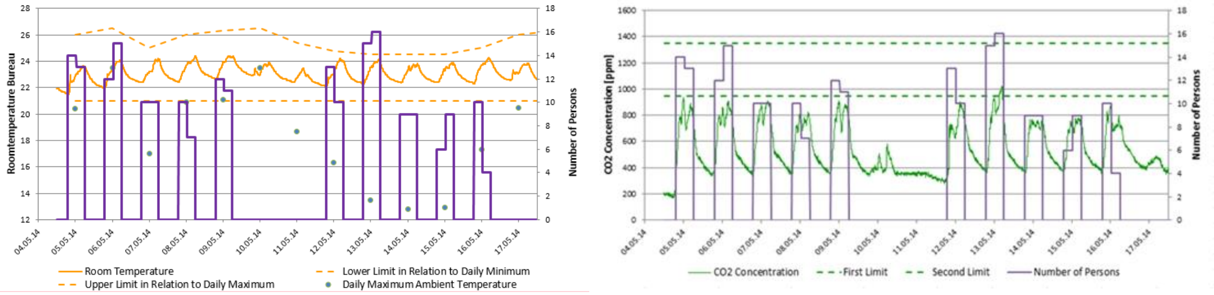


Figure 93: Room air temperature and CO_2-concentration in the office in May 2014 with limits according to SIA 382/1

3.2.4.8 Self-consumption

Due to the growing number of nZEB equipped with solar PV systems the grid interaction gets more important. The on-site produced photovoltaic energy should have as minimal impact on the grid as possible and should work in line with grid needs.

Therefore, as a metric for the grid interaction and demand response capability, the self-consumption of the office use has been evaluated. The metrics supply cover factor (SCF) and load cover factor (LCF) for the measured period from May 2014 to April 2015 are given in Figure 94 left on the basis of a balancing period of 5 min. The SCF describes how much of the PV yield in the balancing period is consumed on-site. The LCF describes how much of the total energy consumption can be covered by the on-site PV yield. The curves of the two metrics in Figure 94 are thus opposite, since for instance in wintertime, the PV electricity production is low and the electricity consumption is high, so most of the PV electricity can be consumed on-site which leads to a high SCF, while the LCF is low, since the PV electricity can only cover a small part of the total energy consumption. Thus, the self-consumption in terms of the LCF decreases due to the lower PV-yield during wintertime. At the same time the SCF increases due to the increasing electricity consumption during wintertime.

The impact of the balancing time on the metrics is depicted in Figure 94 right exemplary for the SCF. While it is easier to cover the entire demand with on-site production on annual basis, it gets harder with shorter balancing periods, since the compensation possibility is missing and a higher simultaneity is needed for high values. For a balancing period of 5 min the overall SCF is about 40%, which is higher than for single family residential applications, where typical values are about 15-25%. The office hours have a positive effect also for the LCF.

Also the electric car can have a positive effect to the LCF, when the charging time may be shifted to times with high PV production, e.g. during midday. Compared to the heat pump, though, the electric car with 2,000 kWh per year is a rather small consumer in the measurement period.

The charging station has a power of 22 kW, which is in the range of the peak-power (24 kW_p) of the PV-generator and surpasses in combination with other consumers the produced PV-electricity on-site. The presently installed charging station charges the electric car with 100% power, until the electric car is charged to about 80%. Afterwards, the charging power is slowly reduced for the protection and life time of the accumulator.

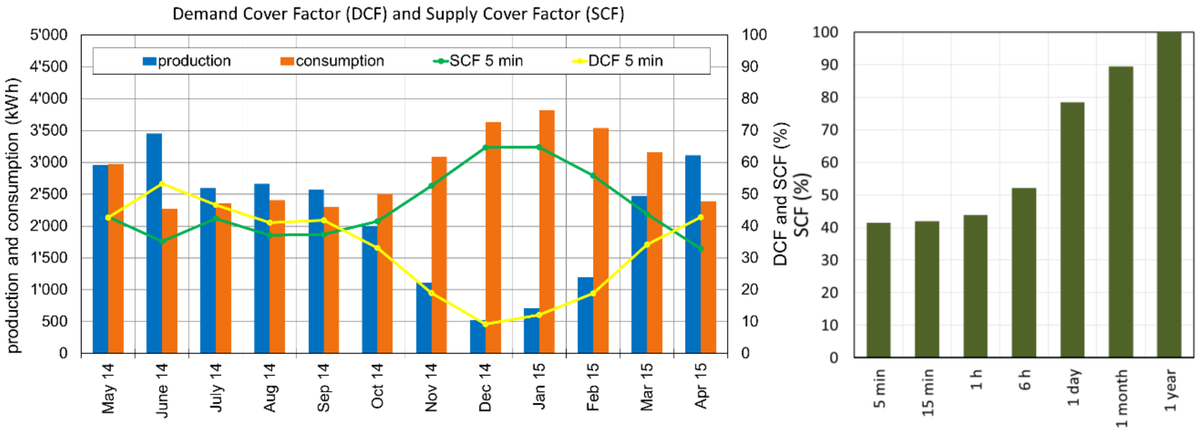


Figure 94: Monthly on-site electricity production and consumption as well as SCF and LCF (left) and dependency of the SCF on balancing period (right)

With an adapted charging power, simulations provide a 5% higher SCF. However, due to the high investment cost related to a rather small financial revenue, this option was not installed for the charging system.

3.2.4.9 Conclusion

As one of the first buildings in Switzerland an nZEB with mixed residential and office use according to the MINERGIE-A® label was monitored. The all electric building is equipped with a large solar PV-system and PV/T-collectors on the roof and a ground-source brine-to-water heat pump as core components of the building technologies. The monitoring has shown that PV/T-collectors and the ground-coupled free-cooling could be well integrated in the building technologies with appropriate planning. Monitoring results of the two years of operation confirm, that the nearly zero energy balance has been reached with a MINERGIE-A® index of -8.6 kWh/(m^2·a) in the first and -15.0 kWh/(m^2·a) in the second year of operation. Regarding these results, the solar PV-system appears slightly oversized regarding the MINERGIE-A® label.

However, compared to the residential use only, the combined office and residential use leads to a higher supply cover factor SCF of 40%. With further adaption of the heat pump running time and the electric car charging operation to the PV generation, also higher values are possible.

Monitoring results of the first year of operation have revealed various optimization potentials in the operation of the building technology, in particular regarding the heat tape and the heat pump standard operation settings. Therefore, the running time of the heat tape was significantly reduced without reducing the comfort of DHW use. Compared with small adjustments of the legionella protection in the DHW storage, the improvements reduce the energy consumption of the additional electric heating elements of about 4,500 kWh, which leads to cost savings of 650 Euros each year. By adjustments of the heat pump standard operation settings, in particular extending the running time, the SPF_H and the overall SPF could be improved from 4.60 to 4.90 and 4.24 to 4.48, respectively. However, a high performance of the ground-coupled heat pump has been achieved due to high source temperatures from the borehole and the low temperature design of the emission system, as well.

Especially during the summer months high source temperatures of about 12-16 °C are measured and therefore a higher performance of the heat pump for DHW operation of 5% was verified.

Based on the monitoring of the PV/T-collectors, the effect of the higher efficiency due to lower collector temperatures could be approved and the thermal and electrical energy production corresponds to the expectations. The preheating of the DHW with the PV/T-collectors from a

thermal view is useful as long as the dimension is deliberately kept concise, what is given for the measured system with 1 m^2 collector area for each apartment.
Currently, a major drawback of the PV/T-collectors are still the high investments costs with a payback time of more than 20 years and the competition of the system with the heat pump for DHW preheating. PV/T-collectors may get interesting, when they get more cost-effective and the low-temperature heat can be used advantageous, for example to regenerate a borehole heat exchanger field or for higher DHW demands. Due to the complexity of the system technology, the additional regeneration of the borehole exchanger field besides the DHW preheating was not considered. However, if the DHW is prepared by a heat pump, the preheating of DHW lead to decreasing performance values of the heat pump, since the heat pump tends to operate longer at higher DHW temperature levels.
From the gained experiences of the monitoring and measurement the following recommenddations could be derived for the additional heat tape and direct electric heating element:

- Beside the heat tape other alternatives to comply with the DHW requirements according to SIA 385/1 (2011) should be taken into account during the planning phase
- An efficient operation of the heat tape requires a controller, otherwise the heat tape will be activated 24 hours a day. In any case, the manufacturer of the heat tape should be included in the planning process to ensure efficient operation and professional installation
- An adaption of the heat tape control to the user behaviour and the building requirements led to reduced energy use. The control setup should be frequently checked and if necessary be adapted
- In larger buildings the energy use of the additional heating systems should be tracked for optimization of the operation and for charging of the costs to the tenants of the apartments

3.3 Building Black & White with mixed residential and office use, CH

3.3.1 Introduction

The building Black & White in the centre of Pfäffikon (SZ) links a commercial, office- and residential use on the total energy reference area of 2,754 m^2. On the ground floor the commercial use of a pharmacy and a body forming studio is integrated on 617 m^2 energy reference area. The first floor serves as office space with 616 m^2, and in the 2-4. floor as well as in the attic 9 flat are located on 1,521 m^2. Thereby, in total 55% of the energy reference area are reserved for residential use, while 45% is non-residential use. The building is integrated in an urban surrounding in vicinity of the central train station. In the planning phase, a net zero energy balance has been envisaged, and henceforth the building is equipped with a large solar photovoltaic system, which is integrated both on the roof and in the east, south and west facades. Figure 95 shows a view of building and the uses.

Figure 95: Building Black & White in the city centre and vicinity of the station in Pfäffikon SZ (left) and section with building uses (right, orange = commercial, green = office, blue = residential)

Larger buildings with mixed residential and non-residential use in an urban surrounding are interesting regarding a net zero energy balance, since due to the mixed use there might be synergies between loads which may lead to higher self-consumption shares due to daytime use of office spaces and internal heat recovery, e.g. a simultaneous DHW production for the residential use and space cooling operation of the office use. However, higher loads for instance by an office use with many electric devices may also be challenging for the net zero energy balance, since the building surface for the energy production is limited, also due to larger window areas in office use. A further interesting aspect of the monitored building is the façade-integrated PV system, which may yield a better seasonal distribution of the PV production and thus may lead to higher self-consumption due to the more even seasonal yield. On the other hand, the yield may be affected by the surrounding buildings due to a reduced irradiation on the facade modules.
The objectives of the monitoring were thus

- Comparison of the real operating data with planning data
- Approval of the detailed overall energy balance regarding the net zero energy balance
- Evaluation of the load behaviour and synergies by the mixed use

3.3.2 Concept building envelope

The intention of the building owner and architects were the creation of the high class residential living space in urban areas with service and commercial areas on the ground floor for the stimulation of the immediate vicinity. An important aspect was thereby also the seamless integration of the energy system technology in a contemporary architectural design The building owner and architect were interested in not only the realisation of the architectural quality, but also in a sustainable and mostly renewable energy supply.
The realisation was intended by a net zero energy balance, which, however, was not defined as an inevitable objective.

The main idea of the building concept is based on simplicity and efficiency of the building envelope, so that the buildings consumes as little energy as possible, but produces as much as possible under the cost boundary conditions and regarding the option to rent the flats.
Challenges for the design were the unknown building use concept on the ground floor, the definition of the net zero energy balance and the thereby necessary electricity production in an urban surrounding and the system manufactures for a PV-façade, which was not a common technology in 2011, as well as the relation between comfort requirements of the users and the zero energy balance.
On this background a highly efficient building envelope was planned in order to reduce the energy consumption as much as possible. The compact thermal building envelope reaches a U-values of the outer wall of 0.16 and 0.12 W/(m²K), respectively, which nearly corresponds to ultra-low energy houses or passive house, denoted as MINERGIE-P® in Switzerland. The windows were also planned better than the standard requirements with an U-value of the glass of U_g = 0.6 W/(m²K) and an average U-value of the windows of U_w = 0.92 W/(m²K). All windows have outer sun shield for the summerly heat protection, the ground floor is equipped with awning and the upper storey have outer sun blinds.

3.3.3 Concept building technology system

Figure 2 shows a sketch of the building technology system.

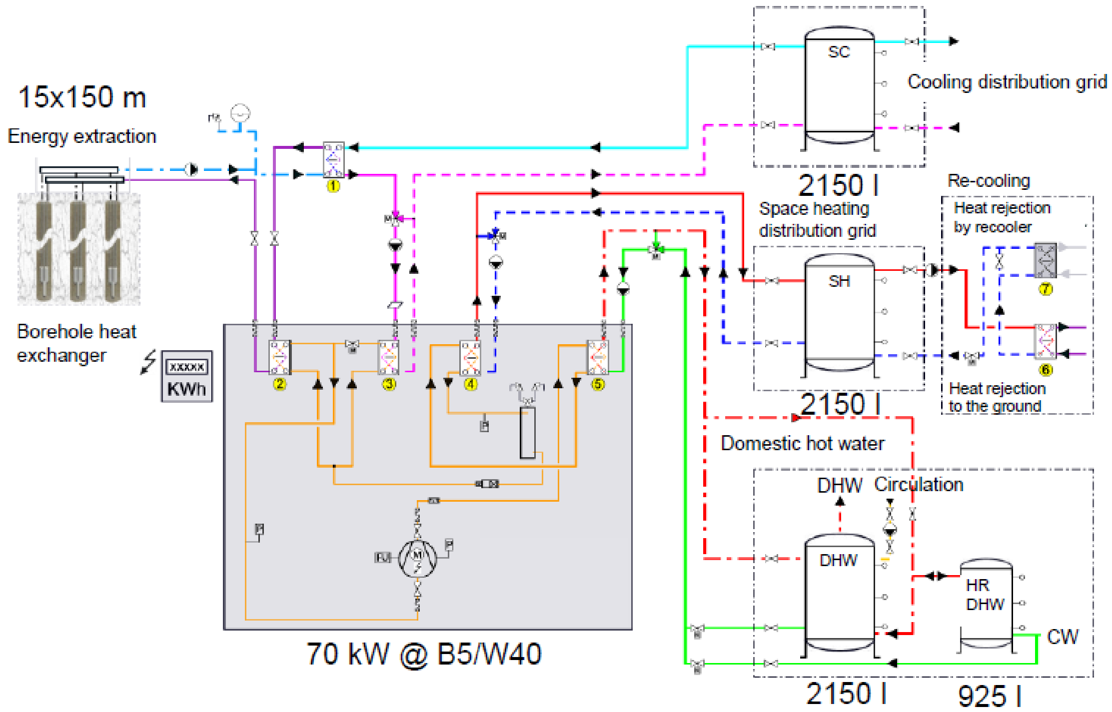


Figure 96: Building technology concept of the Black & White with ground-coupled heat pump and waste heat recovery in space cooling operation

As counterpart to the efficient building envelope also an efficient building technology was planned and the active solar electricity production was designed to high yields. Therefore, a major part of the building outer surface is used for the solar PV-production. As innovative building technology concept with the core component of a 70 kW (B5/W40) ground coupled heat pump has been planned, so that the buildings corresponds to an „All-electric building“. The heat source is a borehole heat exchanger field of 15 Duplex-ground probes of 40 mm diameter and a depth of each 150 m, which guarantees an efficient space heating and DHW operation, but is also integrated in the cooling concept. For the space cooling operation, a "5-phase-concept" is considered: The system is planned in that way, that both the ground and a heat recovery for the DHW and space heating operation cover the re-cooling of the heat pump in cooling operation, i.e. also for the active cooling operation, no re-cooler to the outside air shall be required and all recooling energy is recovered for heating purpose.

However, the focus of the cooling concept is a high degree of coverage in ground-coupled free-cooling (phase 1), and only at higher cooling loads, the active cooling with reverse operation of the heat pump is used. The maximum cooling capacity in active cooling mode is 53 kW. Thereby, the re-cooling heat is transferred primarily in the DHW preheating storage (phase 2) or at simultaneous space heating and cooling demand in the heating buffer storage (phase 3), and only in case of a surplus heat the ground is regenerated (phase 4). If the ground cannot absorb the surplus heat anymore, a re-cooler to the outside air has to be operated (phase 5).
For balancing of the profile of the load and production a heating and cooling buffer storage of each 2,150 l are installed. Additionally, two DHW storages are installed, a preheating storage of 925 l for the use of re-cooling heat and a DHW storage of 2,150 l. Moreover, for the different uses, ventilation systems with heat recovery are installed, which supply the building with an overall volume flow rate of 8,450 m^3/h. The commercial areas are cooled by cooling ceilings, which enhances the free-cooling use due to the higher possible supply temperature levels, and henceforth the reverse operation of the heat pump for space cooling can be limited to peak loads in summer. Additionally, the ground probes are used to preheat the ventilation are in wintertime in order to avoid frost formation on the heat recovery heat exchangers.
For balancing the energy consumption a large PV-system with totally 74 kW$_p$ is integrated. On the roof 26.1 kW$_p$ are installed with an inclination angle of 10° in order to maximise the yield, and 47.9 kW$_p$ are integrated in the south, east and west façade. The efficiency of the roof modules is with 21% notably higher than the thin film CIS-module in the façade with an efficiency of 11%. Moreover, the building is integrated in the city centre, so that the facades are temporarily shaded. Figure 97 summarise the active parts of the envelope technology.

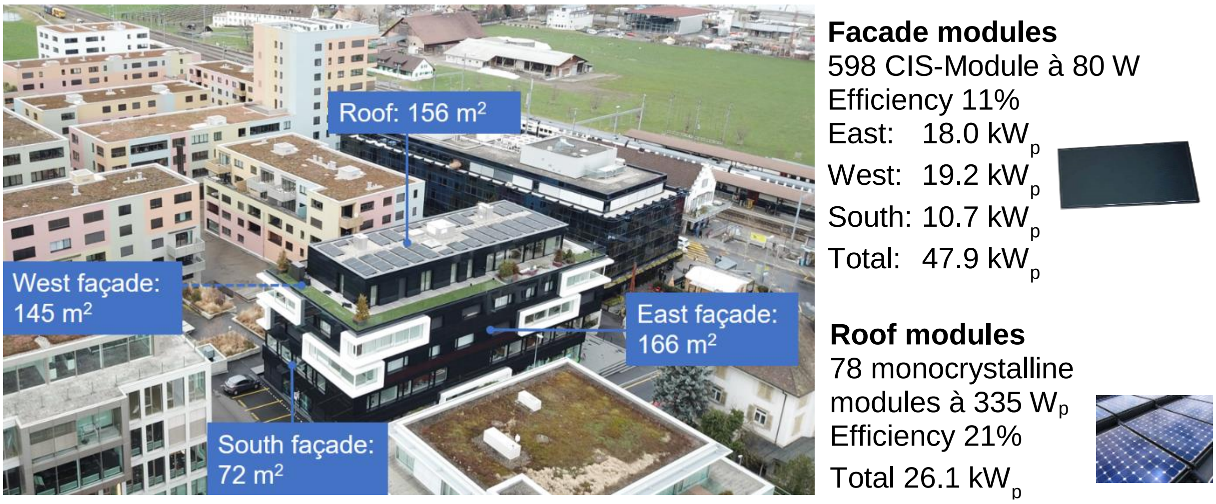


Figure 97: Roof and facade-integrated PV system in the building Black & White

3.3.4 Monitoring concept

All relevant data of the main components of the building technology and the energy consumptions of the uses are acquired and recorded. In total the monitoring system consists of more than 100 measurement points. The monitoring concept with balance boundaries are depicted in Figure 98. The building has been operated since 2014 and continuously measured in the operation. The evaluation of the monitoring data refers to the annual measurement period of October 1, 2016 to September 30, 2017.

3.3.5 Monitoring results

In the following the different results for the energy consumption and energy production are discussed.

3.3.5.1 Overall thermal and electric balance

Figure 99 shows an overview of the thermal and electric energy consumption. If solely the heat demand is considered, despite the very good building envelope the space heating demand is with 68% the major part due to the office and commercial use. The DHW fraction is only 32% of the total heat demand, of which 85% occur in the residential use.

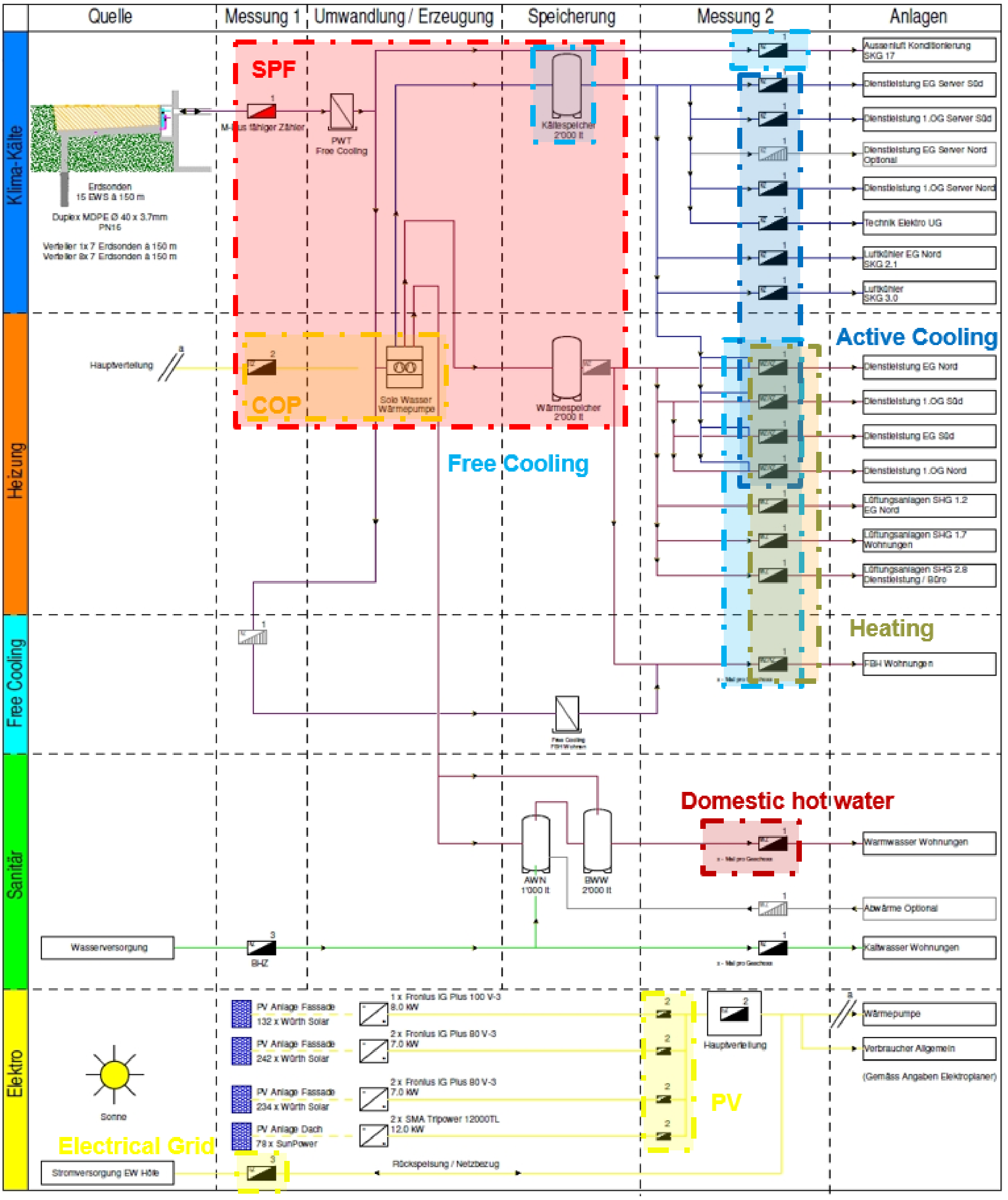


Figure 98: Installed measurement sensors and measurement concept with balance boundary of the Black & White

The measured space heating demand is with 22 kWh/(m²a) in the range of low energy houses according to MINERGIE®. The space cooling energy fraction is 21% of the total thermal energy, of which only about one third is covered by active cooling. For the balancing period, the total waste heat of the active cooling operation could be stored in the DHW and space heating storage or used for the regeneration of the ground. A re-cooler which rejects the surplus waste heat to the ambient air, has not been installed, yet, and is not needed for the balancing period, since the capacity of the water storages and the ground is sufficient for the re-cooling.
As core component of the building technology, the heat pump is in the focus of the efficiency assessment. The overall amount of heat including the use of the ground source, the free-cooling/air-preheating/-cooling the heat pump delivers an energy amount of 158,161 kWh.

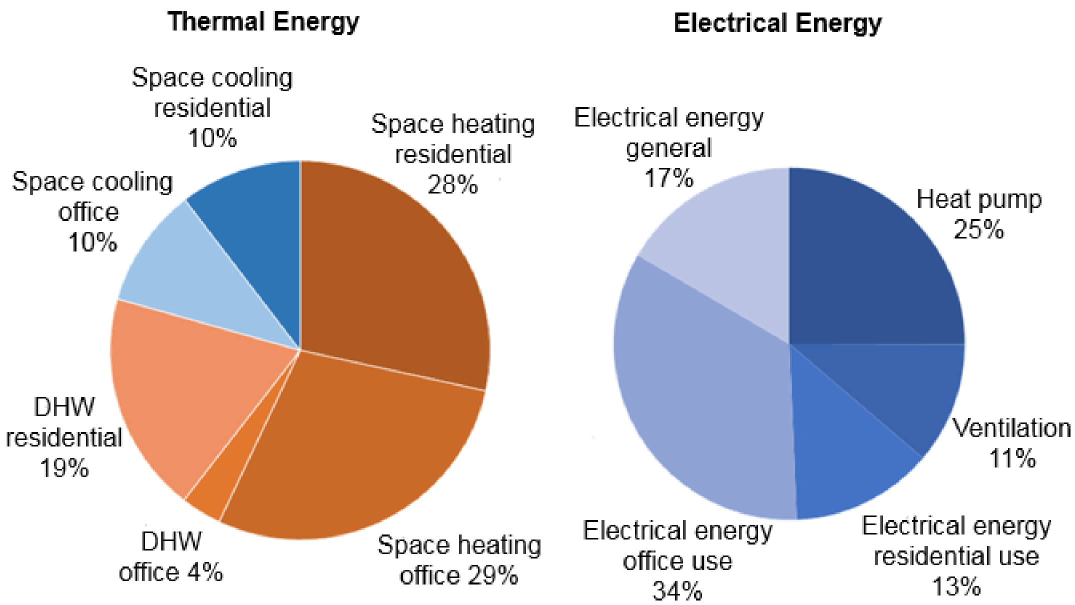


Figure 99: Shares of the thermal and electric energy in the Black & White

For the overall balance of the building technology the ground-source has been used in order to distinguish the operation modes of the heat extraction and regeneration of the ground during the cooling operation. The heat pump reaches a good overall seasonal performance factor of all operation modes is 5.16 including the free-cooling.

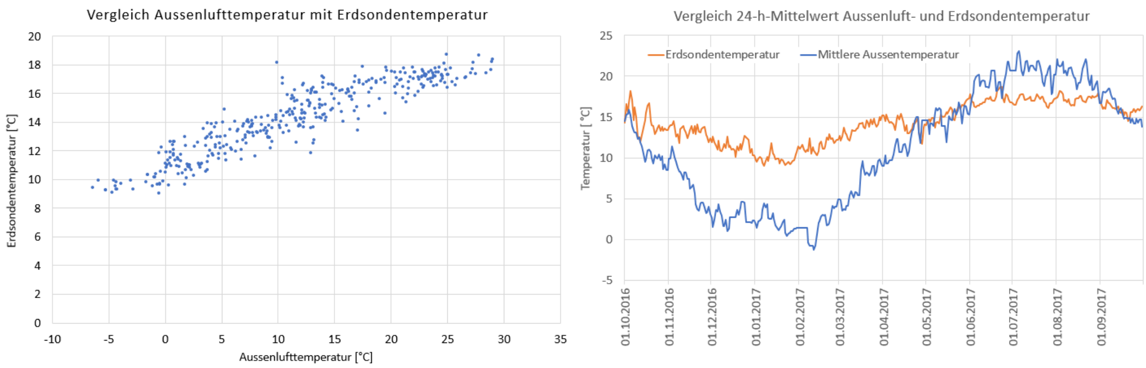


Figure 100: Temperatures of the ground probes in dependency of the outdoor air temperature (left) and annual evolution of 24-h-average values of the source temperature (right)

One reason for the good seasonal performance factor is the source temperature dependent on the outdoor air temperature depicted in Figure 100 left and the annual 24-hour-averaged values in Figure 100 right. Even in wintertime, the 24-hour-averaged values of the inlet temperature to the heat pump are only slightly below 10 °C, which guarantees a good source temperature. The maximum heat extraction power is around 36 W/m, which corresponds to the recommended thermal power extraction of 40 W/m in canton Zurich.

Also at maximum supply temperatures of 40 °C in the space heating storage, of which the heating circuits with design supply/return temperatures of 35 °C/28 °C are supplied, the favourable source temperatures lead to high performance values of the heat pump. The higher heating fraction compared to the DHW operation, which is designed to 60 °C for the storage loading and 50 °C at the tapping, also contributes to the high overall seasonal performance factor.

If the seasonal performance factors are separated according the different operation modes, the space heating operation yield an SPF_h of 4.9 and for SPF_c of 5.9 for the active space cooling operation due to the high supply temperatures of the cooling ceilings of design values 17 °C/21 °C and the low re-cooling temperatures of the ground and the preheating storages. Die SPF_W of 3.1 in the DHW mode is lower due to the higher supply temperature of 60 °C to the DHW storage.

For the energy production side, the solar PV-system yield an annual energy of 37,017 $kWh_{el.}/a$ or 13.4 $kWh_{el.}/(m^2a)$, respectively. Thereby, the solar PV-system produces in the annual balance about 30% of the total electricity demand. Despite the lower installed capacity on the roof of 26 kW_p in comparison to 48 kW_p in the façade, the fraction of the roof system is 66% of the total annual PV-yield. Figure 102 shows a comparison of the monthly consumption of the building technology for heat pump and ventilation and the solar PV yield. Since the dominating PV yield stems from the roof system Figure 102 shows the well-known picture of a surplus in summer and a deficit in wintertime. By the lower PV yield of the façade-integrated systems, only little seasonal effects of a more evenly spread PV production in the transitional and winter are visible. Over the annual period about 55% of the produced PV electricity are used on-site, and 45% are fed into the grid.

3.3.5.2 Seasonal behaviour and self-consumption of the produced PV electricity

As more detailed analysis of the PV-yield evaluations of the seasonal PV production and of the load cover factor and the supply cover factor have been carried out. In Figure 101 the PV yield in winter (December – February), the transitional period and in summer (June – August) is shown distinguished between façade and roof system.

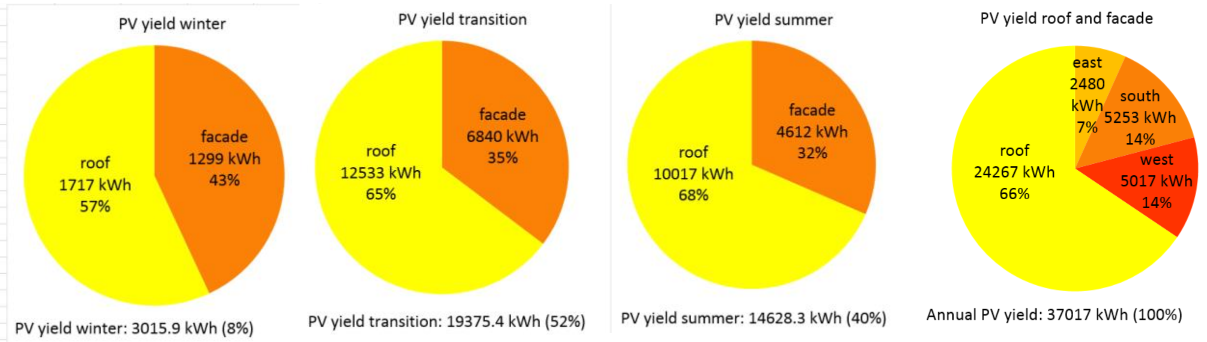


Figure 101: Share of PV yields in dependencies of the orientation and season

Despite of the larger installed PV-capacity in the façade about 40% of the PV-electricity is produced in the three-month summer period, in the three month winter period, though, only 8%. Since the total façade fraction yields only 34% of the PV electricity, also the seasonal advantages of the façade integration are only moderate. Although there is a slight increase of the façade fraction from 32% in summer to 43% in winter, still in winter the lower installed capacity on the roof, which is only about half of the façade integrated capacity, yield about double electricity energy amount of the façade. The specific yield of the roof system meets with 928 $kWh_{el.}/kW_p$ the expectations of roof systems in Switzerland, the façade system achieves in the south only 490 kWh_{el}/kW_p, in the west only 262 kWh_{el}/kW_p und in the east only 137 kWh_{el}/kW_p. The average yield of the PV areas decreases thereby to 500 $kWh_{el.}/kW_p$. The principle advantages of a more evenly spread by façade integrated systems is thus not visible due to the very low yield of the façade system.
This has also consequences for the evaluation of the PV self-production expressed by the supply cover factor, which relates the PV electricity consumed on-site to the total PV-production, and self-consumption expressed by the load cover factor, which relates the PV electricity consumed on-site to the total building electricity consumption.
The two characteristics are significantly affected by the time step resolution of the measurement data, since for instance with daily time step, the daytime yield can also be used for nighttime consumption, which in reality can only be achieved taking into account storage. In the annual balance, also seasonal effects are balanced. Thus, the longer the balancing period, the higher the values of self-consumption and self-production. Thus, the highest available resolution of hourly measurement data has been used. However, due to the available measurements, only the electricity consumption of the building technology could be evaluated, since household electricity was only available as monthly aggregated data.
Figure 102 shows the load cover factor LCF and supply cover factor SCF. The contrary evolution of the two factors can be seen clearly. In wintertime the PV yield is low, so the supply cover factor rises, since almost the entire PV yield can be consumed on-site.

The load cover factor or self-sufficiency, however, is low, since only a small fraction of the total consumption can be covered by on-site PV electricity. On contrary, in summertime there is a PV surplus, so the load cover factor rises, but the supply cover factor is low, since only a fraction of the PV production can be consumed on-site. The annual value of the on-site PV consumption is 20,294 kWh and thereby about 54% of the total annual yield of 37,017 kWh/a. The supply cover factor and load cover factor are with 25% and 30% rather low for a mixed use, since these values are achievable with heat pump also in single family houses [3]. However, as limiting factor in this evaluation only the consumption of the building technology could be taken into account, which makes up only 40% of the total consumption, so that the values would be higher with the consideration of the total electricity consumption.

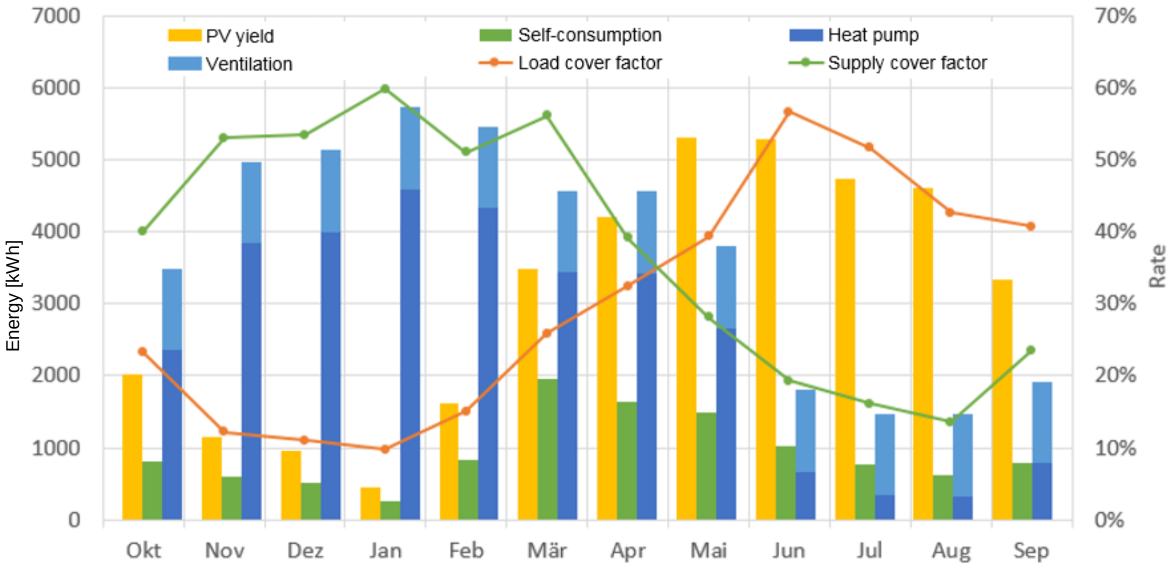


Figure 102: Monthly PV-yield, consumption of building technology and self-consumption as well as load- and supply cover factor on the basis of hourly monitoring values of the electricity consumption for the building technology

3.3.5.3 Renewable fraction for building service technologies

For all operation modes and building services the total thermal energy for space heating, space cooling and DHW of 158,161 kWh_{th}/a is supplied. Figure 103 contrasts the total thermal energy and the single fractions of the production of the thermal energy supply.

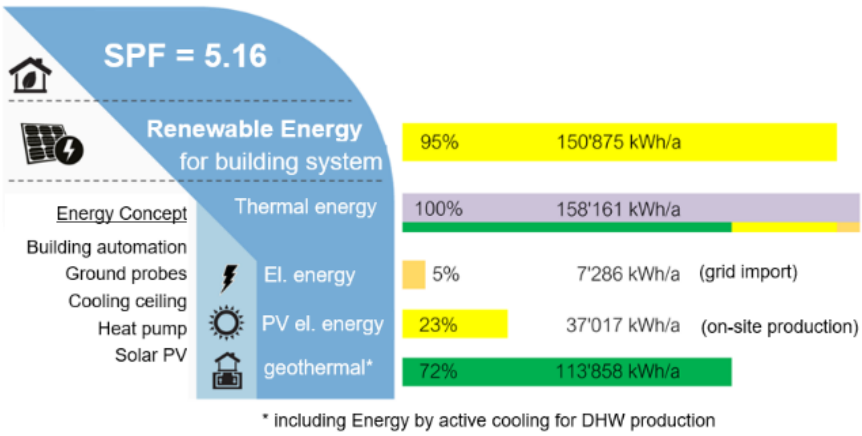


Figure 103: Comparison of thermal energy and renewable energy for the balance boundary building technology

With 72% or 113,858 kWh_{th}/a the major part of the space heating and cooling energy stems from the ground. With an additional PV-production on-site of 37,017 kWh/a, totally 150,875 kWh/a, 95% of the thermal energy are supplied from renewable sources. Based on the total renewable energy only 5% of the annual balance has to be supply from off-site sources for the balance boundary of the building technology.

3.3.6 Comparison with design data

Table 23 shows a comparison of the electrical monitoring data with the design data. In comparison to the design data the electricity consumption for space heating and DHW corresponds with measured 10.2 kWh/(m^{2}a) relatively well to the calculated value of 11.4 kWh/(m^{2}a). The ventilation value of monitored 5.2 kWh/(m^{2}a) and calculated 4.9 kWh/(m^{2}a) also correspond very well. The electrical overall consumption of the building technology of 16.1 kWh/(m²a) and thereby a the weighted value (weighting factor electricity of 2) of 32.2 kWh/(m^{2}a) would also meet the 35 or 40 kWh/(m^{2}a) for residential or office use, respectively, of the new building regulation MuKEn 2014 (2018). The measured free-cooling energy, though, is significantly lower than the design value, since not all planned heat loads have been realised with the real use of the building. The total monitored value of the electricity use of 49.1 kWh/(m^{2}a) including the building technology is also in good correspondence to the monitored values of 49.3 kWh/(m^{2}a).

Table 23: Comparison of the design data with the results of the Monitoring

	Calculation	Monitoring	Deviation
Space heating + DHW	11.4 kWh$_{el.}$/(m^{2}a)	10.2 kWh$_{el.}$/(m^{2}a)	-10%
Ventilation	5.2 kWh$_{el.}$/(m^{2}a)	4.9 kWh$_{el.}$/(m^{2}a)	-5%
Space cooling/free cooling	5.2 kWh$_{el.}$/(m^{2}a)	1.0 kWh$_{el.}$/(m^{2}a)	-80%
Electricity consumption	49.1 kWh$_{el.}$/(m^{2}a)	49.3 kWh$_{el.}$/(m^{2}a)	+0.4%
Electricity production PV	20 (16) kWh$_{el.}$/(m^{2}a)	13.4 kWh$_{el.}$/(m^{2}a)	-33% (-16%)
Overall SPF	5.0	5.2	+4%

In contrast, the yield of the PV-systems on the roof and in the façades of totally 13.4 kWh/(m^{2}a) is significantly lower than the planned value of 20 kWh/(m^{2}a). The main reason are the PV-CIS-modules in the facade, which have a significantly lower yield as planned. This becomes especially clear by the specific yield.
The total system delivers on average only 500 kWh$_{el}$/kW$_p$, while for the planned 20 kWh$_{el}$/(m^{2}a) a yield of minimum 750 kWh$_{el}$/kW$_p$ would be necessary. The measured overall seasonal performance for all operation modes is slightly higher as the design values, which underlines the good functionality and efficient measured operation of the building technology. From the measured data an overall electric consumption of the building technology of 16.1 kWh/(m^{2}a) results, which cannot be balanced in the annually by the yearly PV-production of 13.4 kWh/(m^{2}a) due to the low PV yield of the façade-integrated modules. However, based on the design data a net zero energy balance in the balance boundary of the building technology is possible.
On the other hand, if the total monitored electricity consumption of 49.3 kWh/(m^{2}a) is considered, it becomes clear, that more than double of the planned PV yield of 20 kWh/(m^{2}a) would be required to reach the net zero balance, even though already a large fraction of the roof and façade are used for PV production and the building technology is already very efficient. Thus, the balance boundary of entire energy including plug loads and appliances seems to be quite ambitious for these types of building use.

3.3.7 Discussion and conclusion of the monitoring results

The building Black & White in Pfäffikon (SZ) with commercial, office and residential use of a multi-family house, that with an appealing architectural design also for multi-storey buildings in urban surrounding a net zero energy balance with the balance boundary building technology is realistic. The building has been built in the centre of Pfäffikon SZ in vicinity of the central station and reaches by the efficient building envelope and a highly integrated building technology with the core component of a ground-coupled heat pump a very good overall balance, in which 95% of the annually used thermal energy are covered by the use of the ground and by on-site solar PV energy production.

By the detailed monitoring the good functioning of the different operating modes of the building technology and the energy demand of the building could be approved.
The cooling demand is covered by two thirds by free-cooling and in active cooling mode the entired re-cooling energy is used for SH, DHW or ground regeneration, was leads to the high overall performance factor of the heat pump of 5.16 for all operating modes including free-cooling, which even surpasses the planning value of an SPF of 5.
However, by the significant lower yield of the façade-integrated solar PV-system the self-production is notably lower than planned. On the one hand this affects the seasonal yield of the produced electricity on-site, since by the dominating roof yield a pronounced summer peak results, and thereby the self-consumption is limited to about 30% despite the mixed use, which could be an advantage due to daytime office and commercial use, but in this case, rather an average for residential buildings is reached. It has to be taken into account, however, that due to the monitoring system, only the electricity for the building technology could be taken into account, which only makes up 40% of the total annual electricity consumption.
On the other hand, the net zero energy balance for the building services space heating and -cooling as well as DHW and is reached, while for the total building technology including ventilation it is slightly missed. With the planned solar PV yield of the façade modules, though, the balance would be achievable. Thereby, also the seasonal distribution of the on-site electricity production would also be affected, since a more evenly spread annual yield and a higher self-consumption would result.
The new MINERGIE-A®-standard of 2017, however, requires an annual balance of the overall building energy including appliances and lighting with on-site PV-electricity. In the investigated building the fulfilment of this requirement would required the double PV-yield, even though already a high fraction of the building envelope is used for PV production and the building envelope and building technology are very efficient. Thus, reaching this requirement seems to be very ambitious for this kind of building use. Moreover, the MINERGIE®-characteristic is only weighted with 2 for self-consumption of the electricity, and electricity fed into a grid is reduced by a factor of 0.4. This hinders the compliance with the MINERGIE®-characteristic, but may be an incentive for local storage of electricity. At better yield of the façade integrated PV-system this requirement may be less critical due to the higher self-consumption in the transitional and winter season.

3.4 Office Building Post am Rochus, Vienna, AT

Current weather caprioles and climate changes cause again a lively debate on future building standards such as net or nearly-zero energy buildings (nZEB/NZEB). On the one hand, harsher weather conditions are leading to increased awareness of the climate change and political/regulatory requirements for energy efficiency are set up in the building sector. On the other hand, these changes of weather conditions also influence the technical capabilities and user expectations of modern office buildings in terms of (thermal) comfort. In order to tackle these challenges by technical measures, the processes of planning, construction, commissioning and operation play a key role and therefore require high quality. Practically, buildings often function under suboptimal conditions, as various technical and non-technical barriers lead to inefficiency and discomfort, i.e. "dissatisfaction" in residential buildings and sometimes "loss of productivity" (mainly) in office buildings. One reason for this is the common practice of designing and dimensioning the system for peak load operation (which often requires a building permit by law), even though this scenario may never occur during the entire building life cycle. In order to fully exploit the potential of high energy efficiencies of the various energy systems and its components (compression chillers, heat pumps, free-cooling, etc.), it is reasonable to design and analyse deeply all relevant operating conditions (especially partial load performance, transition period performance, etc.), program the building management system (BMS) and document for facility management. In the commissioning phase all sensors and actuators are tested in terms of physical presence, correct functioning and its positioning, additionally also the test of the correct implementation and functioning of the various control strategies within the building automation system is a high-quality measure.

This chapter reports on the Austrian research project PEAR[1] and on lessons learnt, recommendations and improvements for future similarly ambitious building projects. The report focuses on use of simulation models/results by experts in the first years of the building life cycle in order to operate the complex building services systems efficiently from the beginning on and to ensure high user comfort. The data analytics of recorded monitoring data from the real building operation and the use of the "Controller in the Loop" method are not part of this report. A summary of all activities can be found on the website of the Austrian Research Promotion Agency (FFG).[2]

3.4.1 The “Post am Rochus” building

The building owner’s goal was to plan, build and use a modern, comfortable building with very high standards in terms of sustainability and energy efficiency not only on paper during planning but also in the phases of construction, commissioning and operation. Therefore, the building project was scientifically supported by research experts in the framework of a public funded research project "Post am Rochus" (PEAR).

Figure 104: Rendering of the “Post am Rochus” building (source: Post AG).

[1] PEAR "Prüfstand für energieeffiziente Automation und Regelung von Gebäuden" (FFG-Projektnummer 850122)

[2] https://nachhaltigwirtschaften.at/en/sdz/projects/pear-test-facility-for-energy-efficient-automation-and-control-of-buildings.php (access 24th March 2020; 11:34)

The overall PEAR objective was to shorten the commissioning phase by very detailed investigation and optimization of the control strategies of the heating, ventilation and air-conditioning (HVAC) systems. By applying the integrative planning method, the contracted planning, construction and operation companies teamed-up with the experts from the Austrian Institute of Technology (AIT). The results from research investigation should not only be clearly documented, but also the developed control strategies should be tested by hardware in advance, thus malfunctioning of the designed control strategies can be detected, avoided and corrected. The contracted companies were also actively involved in the research project and mainly contributed to the implementation of the final control strategy. The following chapter briefly describes the process of control strategy development.
Regarding the energy and HVAC system concepts, the following technical features of the building project are highlighted:

- Three highly energy efficient compression chillers with 1 MW (thermal) capacity each,
- Heat recovery during the cooling period (re-heating register during dehumidification),
- Thermal usage of a 320 m³ sprinkler water basin as cold storage for free cooling
- Concrete core activation of building elements for cooling, and
- The central air-handling unit are equipped with a latent and sensitive recovery system (enthalpy rotor with bypass)

The warm water pumped through both the concrete core activation and the heating exchangers of the central air-handling unit is heated by the local district heating network. Hot water is produced by decentral electric flow heaters.

3.4.2 The planning process

The ambitious goal was to drastically shorten the commissioning phase. To achieve this, all relevant parties (HVAC planners, instrumentation and control engineers, owners and operators) were involved two years before commissioning. Due to this approach the commissioning was started with a high level of detailed system understanding and effective control strategies compared to the standard procedure. The involved parties were well informed by a well-documented description of the functionalities of the energy system control strategies and its set points and performance targets for the building operating phase. The AIT researchers produced a data basis generated by numerous dynamic thermal building and system simulations to predict, check and optimize the effectiveness of several control strategies and to implement finally best solutions and settings in the building management system. This chapter documents on the performed system simulations for assessing the operational building performance.

3.4.3 System integration and development of control strategies

Within the research project, nine different energy system operating modes were identified, see Figure 2. For each operating mode, cost-optimized control strategies were defined and checked by parameter variations in the settings of simulation runs, e.g. set points, hysteresis, schedules, cross-dependency curves (i.e. power cascades), etc. The simulation results and its interpretation led to a database that control engineers and operators receive practical instructions for programming, well-functioning operation and troubleshooting. All involved parties had access to the same database and documentation, i.e. a "function manual".
After the implementation of the control strategies into the building management systems and its subsystems, certain parts of the building automation software were tested using the "controller-in-the-loop" approach. This method allows to test control strategies on the controller hardware and software to be implemented in the building automation system. Prior the implementation into the BMS, functional tests were carried out for all operating modes independent of actual weather conditions during commissioning, which is an important advantage since the cooling systems can hardly be fully tested during the heating period. This "controller-in-the-loop" approach reduces the commissioning time, as errors and mal-functioning could be detected before the software and hardware was finally implemented in the "Post am Rochus" building, for further details see e.g. [1].

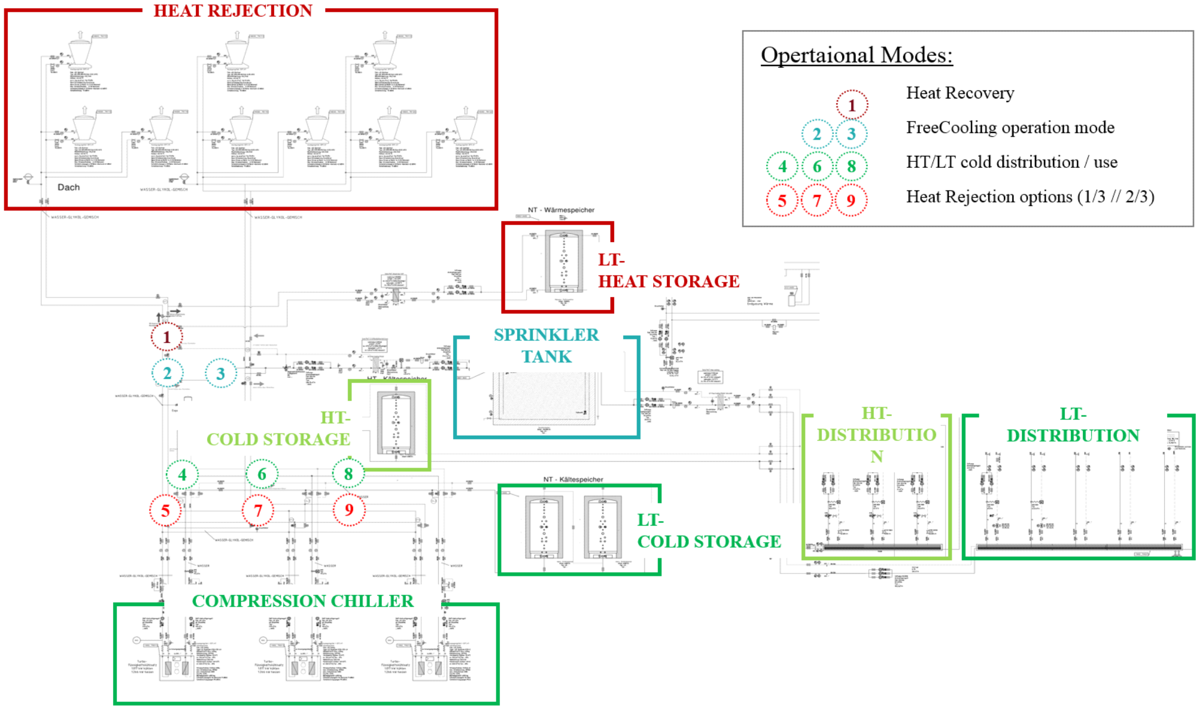


Figure 105: Overview of key thermal system components and operational modi (Source AIT)

3.4.4 Modelling and Simulation

The software TRNSYS 17.02 was applied for the transient building and energy system modelling and simulations, it was used by all modelling and simulation team members involved. Due to the complexity of the modelling and simulation tasks and to facilitate the workflows in the different offices, the HVAC overall model was divided into three independently functioning, decoupled sub-models. The following documentation of investigations are based on the second sub-model:

1. Multi-zone building model: Optimization of the shell, development of the control strategy for concrete core activation, calculation of the heating and cooling loads (input for the thermal system)
2. Thermal (cooling) system: Development of the control strategy and optimization of all operating modes (see Figure 2)
3. Air-treatment system: Development and optimization of the control strategy for different operating modes of the air handling units

The simulation results of the sub-models were validated individually and used as input data for the thermal model of the cooling system. The cooling load profiles calculated by the multi-zone building and the air-treatment model represent to different temperature levels; a) cold water temperatures for the concrete core activation and b) chilled water temperatures for fan-coils and cooling registers of the air-handling-units. The load curves of the supermarket and server rooms were estimated according to standards (SIA 2024, 2015).

3.4.5 Validation of component models

In a first step within the model creation phase, the main tendered technical HVAC components for were modelled and validated against the manufacturers' data sheets. An example for the compression chiller and the heat rejection unit is displayed in figure 3. The four standard storage tanks (each with a volume of 3 m³) were modelled by a multi-layer stratified storage model (TRNSYS type 4b). The two irrigation basins with a volume of 170 m³ each (dimensions: 6 x 6 x 5 m) were modelled with TRNSYS type 531.

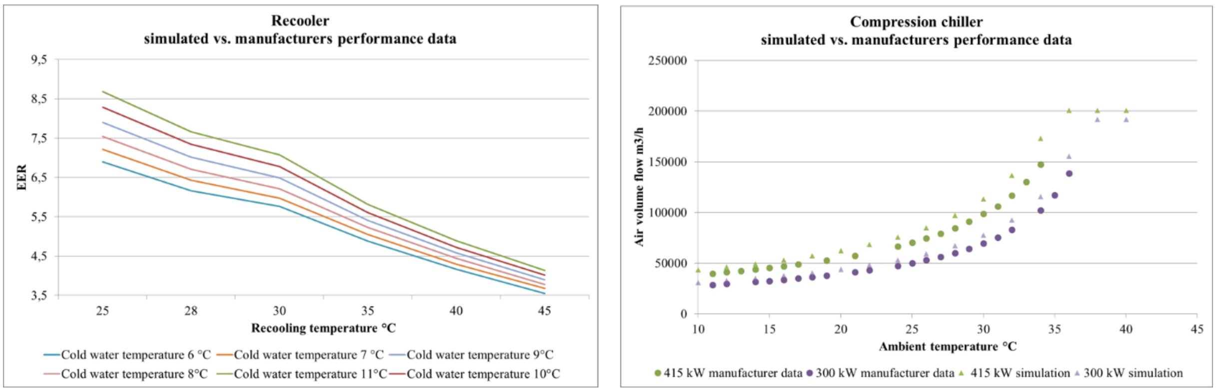


Figure 106: Simulated capacity compared to the manufacturer's specifications of the recirculating chiller (left) and the compression chiller (right).

The PEAR project applied the modeling and simulations approach because of two purposes: a) on the one hand to analyze typical/potential failures reported by the facility management of similar components/plants, b) on the other hand to optimize control strategies.

3.4.6 Subsystem models

The individually validated models of components were implemented into the modelled subsystems for optimizing the design (hydraulic pipe system and its connection, temperature levels of each individual component) of the entire HVAC model. Parameter variations regarding the temperature levels of the high and low temperature circuit were performed to identify the cost-optimal configuration. The optimization method was applied as well for following technical subsystems and/or components: a) Fan-coils, b) server rooms and c) concrete core activation as well as d) the operating discharge strategies for the thermal storages, e) heat rejection system and f) all three compression chillers.
Additionally, sensitivity analyses were performed to quantify the impact of assumed pre-condition, such as the cooling demand for the server rooms.

3.4.7 Conclusions and recommendations

3.4.8 The commissioning phase

The main objective of this activities was to drastically shorten the commissioning phase. Unfortunately, the test operation of the overall HVAC system could not take place as planned due to delays in the construction process, the building was quickly occupied. Based on the project experience, a successful commissioning phase is supported by the following factors:

- Functional quality management at component level
- Correct functioning of the entire hydraulic system including extensive hydraulic balancing
- Clear documentation on the functioning of all major components (building automation, energy efficiency/performance targets, setpoints, etc.)
- Definition of suitable and pre-tested overall control strategies and operating modes for the overall HVAC system.

It is highly recommended to implement a quality management system for the commissioning operation phase for achieving an energy efficient operation. Therefore, the main operating modes and process steps to be tested must be clearly defined together with the control engineers.

3.4.9 Owner perspective

The building owner (Österreichische Post AG) was actively involved in the research project. Based on its experience in various specialist areas such as internal technical facility management and the Group Real Estate Department, the building owner made both promoting and demanding active contributions. The feedback to the PEAR results and approach was very positive overall, as costly failures and delays could be identified and avoided at an early building project stage. Maintaining an interdisciplinary approach throughout the entire construction and commissioning phase and the active integration of research results into practice were essential pillars for efficient building operation. The quality management process of the building project should include the Facility Management as well as demand and promote it from the very beginning on. The application of the integral planning process, the usage of advanced simulation results, the intensive discussions on new technical and process solution form the basis for success. Periodic workshops with various experts and specialists form the communication for the entire process. It is essential that these workshops are continued at a higher frequency in the first weeks of operation, as the understanding of the overall system operation built up in previous years should be used as much as possible. In this way, possible errors, mal-functioning and inefficient operation modes can be identified, improvements or necessary adjustments can be immediately "identified", discussed and implemented. Even though the commission phase is often a time-critical process (which in reality is often skipped or delayed), sufficient time should be reserved for acceptance, handover and test operation of the entire HVAC and its automation management system (including all sensors, actuators and data handling/visualization). These processes must be carried out and documented in a well-structured and coordinated manner. Special attention should be paid as well to the legal/contractual conditions in the early planning phase, as most of all efforts during the planning and construction phase culminate into these issues.

3.4.10 Research and general

The project has proved to be successful, but there is still a long way to go. The common establishment and acceptance of the integral planning approach and "educated commissioning" in practice of complex NZEBs will take a while. The usage of transient energy system and building simulations and its results interpretation by experts helps designing and optimizing the building automation and control system at an early stage, as it is an essential prerequisite for the successful implementation of high-quality and convenient nZEB.
A successful integration of heat pumps into the energy system of building functions well with an integral approach. In practice, a lack of information concerning technical data and energy system performance is typical in the early planning phase and during implementation of technical equipment, as some components are technically fixed in the last minutes. This fact leads to high number of assumptions by the planners, which influence the quality and reliability of design decisions taken. The time required to create such complex models including troubleshooting, plausibility checks and adequate visualization of the results is problematic, since decisions are often time-critical and time of course also means costs, which is challenging in building construction processes.
The applied decoupling of building and system models (even in the same software) has been proven to be a feasible approach for specific investigations. The several sub-systems could be treated independently, since the energy loads were synchronized and the (thermal) comfort was guaranteed. For scenarios where the thermal activation of building construction elements is part of the building energy system concept, a coupling of both models building and energy system is a must.
Hydraulic problems occurred during the handover and commissioning phase, that coursed a suboptimal operation of the free cooling modus and an On-Off switching of the compression chiller operation appeared. In this specific case, the mechanical dampers could not open the circuit for free cooling, the pressure in the relevant pipe was to high due to the altitude difference between the roof (Heat rejection system) and the basement (chillers). For certain key fluid components it is advantageous to perform some fluid dynamic calculation/simulation, either by very experienced experts or preferably in the long run by data driven methods. Therefore, the digitalization of all relevant data is an essential prerequisite, the digitalization of information and data is expected to make remarkable progress in the coming years, especially driven by the rapid development of the Building Information Modelling (BIM) industry. This BIM reduce data losses, which typically occurs at all building development phases and in-between different disciplines and software tools, such as

- Planning <-> construction <-> commissioning <-> operation
- HVAC planning <-> control engineering or
- Building automation and <-> facility management.

From a legal point of view, it must be clearly regulated how the simulation results are to be dealt with in the context of the construction project, i.e. whether it is merely additional information, or the simulation results are reliable data base for the functional technical description. Another legal issue is the operator contract (Facility management). Those contracts contain often "energy saving targets", which are usually indicated in relative savings compared to the energy consumption of previous period in the first 3-5 years of operation. This is obviously not the best solution, because at least the first year of operation isn't representing the normal operation! Using the energy target values from the design phase is as well not feasible, many changes during the planning and construction phase occur, e.g. lower internal cooling loads due to new technologies such as LED. This requires a recalibration of the existing and created building and energy systems models with as-built values, the simulation results should be validated by monitoring data. This "as-built" model would provide digital data and information baseline, updateable baseline over the entire life cycle of the building (digital twin). In addition, the so-called digital twin would be capable to automatically detect faults, mal-functioning and inefficiencies, i.e. generally the quality of the entire building development process is improvable and there is a check that the theoretic potential for energy savings and high indoor comfort is met.

3.5 Conclusions of monitoring in office buildings

Monitoring results in office buildings in Annex 49 are related on the one hand to the evaluation of offices buildings with mixed office and residential (and also commercial use), which may become a trend for including shops and retails on the ground floor in buildings with residential or office use in the upper floors. On the other hand a complex high rise building with office and commercial use with a focus on the integral planning and commissioning phase is considered. An interesting aspect by the combination of different uses, in particular office and residential, is that different load structures are combined which may have advantages for load balancing. For instance regarding self-consumption, the daytime operation in office or commercial use may have advantages compared to the absence during daytime for residential use. Moreover, on the thermal side, a combination of higher space cooling loads in office use with higher DHW demands in residential use may offer synergies for simultaneous operation of heat pumps.

The two Swiss office buildings with mixed use were both designed already in 2010 – 2012 and the balance boundary was related to the upcoming MINERGIE-A® label at the time, which set the building technology as balance boundary for the nearly zero energy balance. Both buildings confirm, that the balance can be reached by using the building surfaces. Both building are all electric buildings with ground-source heat pump and have a high performance building envelope. Monitoring data of both building are in good agreement with the design data and both buildings have a high heat pump overall performance in the range of 4.5 -5.

In the case of moderate office share in the building in Uster, the roof area is sufficient for the balance, in case of larger office and commercial use, also the façade is needed to reach the balance. Even though the balance could not be confirmed in the monitoring due to low PV façade yields, simulations confirm that the balance can be met.

However, the results also indicate, that the overall balance including appliances and plug loads can be quite challenging, even when including the façade for energy generation. In the larger office/residential buildings like the Black & White, the façade is already used to a large extend for PV-generation, and even with the expected maximum PV yield, there is a significant gap to balance the energy demand although the heat pump performance with an overall values of 5.2 for all operation modes is already high and building loads are already quite reduced due to a good building envelope performance. This situation may be overcome by groups of buildings in neighbourhoods, where different load situations can be outweighed among the different uses and load profiles. Monitoring results on groups of buildings are reported in chap. 5.

The third office building is a high rise building with mixed commercial and office use, of which no monitoring values are available, yet. However, the objective of the project was the investigation of the integral planning process for complex non-residential nZEB. Moreover, software aided approaches including control system design by simulations and software assisted commissioning was the focus of the investigations. Experiences are cautiously optimistic, although experience also shows a long way to go. Digitalisation and BIM are a vision and perspective to link all professions closer together, but in details there are still many interfaces to be dealt with.

4 Monitoring results with other non-residential use

In this chapter the monitoring results of non-residential buildings of different use categories contributed to IEA HPT Annex 49 are summarised. They comprise a large hotel, 2 schools and a kindergarden as well as a supermarket.
Non-residential applications apart from office use may vary in the load structure and may form by their use a quite different situation compared to residential or office, e.g. in schools, where there may be a holiday period in the time of best solar yields. Moreover, many of the applications are still early P&D where not many examples exist of the use category. Thus, it can be expected, that fundamental experiences can be made by a detailed monitoring and a basic question for the monitoring is the fulfilment of the nZE-balance with the chosen building envelope and system concept. However, also for the non-residential buildings particular items have been investigated, which comprise:

- Solar thermal integration for larger hotels
- Heat export of recooling energy from supermarket refrigeration
- Energy piles and agrothermal fields as heat and cold source
- Regeneration of boreholes and other ground collectors by recooling waste heat and free-cooling
- Building refurbishment of historical building to nZEB
- Adapted heating emission system design for application of a CO_2-heat pump

4.1 Overview

The **Scandic Lerkendal Hotel in Trondheim, Norway** was finished in 2014. It consists of a hotel part with a heated area of 11,434 m^2 of passive house standard according to the Norwegian standard NS 3701 with a Norwegian energy label A, and one part with offices, congress centre and parking areas of around 25,000 m^2 with a Norwegian energy label of B. This monitoring describes and analyses the heating system in the hotel part. The calculated specific energy demand suggested that Scandic Lerkendal Hotel could be one of the most energy efficient hotels in the world, although measurements have proved that the actual energy use was significantly higher than estimated.

The **Medbroen Kindergarten in Stjørdalin, Norway** which close to Trondheim, is a building which was originally an agricultural building from 1908, but parts of it of an area of 833 m^2 was refurbished to the Norwegian passive house standard NS 3701 in 2015. A ground source heat pump system supplies heat to a low-temperature floor heating system and the heating coil of the air handling unit (AHU). It also preheats domestic hot water (DHW). An electric boiler is used as peak load. The refurbishment of an over 100-year-old building to passive house standard makes this project unique. Unfortunately, due to malfunctioning of the heating system during the first couple of years due to several errors, it was not possible to perform realistic field measurements for a full year, but several errors have been discovered and improvements have been suggested.

The **Willibald-Gluck secondary school, Neumarkt in der Oberpfalz, Germany** is a secondary school for about 1,400 pupils, which comprise the main four-storey school building and a sport hall of a total energy reference area of 14,400 m^2. The school with its interior atria started operation in the winter school year of 2015/16. In addition to the school building a three-field sports hall and a sports field were also built. The building envelope is well insulated and reach 50% lower heat losses than the standard requirements at the time with U-values in the range of 0.15 W/(m^{2}K) for opaque components and 0.8 W/(m^{2}K) for windows, with g-values of 0.28 – 0.5. The concept also features a controlled ventilation with heat recovery efficiency of 85% and a maximum air flow of 80,000 m^3/h. The building system contains a 85 kW_{th} ground coupled heat pump connected to 96 energy piles below the building and a 4,400 m^2 agrothermal field below the sport field as heat source. The ground installations are also used for free-cooling and are thereby regenerated. In order to meet a plus energy balance a 291 kWp PV-system is integrated on the roof. As electric storage, a 130 kWh Vanadium Redox Flow battery is integrated. The monitoring was carried out for 4 years from 2016 – 2019. Besides the energy balance, also the thermal behaviour of the ground source components and the battery storage are items to be investigated in the monitoring.

The **Justvik Skole in Kristiansand, Norway** is a primary school in the Southern part of Norway, which was completed in 2017. It is designed according to the Norwegian passive house standard (NS3701, 2012). The total heated area is 3,480 m^2, incl. 535 m^2 for a sports building. The building system technology uses a CO_2 ground-source heat pump, which covers the heating and cooling demands. The contractor for Justvik skole (Veidekke ASA) received the Norwegian Heat Pump Award 2018 due to the unique design of the CO_2 ground-source heat pump system, which uses a particular adapted heat emission system as serial combination of radiators, a floor heating system and the heating of the ventilation air in order to make the best use of the particular characteristic of the CO_2-refrigerant at large temperature spreads for the heat rejection of the gas coolers. The DHW production is integrated as parallel cycle.

The **KIWI Dalgård supermarket in Trondheim, Norway** was finished in 2017, and was the fourth "green" KIWI store with an extra focus on sustainability. It has a heated floor area of 1250 m^2, is built according to the Norwegian passive house standard NS3701 (2012). The total energy consumption is 100 kWh/(m^2a). It is planned to produce more energy during operation than it uses due to the application of 560 m^2 roof-mounted solar photovoltaic (PV) panels and two 39.7 kW_{th} ground-source heat pump system connected the BTES of 8 ground probes with . Heat recovery from the refrigeration system is used to heat the ventilation air in the supermarket and to regenerate the BTES. Surplus heat is delivered to 60 apartments in three neighbouring buildings, i.e. the use of commercially available waste heat from the supermarket is used for on-site heating purpose and adjacent residential application.

4.2 Hotel Scandic Lerkendal – Trondheim, NO

Scandic Lerkendal Hotel, which is located in Trondheim, Norway, was finished in 2014. It consists of a hotel part with a heated area of 11,434 m^2 of passive house standard according to NS 3701 (2012) with a Norwegian energy label of A, and one part with offices, congress centre and parking areas of around 25,000 m^2 with a Norwegian energy label of B. This report describes and analyses the heating system in the hotel part. The calculated specific energy demand suggested that Scandic Lerkendal Hotel could be one of the most energy efficient hotels in the world, although measurements have proved that the actual energy use was significantly higher than estimated. Information about the project is mainly based on the analysis performed in the Master thesis of Aashammer (2016).

Figure 107: Picture of Scandic Lerkendal Hotel (Dagens Næringsliv, 2014) and solar thermal system

4.2.1 Calculated energy and heating demands

Scandic Lerkendal Hotel has a calculated net energy demand of 68.8 kWh/(m^2a), and delivered energy demand of 46.9 kWh/(m^2a). The energy label is dark green A, which means that the estimated annual energy use is lower than 140 kWh/(m^2a) and less than 30% of the heating demand is covered by fossil fuels or electricity (Enova SF, 2015). The calculated energy demand is also significantly lower than the measured energy use for hotels in Enova's building statistics. When the hotel was built in 2014, the average energy use for hotels in Norway was 246 kWh/(m^2a) for all hotels and 170 kWh/(m^2a) for hotels of passive house and low-energy standard (Enova SF, 2014). The calculated energy demand for DHW heating was 230,465 kWh/a, corresponding to 20.2 kWh/(m^2a). According to the design this should be covered by the following systems:

- 30 % from heat recovery from cold storage rooms – approx. 6 kWh/(m^2a)
- 50 % from a solar collector system – approx. 10 kWh/(m^2a)
- 20 % from district heating (peak load system) – approx. 4 kWh/(m^2·a)

The space heating demand is covered by an air-to-water heat pump as base load (80%, 9.4 kWh/m^2a) and district heating as peak load (20%, 2.4 kWh/m^2a).

4.2.2 System for Thermal Energy Supply

Figure 108 shows a principle sketch of the thermal energy system at Scandic Lerkendal Hotel. The main systems, that are described and analysed, are:

- Space heating
  - Air-to-water heat pump for space heating (base load) / District heating (peak load)
- DHW heating
  - Heat recovery from cold storage rooms / Solar collector / District heating (peak load)

Figure 108 shows that the heat recovery system and the solar collector system are connected in series before the district heating heat exchanger.

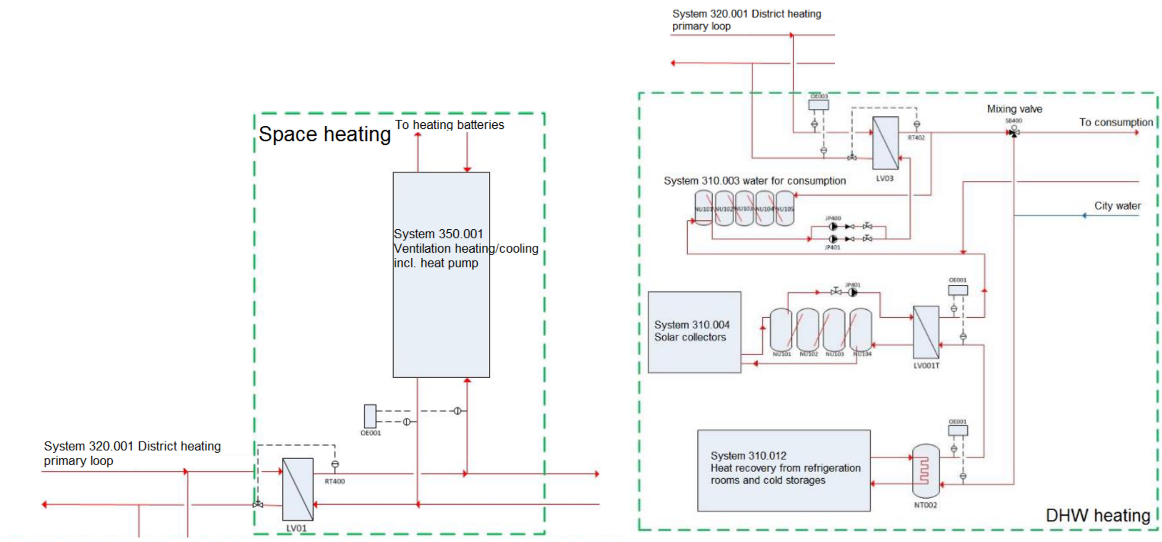


Figure 108: Principle sketch of the thermal energy system at Scandic Lerkendal hotel (Aashammer, 2016).

4.2.2.1 Heat Pump System – Space Heating

The R410A air-to-water heat pump unit with 4 hermetic scroll-compressors with intermittent (on/off) control heats ventilation air that is used for space heating in the hotel rooms (no hydronic radiator system installed). The heat pump can work in reverse operation to supply both heating and cooling. However, there was no cooling demand during the measuring period. The nominal heating capacity of the heat pump unit is 200 kW at 7/45 °C. The heat exchangers in the air handling units (AHU) has a design temperature level of 40/30 °C, and the heat pump is operated at a fixed supply/return temperature of 43/38 °C. The hotel has a decentralized ventilation system with two demand controlled (VAV) AHU for each floor. The ventilation system has a very low SFP factor due to the decentralized design and the fact that the emergency staircase is used as an air duct utilizing natural forces (the chimney effect) to transport the exhaust air. The hotel is also using a booking system where they are renting the bottom floors first, and the ventilation system is only operated at full capacity in floors where all the rooms are booked.

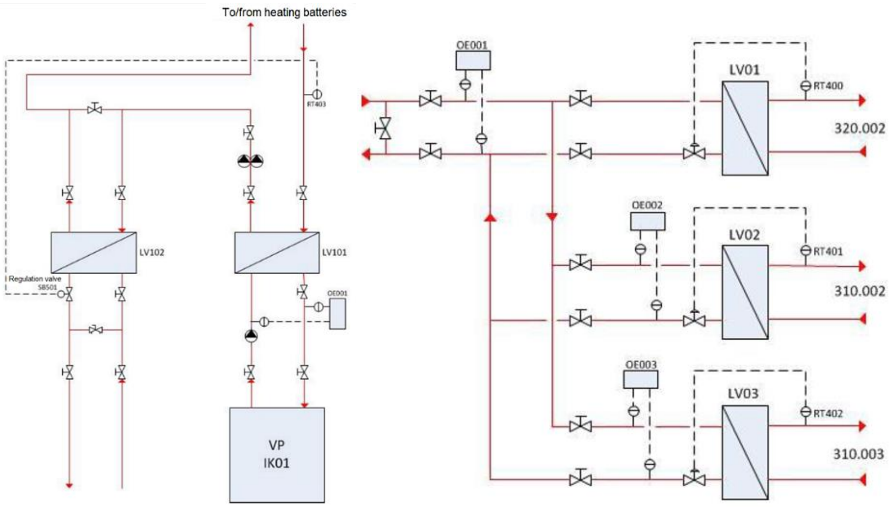


Figure 109: Principle sketch of the heat pump system (350.001) at Scandic Lerkendal Hotel (left, VP IK01 – heat pump, OE001- energy meter, LV101-102 heat exchangers) and principle sketch of system 320.001 district heating primary loop (right, OE001-003 – energy meters, RT400-402 temperature sensors, LV01-03 heat exchangers) (Aashammer, 2016)

4.2.2.2 District Heating – Peak Load for Space Heating and Heating of DHW

District heating is used as peak load for both space and DHW heating. The hydronic heating system is connected to the district heating grid by plate heat exchangers. Figure 108 shows a principle sketch of the district heating peak load system.

For DHW heating, the district heating heat exchanger is placed in series after the solar collector system, and it was designed to cover the remaining 20% of the annual DHW demand. In the space heating system, the district heating heat exchanger is also placed in series after the heat pump condenser, and it was designed to cover 20% of the annual space heating demand. Individual plate heat exchangers are installed for each of the different systems using peak load – LV01 for the space heating and LV03 for DHW. Temperature sensors control the water flow rate by means of a motor valve, and energy meters are measuring the heat supply from the peak load system.

4.2.2.3 Heat Recovery from Cold Storage Rooms – Heating of DHW

Heat recovered from the cold storage rooms are used to preheat domestic hot water (DHW). During DHW draw-off city water enters the building and passes through a tank with a shell-and-tube heat exchanger, NT002 in Figure 110, where surplus heat from the condensers of the refrigeration plants are utilized. The accumulation tank (CTC FerroModul T400 K30) has a volume of 390 litres and a heating capacity of 30 kW at an average temperature difference (ΔT) of 35 K at low water velocities through the tank.

This system is placed in front of the solar collector system, and was designed to cover 30% of the annual DHW heating demand. The outlet water temperature from the tank, which depends on both the draw-off water flow rate and seasonal variations in the city water temperature (5-10 °C), varies between 8 °C and 36 °C. Potential surplus heat is rejected through the dry cooler LB001.

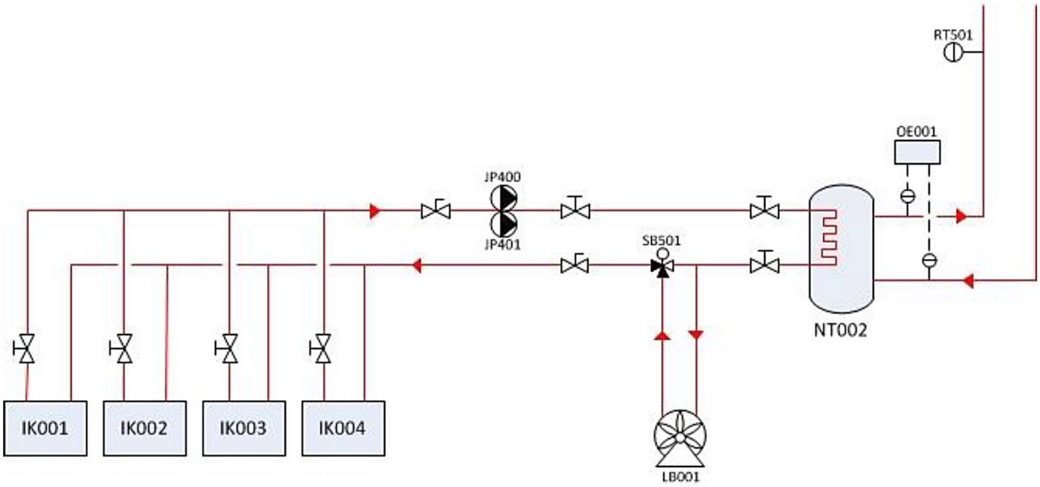


Figure 110: Principle sketch of the system for heat recovery from the refrigeration plants (310.012) (Aashammer, 2016). OE001 – energy meter.

4.2.2.4 Solar Collector System – Heating of DHW

Since DHW heating constitutes a large part of the total heating demand in a hotel of passive house standard, solar collectors were installed to cover 50% of the annual heating demand. 350 m^2 of flat plate collectors are connected to 4 x 5000 litres accumulation tanks as illustrated in Figure 111. The specific energy demand for operating the solar collector system and delivered heat from the collectors was calculated to be 1 kWh/(m^2·a) and 10 kWh/(m^2·a), respectively, resulting in a system energy efficiency of approximately 10.

The solar system is an indirect system with forced circulation of 35% propylene glycol. Heat from the collectors are transferred through three solar collector modules with integrated pumps and heat exchangers and stored in four accumulation tanks. During DHW draw-off heat is instantaneously transferred through the plate heat exchanger LV001T.

The system is controlled to start when the temperature difference (ΔT) between the solar collectors and the accumulation tanks exceeds 10 K. The energy meter OE001 measures the thermal energy transferred to the DHW from the solar collector system. The temperature of the DHW after the solar collector system varies throughout the year. However, no historic measurement of the DHW temperatures exists.

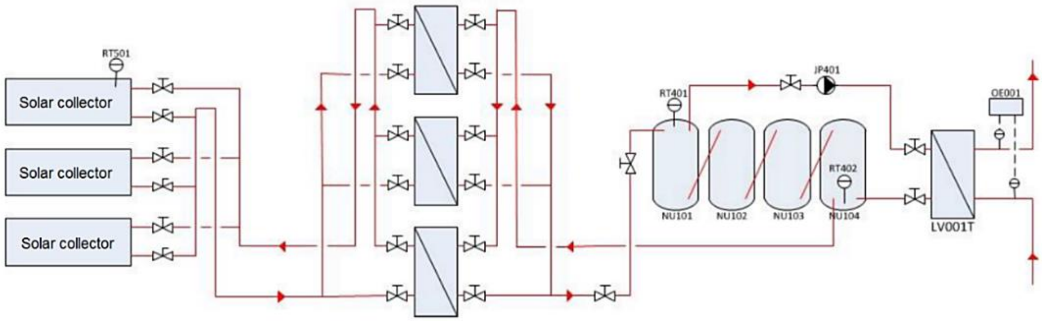


Figure 111:Principle sketch of the solar collector system (310.004) (Aashammer, 2016). OE001 – energy meter.

4.2.2.5 DHW System

Figure 112 shows a principle sketch of the DHW system for the hotel. In periods without water consumption, the tanks NU101-NU105 are charged with DHW by the pumps JP400 and JP401. The tanks (CTC FerroModul T400) have each a volume of 400 litres. The temperature sensor RT402 ensures that the water is reheated to 70 °C to avoid the Legionella bacteria.

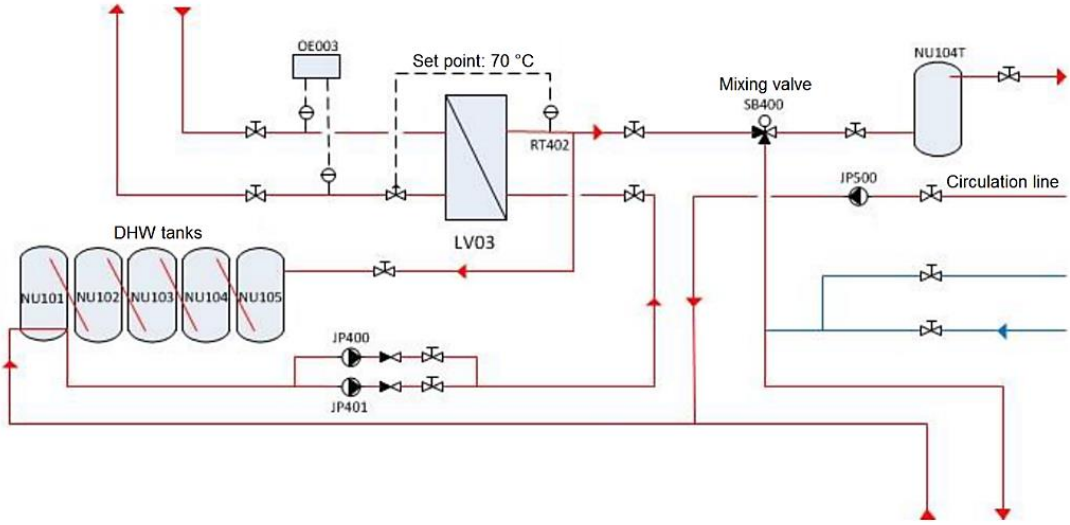


Figure 112: Principle sketch of DHW system (310.003) (Aashammer, 2016). OE003 – energy meter, RT402 – temperature sensors

4.2.3 Monitoring Results (2014-15)

The energy meters and temperature sensors are included in the principle sketches of the system, i.e. Figure 108 to Figure 112. Two measurement periods were performed, one during the project assignment of Aashammer (01.09.2014 – 31.08.2015, first operation year) and later during the Master thesis (01.01.2015 – 31.12.2015). Table 24 and Table 25 show a comparison between estimated and measured delivered energy from the first year of operation, for space heating and DHW heating, respectively. The measured total delivered energy for space heating and DHW heating were as much as 63% and 28% higher than the design values. For space heating, the deviation between the different sources ranged from +53% to +77%. For DHW heating the heat recovery (-30%) and solar collector system (-54%) delivered significantly less heat than designed, while the heat supply from the peak load was correspondingly high (+321%). In addition, the number of guests in the hotel were lower than estimated, so the energy use could have been even higher.

During the second measuring period (01.01.2015 – 31.12.2015) the specific energy use for space heating was found to be 33.5 kWh/(m^2·a), which is 70% higher than estimated, and slightly higher than the first measurement period. The SPF_{HP} was measured to be 2.2 including energy used for defrosting, which is rather low, leading to energy savings of 54 % compared to direct electric heating. The SPF_{sys} including the district heating with efficiency of 0.96 and energy coverage factors of 0.8 and 0.2 for the heat pump and district heating, respectively, was 2.0 for space heating.

Table 24: Comparison between calculated and measured delivered energy for space heating in the period 01.09.2014-31.08.2015 (Aashammer, 2016). HP – heat pump.

Parameter	Calculated [kWh/a]	Calculated specific [kWh/(m²a)]	Measured [kWh/a]	Measured specific [kWh/(m²·a)]	Devia-tion
Delivered heat from peak load	45 015	3.9	68 689	6.0	+53 %
Delivered heat from HP	180 058	15.7	298 107	26.1	+66 %
Delivered el. energy to HP	84 933	7.4	150 172	13.1	+77 %
Total	225 073	19.7	366 796	32.1	+63 %

As the energy use for space heating was higher than estimated, it is even more important to achieve a high SPF for the heat pump. The energy coverage factor was both calculated and measured to be 80%. This indicates that the problem with excessive energy use is not caused by the energy central, but may be related to the heat recovery in the AHUs and problems related to the building envelope, i.e. infiltration, thermal bridges, etc. The operating personnel confirmed that there were issues with operation of the heat recovery system, leading to no heat recovery for certain periods in some of the AHUs. On a positive note, there has been no need for cooling of the building. Due to a limited window area and automated exterior solar shading, the cooling demands are minimized. The system for DHW heating is the most innovative part of the energy system.

Table 25: Comparison between calculated and measured delivered energy for DHW heating in the period 01.09.2014 - 31.08.2015 (Aashammer, 2016). HP – heat pump.

Parameter	Calculated (kWh/a)	Calculated specific (kWh/m²·a)	Measured (kWh/a)	Measured specific (kWh/m²·a)	Deviation
Heat recovery	68 604	6.0	48 411	4.2	-30 %
Solar system	115 483	10.1	52 954	4.6	-54 %
Peak load	45 736	4.0	192 523	16.8	+321 %
Total	229 823	20.1	293 88	25.7	+28 %

Unfortunately, the energy use for DHW heating was measured to be 24.5 kWh/(m²·a), which is 22% higher than estimated. In addition, the contributions from the different energy sources are not according to the calculated values. This is shown in Table 26. The main reasons for the deviations are too low utilization of the heat from the solar collectors and an undersized heat exchanger for the heat recovery from the refrigeration plants. The master thesis said that inadequate design of the system led to multiple assumptions from the manufacturer and consequently poor design.

Table 26: Measured and calculated contributions for DHW heating from different energy sources in 2015 (Aashammer, 2016)

Contribution to DHW heating	Measured		Calculated	
Solar collectors	4.11 kWh/(m²·a)	**17 %**	10.1 kWh/(m²·a)	**50 %**
Heat recovery from cold storage room	4.11 kWh/(m²·a)	**17 %**	6.0 kWh/(m²·a)	**30 %**
District heating (peak load)	16.3 kWh/(m²·a)	66 %	4.0 kWh/(m²·a)	20 %

Other reasons for the deviations are listed below:

- The booking system is not operated as planned, and the location of the rented rooms were randomly selected. The benefit of two ventilation systems per floor and inoperative ventilation systems in empty floors was therefore not utilized
- Low-energy shower heads were not used, leading to higher DHW consumption
- Higher energy use for space heating may imply that residents increased the set-point temperature in the hotel rooms, to compensate for missing floor heating in the bathrooms
- The ventilation system is likely to have been operated at higher airflow rates during the first operation year to remove emissions from materials, etc.
- "Single-zone" simulations in the Norwegian building simulation program (SIMIEN) might have led to an underestimated heating demand in the design phase

4.2.4 Results and Discussion – Improvement of the Existing System

The master thesis revealed some errors with the thermal energy system, and it is expected, but not confirmed, that they have been improved afterwards. This underlines the importance and benefit of evaluating the energy performance and perform quality assurance of the thermal energy system during the first year of operation.

Recommended improvement measures are:

Undersized heat exchanger and incorrect pump control

- Current system – The heat exchanger (LV001T) is undersized and the control of the pump (JP401) is incorrect, since it is running continuously instead of controlling the flow rate. The return pipeline from the circulation system was also wrongly connected.
    - Improvement – Replace the heat exchanger LV001T and the pump JP401 with an AquaEfficiency-solution. Fix the connection of the return pipe.
    - Benefit – Significant better utilization of the heat from the solar collector system, with an estimated payback period of 1-2 years.

Poorly designed heating system

- Current system – There were some errors with the heat recovery system and solar collector system leading to lower annual heat supply from these sources and consequently more heat supply from the peak load. In addition, both the space heating and DHW heating demands were underestimated in the design phase.
    - Improvement – For new buildings, make sure that the design and calculations are of high quality. Underestimation of the heating demand may also lead to less ambitious solutions with regards to energy efficiency due to lower profitability from energy savings. There can be many reasons for the deviations and the reasons have not been evaluated.
    - Benefit – Better performance with increased energy efficiency and no need to improve errors and new investments to improve the thermal energy system.

Air-source heat pump not designed for cold climate operation

- Current system – The air-source heat pump (actually a standard liquid chiller) can only supply heat at outdoor temperatures above -8 °C (stop temperature) which increases the use of peak load at lower outdoor temperatures (reduced energy saving).
    - Improvement – Installation of a high-quality air-source heat pump with a stop temperature of -20 °C or a ground-source heat pump (GSHP). GSHPs achieves higher SCOP and higher energy coverage factor, but has a larger investment cost, and the local ground conditions are also an important factor.
    - Benefit – Higher SCOP and increased energy coverage factor.

High GWP HFC working fluid (refrigerant)

- Current system – The heat pump is charged with R410A, which is controlled by the F-gas Directive. The Global Warming Potential (GWP) is 2 090 CO_2-equivalents.
    - Improvement – Installation of e.g. a propane (R290, GWP=4) heat pump unit, air-source or ground-source.
    - Benefit – Improves the eco-friendly profile of the unique building. The drawbacks are higher investment costs and requirement for safety measures due to flammability.

Constant supply temperature from the heat pump

- Current system – The heat pump is operated with a fixed supply/return temperature of 43/38 °C and the heat pump has four hermetic scroll compressors with intermittent (on/off) control.
    - Improvement – Variable speed drive (VSD) compressors were not widely available when Scandic Lerkendal Hotel was built, but are superior to on/off control with regards to energy efficiency and lifetime. The use of buffer tanks improves the on/off-control method, but this is not implemented at Scandic Lerkendal Hotel.
    - Benefit – VSD leads to SCOP and reduces the number of compressor starts, reducing wear-and-tear and prolonging the lifetime of the compressors.

4.2.5 Conclusions – Recommendation with regard to design and operation

Recommendations regarding solar collectors used for DHW heating (Aashammer, 2016):

- Create a detailed simulation model with software, e.g. Polysun that takes into account local climatic conditions.
- For Norwegian conditions, flat plate solar collectors are recommended since this is the most robust collector type.
- Design the accumulation volume for a maximum water temperature of 90 °C.
- For the Trondheim area the collectors should have an azimuth angle between 0° and -10°, and an inclination angle between 40° and 75°. The ideal angle for other locations should be investigated using simulations.
- It is important to have sufficient space available for installation of the solar collectors to avoid the panel shading. Shading from trees and surrounding buildings should also be avoided.
- Use "plug and play"-solutions whenever possible, such as between solar collectors and accumulation tanks and between accumulation tanks and the DHW circuit (e.g. PAW Solex solar transfer stations and integrated pump and heat exchanger station).
- Use city water directly on the cold side of the heat exchanger between the accumulation tanks and the DHW circuit, to ensure good heat transfer in the heat exchanger and high efficiency for the solar panels.
- The system must be controlled to ensure cold water into the secondary side heat exchanger(s) between collectors and accumulation tanks.
- When utilizing heat recovery from refrigeration plants, this heat source should be connected in parallel with the solar collector system.
- Install a sufficient number of thermal energy meters for system monitoring.
- The pumps should be controlled to achieve max. stratification in the accumulation tanks.
- When using multiple accumulation tanks, varying tank volume with regards to available solar energy and consumption of domestic hot tap (DHW) should be considered.

For air-to-water heat pumps used for space heating, the following is recommended:

- Install a high-quality air-source heat pump system designed for operation in cold climate or a high-quality ground-source heat pump system. The heat pump should preferably use a natural working fluid, e.g. propane (R290), and VSD compressors.

4.3 Willibald-Gluck secondary school – Neumarkt (i. d. Opf.), Germany

Within the framework of energy-efficient construction inter alia schools play a key role in achieving the climate protection goals. They are not only responsible for the education of future generations, but with their extensive and heterogeneous building stock as well as their new buildings predestined to form a learning laboratory and exemplary projects for "energy-optimized construction and operation".

In the town of Neumarkt (i.d.Opf.), the Neumarkt district built the new "Willibald-Gluck-Gymnasium" (WGG) with a sports hall for about 1,400 pupils and an energy reference area of 14,400 m^2. The four-storey school building with its interior atria started operation in the winter school year of 2015/16. In addition to the school building a three-field sports hall and a sports field were also built. The new construction of the Willibald-Gluck-Gymnasium is a perfect example of integral planning and enables the research of future-oriented technology and energy concepts in educational buildings. The basic idea of the architectural concept is that through light, transparency, open communication and clear orientation, the quality of study and of stay in the school should be increased, thus creating an optimal classroom climate for students and teachers. Contributing to the concept are inter alia the colourful glass panes, which also provide weather protection for the opening wings of the windows and sets cheerful accents. Indoor daylight is provided by two large atriums. Bright traffic routes connect all areas.

Figure 113: Entrance school (left) and school and gym with sports field (right) [Berschneider + Berschneider, phtographer Petra Kellner]

The goal of the new school building includes the following aspects:

- Example of integral planning
- Research into future technologies and energy concepts in educational buildings
- Reduction of the heating energy demand
- Integral consideration of the total electricity demand of a building
- Excellent indoor quality, good indoor climate with low CO_2 concentrations, excellent room acoustics and optimal daylight conditions to create an ideal learning environment

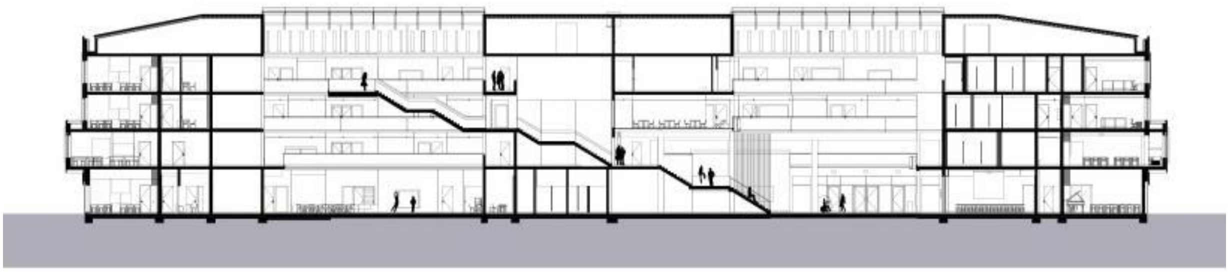


Figure 114: Longitudinal section school

4.3.1 Energy concept

In addition to renewable energy generation by ground-coupled heat pumps and a PV system on the roof of the gym and school (290 kW_p), a Vanadium Redox Flow battery (VRFB) system forms the basis for the promising energy concept.

Table 27: Technical data building technology

	Plant technology	Output/area/volume flow rate
Heating	Ground-source heat pumps	• max. 85.6 kW_{th} (both together) • Agrothermal:47 pcs à 93,5 m, 4.400 m² • Energy piles 96 pcs (18 à 8 m / 38 à 10m / 40 à 12 m) • Server waste heat • Buffer storage 3,000 l
Cooling	Free cooling by agrothermal field and energy piles	
Power generation	Roof-integrated photovoltaics	291 $kW_{p,}$ electrical battery 130 kWh
Ventilation	Controlled supply and exhaust air system with heat recovery	• School: max. 4x 20,000 m³/h • Gym: 10,000 m³/h • Meeting place: 3 x 5,000 m³/h • n_{max} = 4.4 1/h, heat recovery 85 %

The ground is accessed as a low-temperature heat source and sink as well as thermal storage by 96 activated energy piles (foundation piles) and a surface horizontal collector (agrothermal field) under the sports field.
The ground-coupled electric heat pumps generate the required heat for floor heating and concrete core activation as well as the ventilation systems in the school building and for the floor heating installed in the gym and the radiators in the adjoining rooms. Cooling of the classrooms and IT/electrical rooms during summer is "passive" (only circulation pump operation) by the energy piles and the agrothermal field.

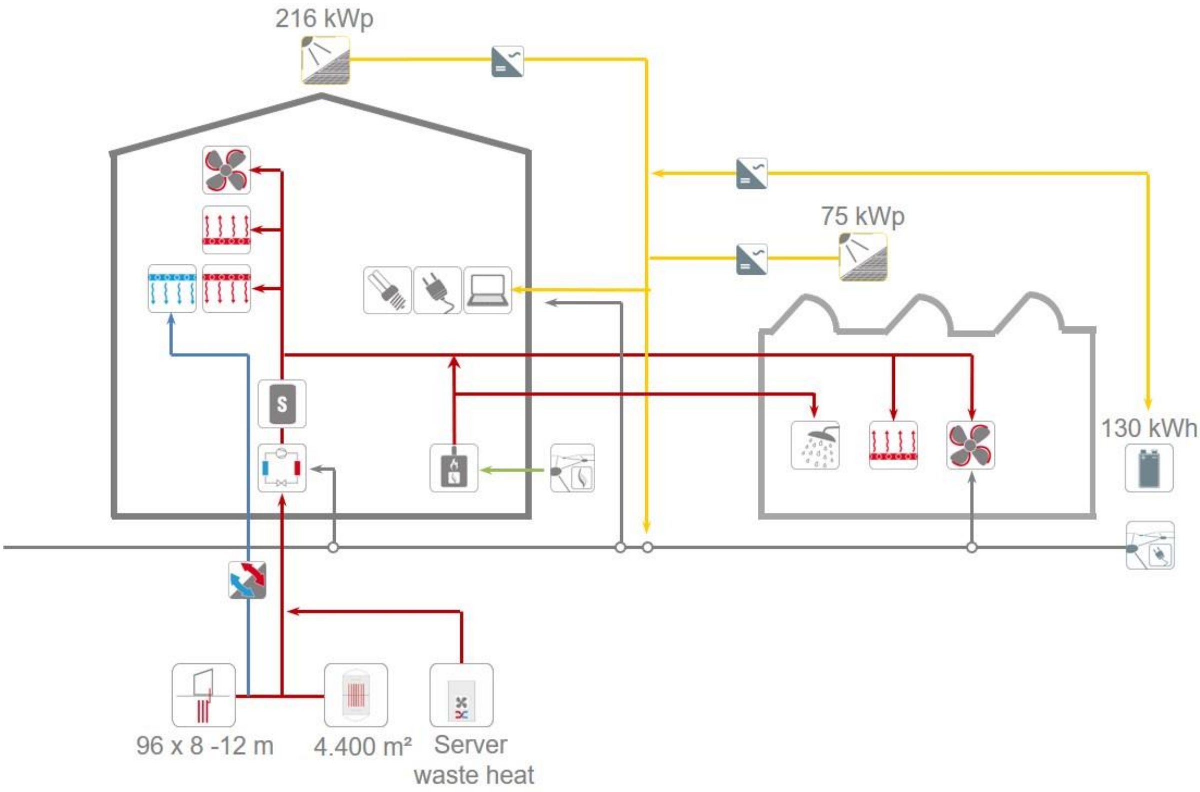


Figure 115: Energy concept - heating and cooling

The energy generation is tuned to the heat sources and provides heat with low system temperatures (Low-Ex systems). The energy concept stipulates that around 70% of the heat requirement is provided by the heat pumps. The peak load (30%) of the heating energy requirement is covered by a gas condensing boiler. The renewably generated electricity from solar photovoltaics (PV) is primarily used in the building or stored in the battery, only surpluses are fed into the public grid. Through the integration of the VRF battery with a usable capacity of 130 kWh, the planning envisages that around 65% of the solar yield can be used locally, while only 35% is fed into the public electricity grid. The PV system in combination with the VRF battery will, according to the planning, achieve a solar coverage share of approx. 40% of the total electricity requirement. All classrooms are ventilated both mechanically and through the windows in a hybrid manner in order to ensure the indoor air quality (CO_2 content less than 1,500 ppm) that is particularly relevant for educational buildings.

Heat recovery (approx. 85%) is integrated to reduce ventilation heat losses, as is adiabatic exhaust air humidification for cooling in summer. The supply air is introduced into the classrooms and flows into the corridors, halls and break zones. Extraction takes place centrally in the roof area of the two atriums. Night ventilation via the ventilation systems supports the cooling of the school during the summer months. In order to quickly heat up the classrooms during the heating period, a morning heating phase is carried out before the start of the school operation. With the ventilation system, variable demand-controlled air volumes per classroom are introduced into the room by the CO_2-concentration (≤ 1,500 ppm). The maximum air exchange rate in the classrooms is limited to 4.4 1/h.

4.3.2 Building envelope

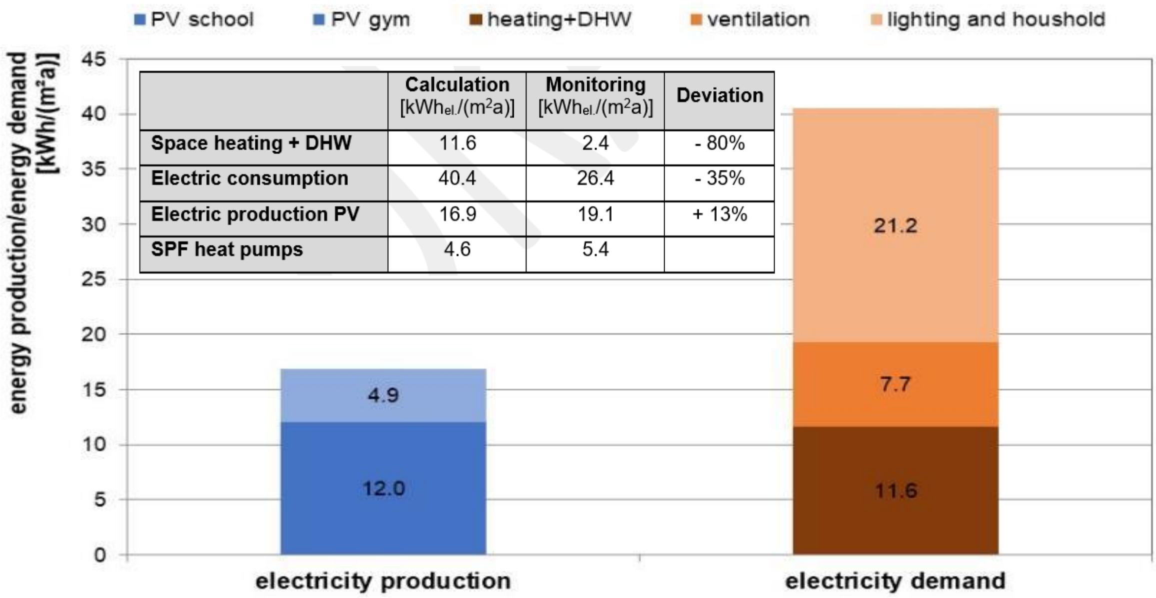
As part of the holistic energy concept, during the planning, construction and detailing of the building envelope attention was paid to prevent thermal bridges and an airtight design. The shell of the high school and the gym were constructed in prefabricated construction. The facade on the ground floor of the school building is a post and beam construction. The outer wall on the upper floor and the gym are sandwich constructions. The construction time on-site could be shortened to a minimum by a large planning effort for a high degree of prefabrication. The concrete elements were assembled using a modular system. During installation, the fair-faced concrete facade already had its finished, insensitive surfaces inside and out. The insulation level is circumferential and is already integrated in the sandwich structure of the outer walls. The 160 cm PUR (WLG 024) insulation level is located between the reinforced concrete substructure and a concrete facing. The transparent elements of the building envelope (fixed windows, turn/tilt windows) are triple-glazed throughout the building. In connection with the external sun protection and the structural colour panels, the summer thermal insulation is maintained. The transmission heat loss H_T' of the envelope of the reference buildings according to EnEV 2009 (2014) is 50% lower in both the school building and the gym.

Table 28: Characteristics of building envelope

Component	U-Value [W/(m²K)]
Exterior wall / Roof / Floor slab	0.15 – 0.17 / 0.14 – 0.15 / 0.08 – 0.09
Window	0.70 – 0.90 / g-value 0.28 – 0.5

4.3.3 Comparison with design data

Figure 116 shows a comparison on calculated and measured energy demand and on-site production.
Due to the thermally insulated and airtight building envelope and the controlled ventilation with heat recovery, an annual heating requirement of 25 kWh/(m^2_{NGF}a) is achieved. For the annual cooling requirement 10 kWh/(m^2_{NGF}a) were calculated. According to EnEV 2014, the annual primary energy requirement is 48 kWh/(m^2_{NGF}a).
The upper table in Figure 116 shows a comparison of the electrical monitoring data with the design data. In comparison to the design data the monitoring data have quite high deviations. The electricity consumption for space heating and DHW is up to 80% lower than calculated. The total monitored value of the electricity use of 26.4 kWh/(m²a) including the building technology is also significantly lower than the estimated value of 40.4 kWh/(m²a). The PV yield delivered about 13 % more electrical energy than calculated.



	Calculation [$kWh_{el}/(m^2a)$]	Monitoring [$kWh_{el}/(m^2a)$]	Deviation
Space heating + DHW	11.6	2.4	- 80%
Electric consumption	40.4	26.4	- 35%
Electric production PV	16.9	19.1	+ 13%
SPF heat pumps	4.6	5.4	

Figure 116: Calculated energy demand and production in planning, WGG

4.3.4 Monitoring concept

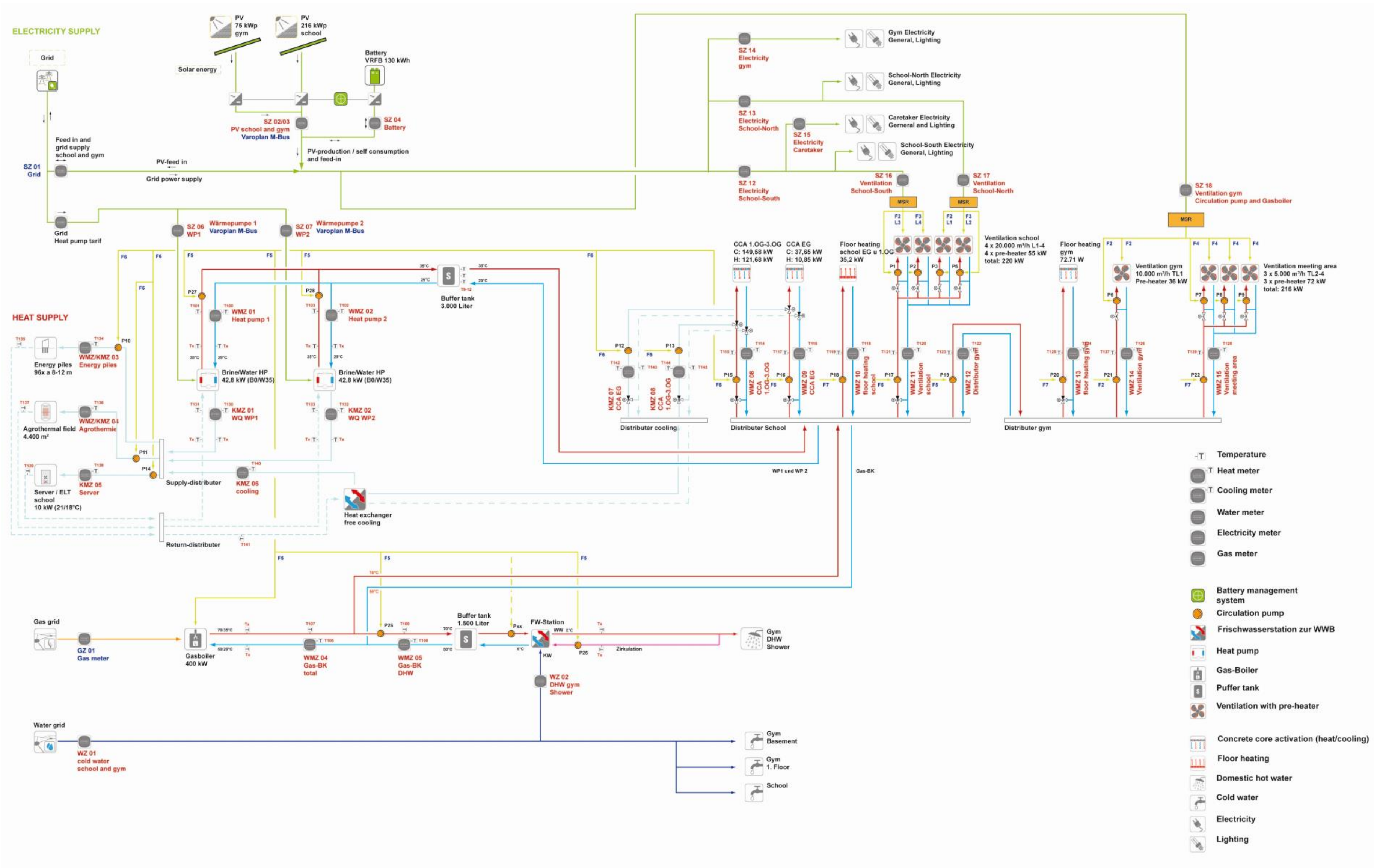
During the design phase, target indicators for system and building performance have already been defined, which allow a detailed analysis and evaluation of energy efficiency and different operating modes. Based on the target definition, a measurement and monitoring concept was set up and corresponding specifications for measurement and control / building automation were defined. As a basis for the detailed evaluation of the heat and electrical power consumption as well as for the preparation of the energy balances in the building, a differentiated measurement concept was implemented. The energy and technical monitoring at the WGG do not only include the balancing of the consumption for room heating and domestic hot water heating, but also the total power consumption of the school and the gymnasium. A total of about 850 data points (meters, sensors and probes) are recorded every 15 min. The data collection and storage was implemented as follows:

- The heat meters / cooling meters and water meters are connected to the BACnet of the building management system via an M-Bus converter. Data transfer and collection is carried out centrally via a BMS computer.
- The electricity meters are connected to each other via a separate and independent M-Bus network. Data recording and storage also takes place on the BMS computer.

Since April 2016, the transmission of data for the evaluation of the operation has been fully operational. Isolated data points on heat meters and controllers (e.g. electricity meter, battery, room temperatures, etc.) were only activated in June 2016. The delay was caused by constructional delays in the implementation of the plant and building management system. There were manufacturer-specific problems with the heat meters for the agrothermal field and the bored piles, which could only be rectified in January 2017.

4.3.5 Monitoring results

The school started operation in autumn 2016 beginning with the school year. Since January 2017, complete measurement data from the installed measurement technology have been available, which enable a detailed analysis of the energy balance, the plant efficiency and the operating conditions. Due to measurement data failures, the November and December values for 2019 can no longer be recorded. The two months are not included in the analysis


ELECTRICITY SUPPLY
Grid
PV 75 kWp gym
PV 216 kWp school
Solar energy
Battery VRFB 130 kWh
SZ 02/03 PV school and gym Varoplan M-Bus
SZ 04 Battery
Feed in and grid supply school and gym
SZ 01 Grid
PV-feed in
Grid power supply
PV-production / self consumption and feed-in
Grid Heat pump tarif
SZ 06 WP1 Wärmepumpe 1 Varoplan M-Bus
SZ 07 WP2 Wärmepumpe 2 Varoplan M-Bus
SZ 14 Electricity gym
Gym Electricity General, Lighting
School-North Electricity General, Lighting
SZ 13 Electricity School-North
SZ 15 Electricity Caretaker
Caretaker Electricity Gerneral and Lighting
School-South Electricity General, Lighting
SZ 12 Electricity School-South
SZ 16 Ventilation School-South
SZ 17 Ventilation School-North
SZ 18 Ventilation gym Circulation pump and Gasboiler
MSR
HEAT SUPPLY
Energy piles 96x à 8-12 m
WMZ/KMZ 03 Energy piles
Agrothermal field 4.400 m²
WMZ/KMZ 04 Agrothermie
Server / ELT school 10 kW (21/18°C)
KMZ 05 Server
KMZ 06 cooling
Supply-distributer
Return-distributer
Heat exchanger free cooling
WMZ 01 Heat pump 1
WMZ 02 Heat pump 2
Brine/Water HP 42,8 kW (B0/W35)
KMZ 01 WQ WP1
KMZ 02 WQ WP2
Buffer tank 3.000 Liter
CCA 1.OG-3.OG C: 149,58 kW H: 121,68 kW
CCA EG C: 37,65 kW H: 10,85 kW
Floor heating school EG u 1.OG 35,2 kW
Ventilation school 4 x 20.000 m³/h L1-4 4 x pre-heater 55 kW total: 220 kW
Floor heating gym 72.71 W
Ventilation gym 10.000 m³/h TL1 Pre-heater 36 kW
Ventilation meeting area 3 x 5.000 m³/h TL2-4 3 x pre-heater 72 kW total: 216 kW
KMZ 07 CCA EG
KMZ 08 CCA 1.OG-3.OG
WMZ 08 CCA 1.OG-3.OG
WMZ 09 CCA EG
WMZ 10 floor heating school
WMZ 11 Ventilation school
WMZ 12 Distributor gym
WMZ 13 floor heating gym
WMZ 14 Ventilation gym
WMZ 15 Ventilation meeting area
Distributer cooling
Distributer School
Distributer gym
WP1 und WP 2
Gas-BK
Gas grid
GZ 01 Gas meter
Gasboiler 400 kW
WMZ 04 Gas-BK total
WMZ 05 Gas-BK DHW
Buffer tank 1.500 Liter
FW-Station
Zirkulation
Gym DHW Shower
WZ 02 DHW gym Shower
Water grid
WZ 01 cold water school and gym
Gym Basement
Gym 1. Floor
School
Temperature
Heat meter
Cooling meter
Water meter
Electricity meter
Gas meter
Battery management system
Circulation pump
Frischwasserstation zur WWB
Heat pump
Gas-Boiler
Puffer tank
Ventilation with pre-heater
Concrete core activation (heat/cooling)
Floor heating
Domestic hot water
Cold water
Electricity
Lighting

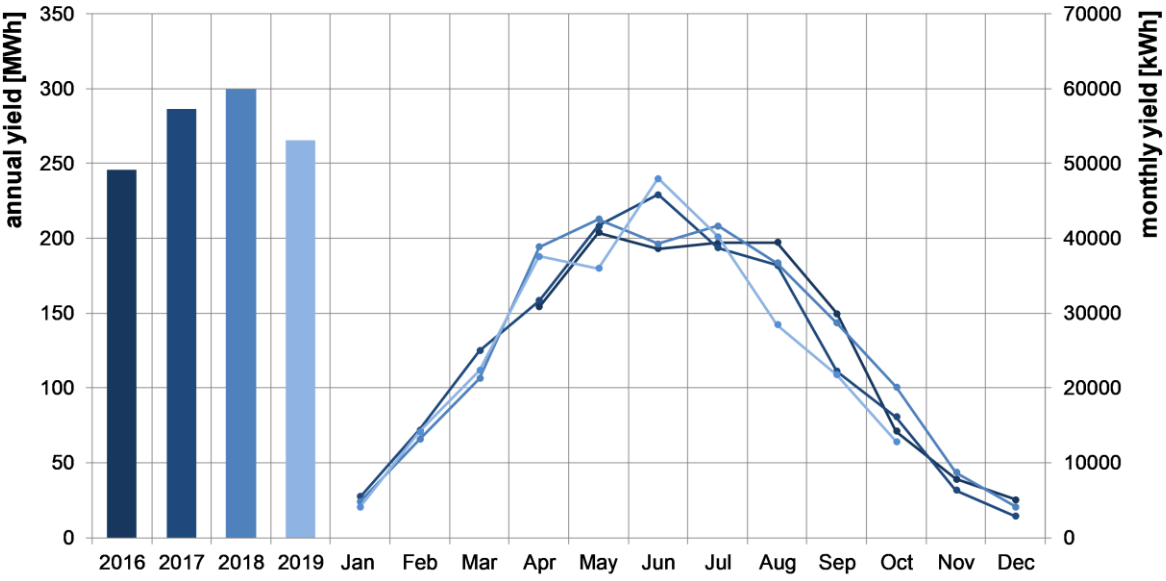


Figure 117: Annual and monthly electric yield of the PV panels, 2016 – 2019

4.3.5.1 PV yield and own electricity use

The building technology primarily envisages the direct use of solar yields from photovoltaics. Only surpluses that cannot be stored will be fed into the public grid. The PV system with a total output of 291 kW_p on the school building (216 kW_p) and the gym roof (75 kW_p) has been in operation since June 2015.

The balanced annual energy production determined from measured data exceeds the planned values in the four operating years (2016 to 2019). Compared to the calculated electricity yield of around 243 MWh/a from the PV system, more than 275 MWh/a were delivered, i.e. around 13% more than assumed in the planning.

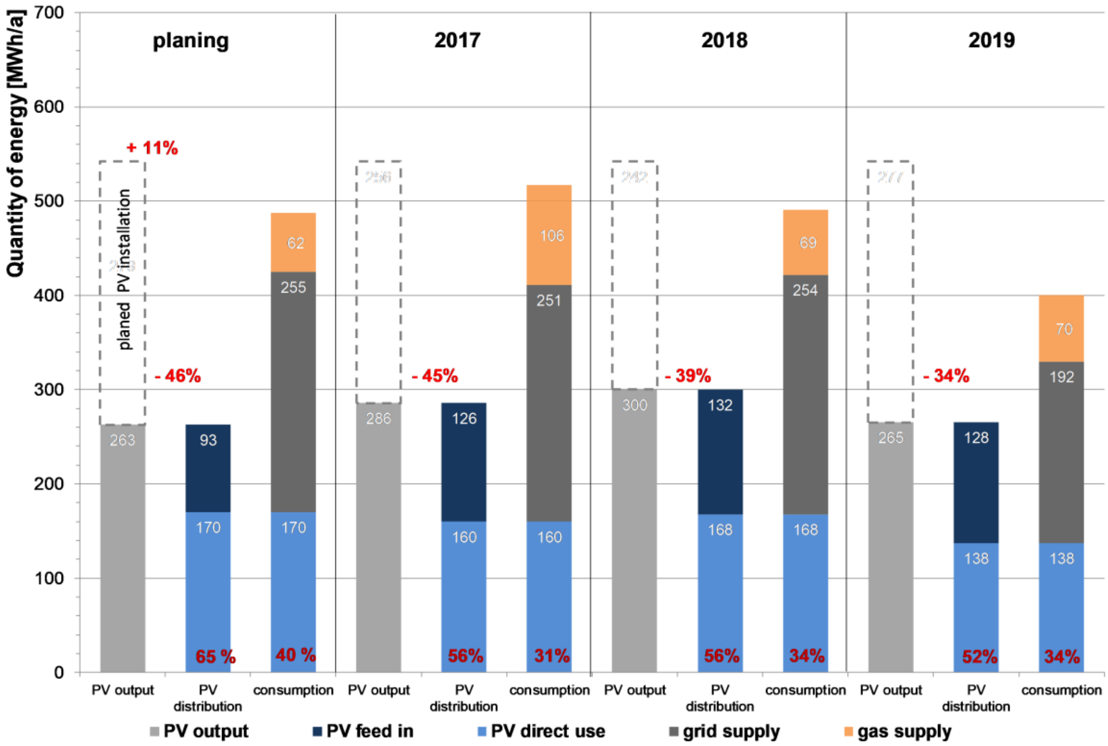


Figure 118: Annual balance of total energy, 2017 – 2019 (red = fraction)

In the four operating years, the PV system delivered an average annual electricity yield of approx. 275 MWh/a and related to the installed capacity of approx. 975 kWh/kW_p (planning 919 kWh/kW_p). The average annual electricity consumption (incl. user electricity, MSR, monitoring) is about 380.2 MWh/a, related to the NFA about 26.4 kWh/(m²a).

There is no annual electricity surplus. Over the period under consideration (2016-2019), approx. 59% of the solar energy was used in the building itself, the remaining part was fed into the public power grid. The solar coverage factor of electricity consumption is around 47% over the years. On a monthly basis, the SCF ranges from 27 % to 98 % and the LCF from 7 % to 77 %. The opposing trend is clearly visible in Figure 118 and Figure 119.
Gas consumption is added to electricity consumption and production. The average is 70 MWh/a. Figure 118 shows the annual final energy balances calculated over the four years. The EnergiePlus standard cannot be met.

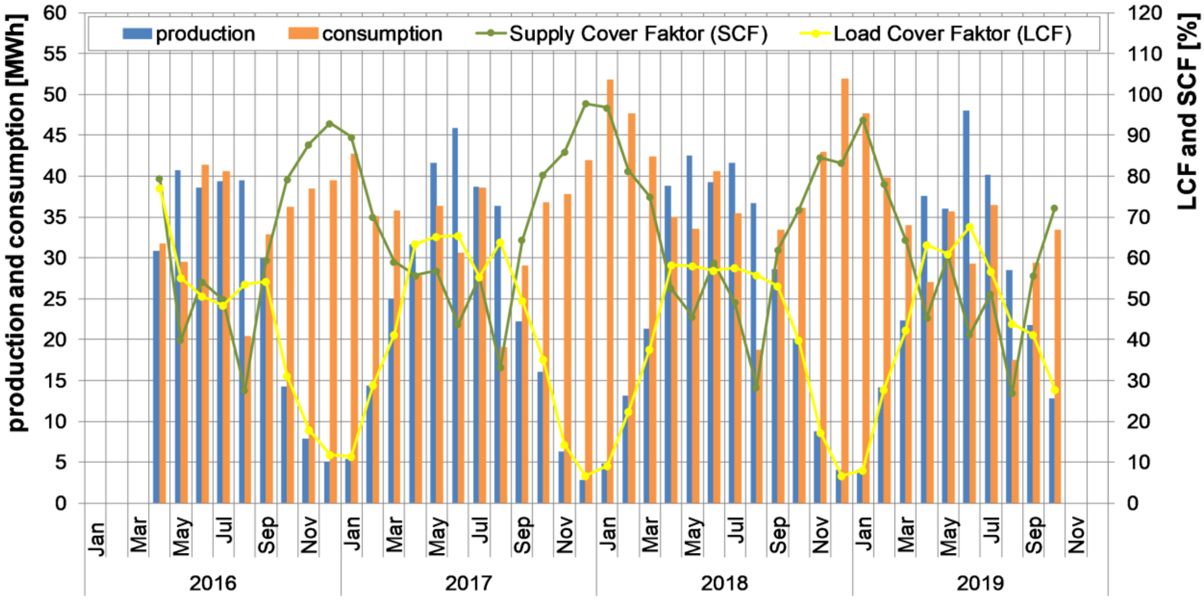


Figure 119: Monthly demand/supply cover factor, 2016 - 2019

4.3.5.2 Final and primary energy and CO_2-emissions

The annual balance of final and primary energy for the years 2014 to 2019 is shown in Figure 120. In accordance with the German standards DIN V 18599-1 and DIN 4701-10 / A1, a primary energy factor of 2.8 is applied to the electricity feed-in and a primary energy factor of 1.8 to the electricity purchase.

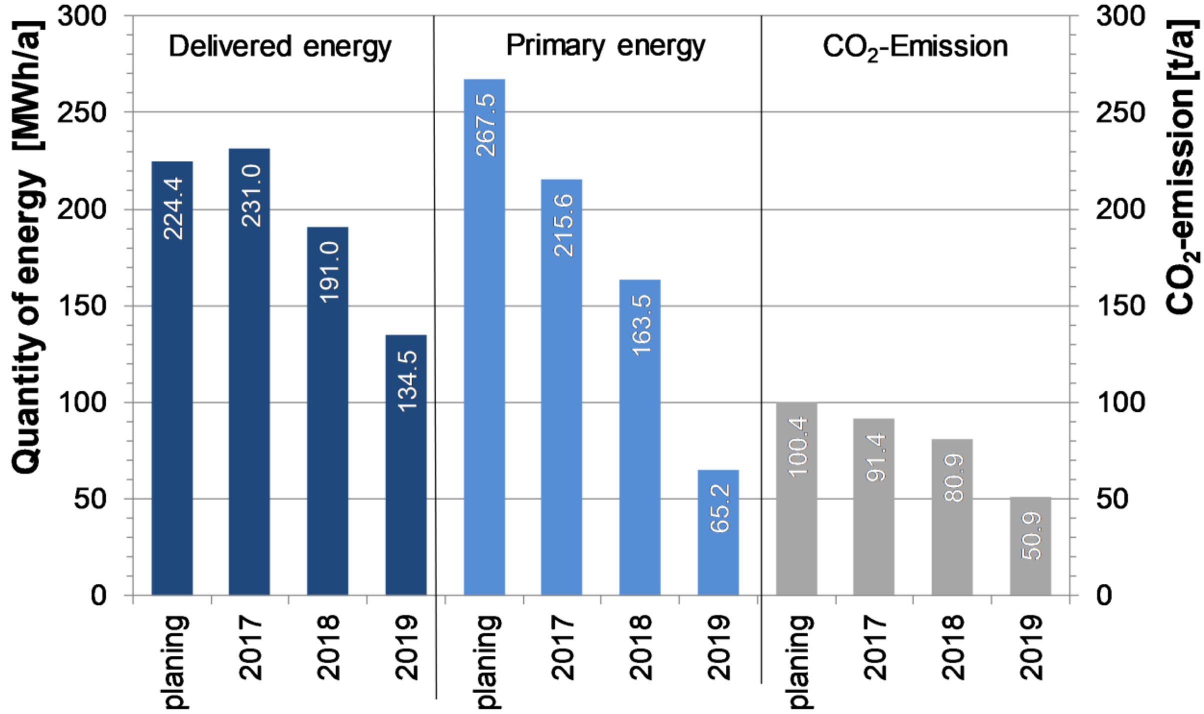


Figure 120: Final energy, primary energy and CO_2-emission (2017 to 2019)

From 2017 to 2019, a primary energy deficit of ~ 150 MWh/a was achieved. With regards to the final energy deficit, values between 135 MWh/a and 231 MWh/a could be calculated. For CO_2 emissions, CO_2 equivalents of 527 g/kWh are used for both electricity savings and grid purchases. This results in CO_2 deficit of 51 to 91 t/a.

4.3.5.3 Electricity balance

The total electricity consumption (approx. 380 MWh/a) of the building in relation to the NFA is on average around 26.4 kWh/(m²a) over the four years of operation.

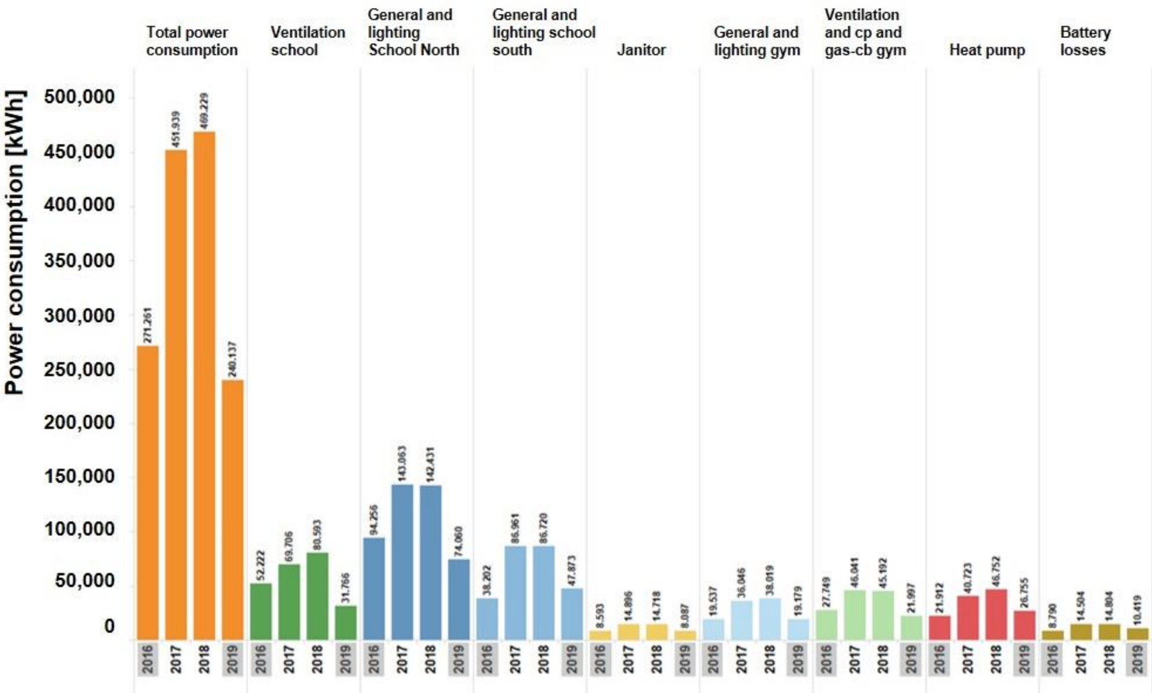


Figure 121: Average annual electricity consumption by category over the measurement period 2016 and 2019

Figure 121 shows the annual electricity balance broken down by individual consumers or consumption types (heat pump, MSR, ventilation, lighting, ...). By far the largest electricity consumer in the building is the general and user electricity for the school and gym with approx. 60% of the total electricity consumption.

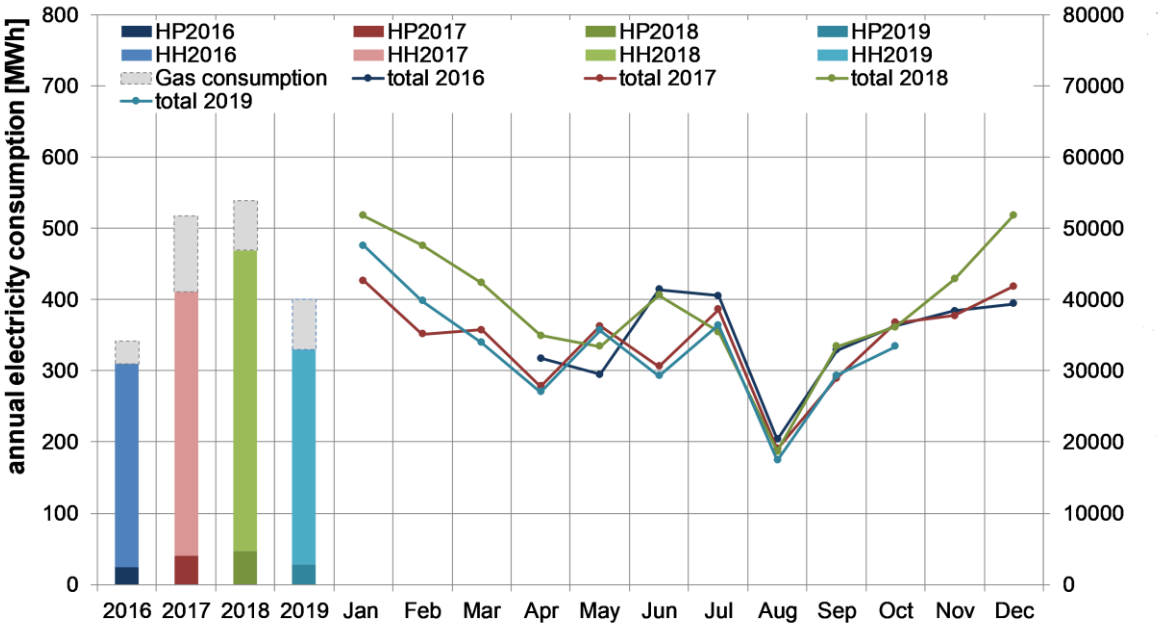


Figure 122: Monthly and annual electricity consumption by category – heat pump and household, 2016 – 2019

Building conditioning (heating, cooling, ventilation) accounts for around 36% of electricity consumption. Electricity storage contributes to an increase in the proportion of electricity used by the building itself. However, losses during loading and unloading as well as standby operation amounting to approx. 2.6% of the total electricity consumption must be taken into account. Figure 122 shows the shares of electricity for the heat pump and individual user consumption. The total annual electricity consumption is about 26.4 kWh/(m²a) (380 MWh/a). The heat pump accounts for approx. 10%, individual consumption for approx. 90% of the annual energy consumption.

4.3.5.4 Thermal balance

Figure 123 shows the shares for heating and domestic hot water for the four years of operation. The proportions are broken down into heat transfer for space heating and domestic hot water.

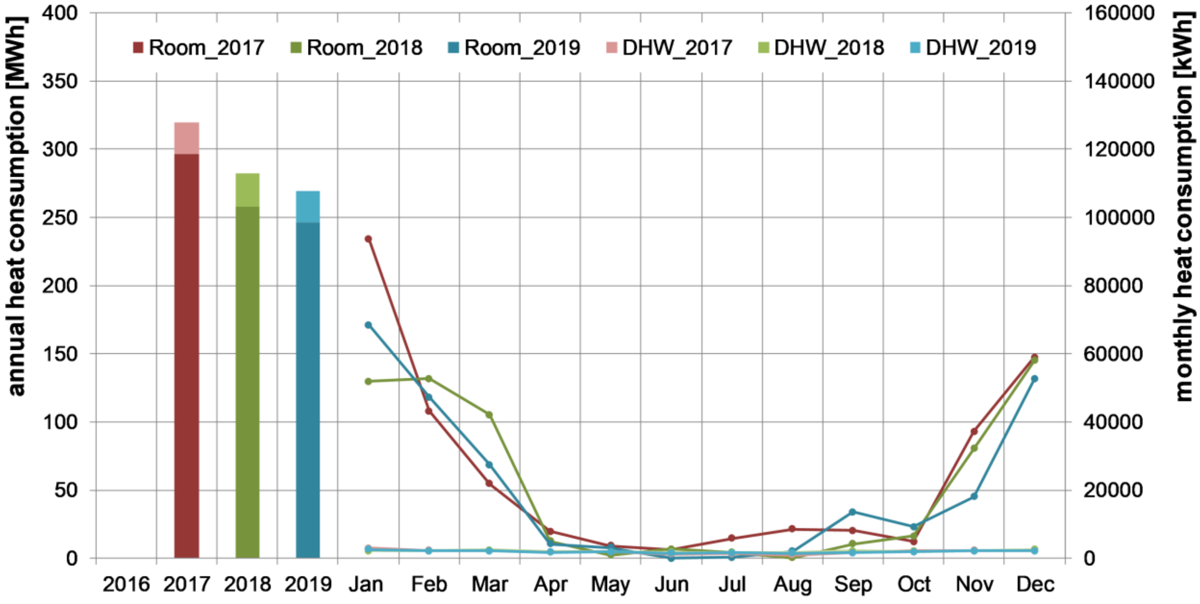


Figure 123: Annual and monthly heat balance, 2016 to 2019

The annual energy consumption (heating, DHW) is about 20.2 kWh/(m²a) (290.7 MWh/a) The room heating accounts for approx. 92%, DHW, storage and distribution losses for approx. 8% of the annual energy consumption. The area-related heating energy consumption in the operating years of 2016 to 2019 ranges from 18 to 22 kWh/(m²a). Between 270 and 320 MWh/a of heat is generated.

Therefore, the share for domestic hot water production (1.65 kWh/(m²a)) is significantly lower than the energy efficiency requirement of 12.5 kWh/(m^2_{NGF}a) required by the EnEV.

4.3.5.5 Seasonal performance factor

The balance boundary for the seasonal performance factor of both heat pumps together is based on the ratio of the thermal energy provided (heat) to the consumed electrical energy.

The monthly performance factors of the two heat pumps (excluding electricity consumption of the brine and circulation pumps) for 2017 to 2019 are between 4.2 and 7.3 (excluding the months in which there was no heating operation, but the buffer storage tank loading was still active). The annual performance factors are between 4.7 and 5.2 for the heat pumps. No SPF is recorded in the summer months, as the heat pumps are not in operation here and the building is conditioned via passive cooling.

Over the measurement period, very good seasonal performance factors were recorded. The provision of domestic hot water only by the gas condensing boiler has proved very successful. The heat pump system can thus be operated with a flow of around 35 °C, which leads to efficient operation and good performance factors.

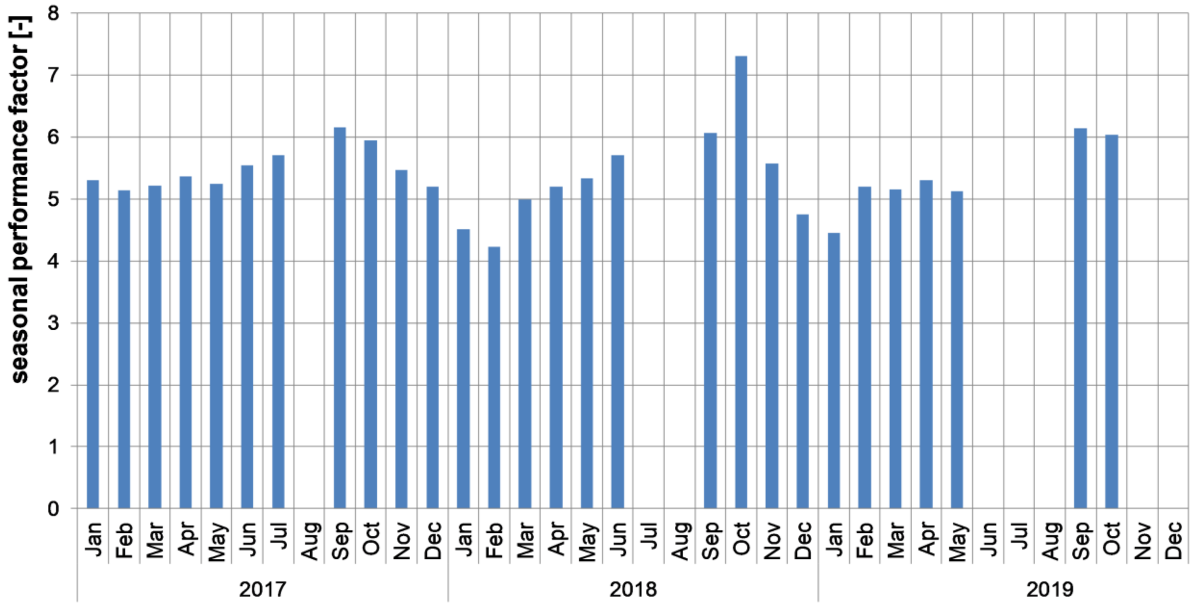


Figure 124: Monthly seasonal performance factors of both heat pumps (2017 to 2019)

4.3.6 Discussion and conclusion

Already after a few months of school attendance, a possible operational optimisation and savings potential of the plant technology becomes apparent. It is only in practical application that it becomes apparent how individual technologies can be used and integrated into the construction process and whether operators or users are able to operate and maintain the systems sensibly. It can be stated that the implementation of an innovative energy concept with low-ex heat sources must be described and planned in detail at the planning stage and intensively monitored after commissioning. A successful implementation can only take place in a joint interaction of all project participants through interdisciplinary processing.

The school as a user has already been integrated into the design process in order to integrate optimal processes and room constellations for teaching with the respective pedagogical concept in the architecture and functions of the building. In joint workshops and brainstorming sessions, everyone was called upon to discuss and coordinate their goals, wishes and suggestions for all areas in and around school life. On the part of the architect, the main questions asked were usage sequences, room programs, pedagogical concepts and their influence on floor plans. These events provided the architects and specialist planners with valuable information for the elaboration of the drafts and implementation of the planning. The result is an updated specification for all parties involved.

There are no complaints regarding user satisfaction. Both teachers and students feel comfortable at school. Good to acceptable room comfort is achieved in the classrooms. The CO_2 content has a high to medium indoor air quality.

The results and findings of the research project help to avoid and optimise problems in future non-residential buildings and their facilities. The new building has an exemplary character and is suitable as a multiplier due to its transferable structure in cities and typical buildings.

The school building with its high solar energy use is an important building block for our future energy supply and the implementation of renewable energies and sources. The pilot project reflects very well the building standard of the future and at the same time shows the framework for the development and evaluation of necessary innovative methods and tools for educational buildings and public buildings.

The following points could be recorded and optimised by the monitoring implemented since the plant was in operation and the continuous evaluation of the measurement data:

4.3.6.1 Room comfort

In order to further improve the already good to acceptable room comfort, the release of the adiabatic cooling, the supply air temperatures, the switchover between summer/winter operation and the control of the night ventilation were adapted to the actual room utilisation and presence of the pupils. With regard to the CO_2-content, a high to medium indoor air quality (DIN EN 15251) is achieved in the classrooms. Moderate indoor air quality occurs in rooms that are used differently than planned during operation. Room by room adjustments were made to the air volume flow control. Since the ventilation concept prefers mechanical ventilation to switch-off automatically when windows are opened, the air quality in classrooms can deteriorate due to tilted or leaned windows. The users still have to get used to and observe this condition and this regulation. In addition, sources of error and deficiencies could be identified and rectified with regard to room comfort, such as deviations in the settings of the building control system as defined in the planning.

4.3.6.2 Hydraulic system

With regard to hydraulics, monitoring in the first years of operation revealed sources of error and deficiencies in execution. Among other things, these are:

- Reduction of the mass flow of the concrete core activation due to excessively high room temperatures in the interior rooms.
- Settings and adjustments of the mass flow of the heating circuit so that the target flow temperature is reached.
- Missing shut-off valve in the flow distributor to the buffer storage tank.
- Volume flow controllers were connected incorrectly

4.3.6.3 Gas condensing boiler

In the first summer months, unplanned operation of the gas condensing boiler was detected. In addition to domestic hot water preparation, heat was temporarily supplied to the heating circuit distribution network. This was caused by incorrectly set deflection valves.

4.3.6.4 VRF battery

The following findings result from the first two years of operation:

- During the winter months, the battery contributes very little to the increase in the use of own electricity, as the PV electricity produced can be used directly in the school during this time. The battery is only minimally charged.
- The battery has an increased standby consumption, which in the winter months must be covered predominantly by the public power grid.
- In the winter months the efficiency is less than 30% and in the summer months the efficiency rises to around 50%.

On the basis of the available findings from two years of monitoring, it is being discussed whether the battery should be switched-off in the winter months and put back into operation only in the spring months. Switching-off the battery for a longer period of time is unproblematic with this technology.

4.3.6.5 Geothermal energy

Based on the recorded brine inlet and outlet temperatures, adjustments have been made to the control strategies of both sources since the commissioning of the geothermal low-temperature sources and their heat exchangers. The year-round inefficient continuous operation of both sources (parallel operation) was replaced by a previously manual adjustment via a priority distribution (activation / deactivation of one source). To increase efficiency, the two sources have been controlled separately in the winter months since the changeover. The switchover is based on the higher brine outlet temperatures per source system. During the heating period, the heat pumps primarily use the energy piles (higher brine temperature level). To ensure that the piles are kept frost-free, they are only operated up to a brine entry temperature of > 3 °C (switch-off criterion for frost-free operation is 2 °C). Heat is then removed from the agrothermal field. A reverse priority is planned for the cooling period. The agrothermal field acts primarily and then the bored piles are controlled in order, among other things, to ensure regeneration of the energy piles. An automatic switching of the sources depending on the brine temperatures is still to be implemented.

4.4 Medbroen Kindergarden – Stjørdal, NO

Medbroen kindergarten is situated in Stjørdal close to Trondheim in Norway. The building was originally an agricultural building from 1908, but parts of it (833 m^2) were refurbished to the Norwegian passive house standard according to NS 3701 (2012) in 2015. A ground source heat pump system has been installed and supplies heat to a low-temperature floor heating system and the heating coil of the air handling unit (AHU). It also preheats domestic hot water (DHW). An electric boiler is used as peak load.

Figure 125: Medbroen kindergarten (Thyholt, 2015).

The fact that an over 100-year-old building is refurbished to passive house standard makes this project unique. Unfortunately, the heating system was not functioning properly during the first couple of years due to several errors. Some of them were discovered through the work with a Master thesis during the spring of 2017. Due to these errors, it was not possible to perform realistic field measurements for a full year. Most of the work with the thesis consisted of describing the system, discovering errors and suggesting improvements. More details about the project can be found in Rønneseth (2017).

4.4.1 Calculated Net Energy Demand

Table 29 shows the calculated energy demand for various applications.

Table 29: Energy budget for Medbroen kindergarten, calculated in SIMIEN (Thyholt, 2015).

	Net energy demand	Specific energy demand
Space heating	16,112 kWh	19.3 kWh/m^2
Ventilation heating (heating coil)	5,149 kWh	6.2 kWh/m^2
Domestic hot water (DHW)	8,347 kWh	10.0 kWh/m^2
Fans	6,613 kWh	7.9 kWh/m^2
Pumps	995 kWh	1.2 kWh/m^2
Lighting	9,567 kWh	11.5 kWh/m^2
Technical equipment	4,348 kWh	5.2 kWh/m^2
Space cooling	0 kWh	0.0 kWh/m^2
Ventilation cooling	0 kWh	0.0 kWh/m^2
Total net energy demand	51,131 kWh	61.4 kWh/m^2

Before and after the refurbishment, the building had a calculated specific energy demand of 276 kWh/(m^2a) and 62 kWh/(m^2a), respectively. The heating demand including the DHW was 36 kWh/(m^2a), corresponding to 58% of the buildings' total energy demand.

4.4.2 System for Thermal Energy Supply

The heating system consists of the following main components:

- Heat pump: Daikin Altherma GS **3-13 kW**, incl. 180 litres DHW tank, 2 x 3 electric heating coils and shuttle valve for prioritized heating of DHW
- Heat source system – 500 m horizontal ground collectors, two parallel circuits
- 200 litres accumulator tank as buffer for the space heating system with 4 x 5 kW integrated electric heater as peak load
- External water heater: OSO Super S 300 (287 litres) with 3 kW electric power
- Floor heating system with 19 kW design power at 35/30 °C
- Air handling unit with rotating heat exchanger and 22 kW heating coil at 45/35 °C

The heat pump and accumulator tank are placed in a technical room, see Figure 126 left. The circulation pumps for the floor heating system and heating coil have variable speed drive (VSD) control. The pumps and other components like energy meters, microbubble deaerator, valves, etc. are included in the principle system sketch shown in Figure 127.

Figure 126: The technical room showing the accumulation tank, the heat pump unit and some of the connected pipes (left, Rønneseth, 2017). Ambient temp. compensation curve for the heat pump (picture of display) (middle, Rønneseth 2017).Location of the pipes for the horizontal ground collector system (right, Thyholt, 2014).

4.4.2.1 Heat Pump Installation

The heat pump (Daikin Altherma GS, R410A) is designed as a base load for the heating system, with a nominal heating capacity of **13 kW** (brine temp. 0/-3 °C and water outlet 35 °C). Water is distributed to an accumulator tank of 200 litres before it is further distributed to the floor heating system and heating coil in the air handling unit. The electric peak load in the accumulator tank is activated in parallel with stage two of the internal peak load in the heat pump, which is a very poor control method. This is further elaborated in chapter 4.4.4.

The heat pump unit has the specifications listed in Table 19. The evaporator and condenser are both brazed plate heat exchangers. The compressor is a Daikin Swing Inverter with stepless variable speed drive (VSD) control. Two circulation pumps are also integrated in the heat pump, one for the brine circuit and one for the heated water, positioned between the condenser and the shuttle valve. The water pump has variable speed drive (VSD) control, while the brine circulation pump has three capacity steps. The heat pump is controlled according to an *outdoor temperature compensation curve*, Figure 85 right.

A shuttle valve in the heat pump switches between space heating and DHW mode. In DHW mode it preheats the water to 50 °C in a 180 litres internal tank, and then an external water heater (287 litres) increases the temperature to 70 °C. The use of accumulation tanks as thermal storage is important for this system, as the heat pump cannot deliver heat to both space heating and DHW simultaneously. The operation modes for DHW heating are:

- Reheating: The heat pump reheats the DHW to 50 °C every three hours.
- Scheduled: The DHW can only be heated according to a specific schedule
- Scheduled + reheating: The DHW is heated according to a specific schedule, but reheating is allowed in-between these cycles

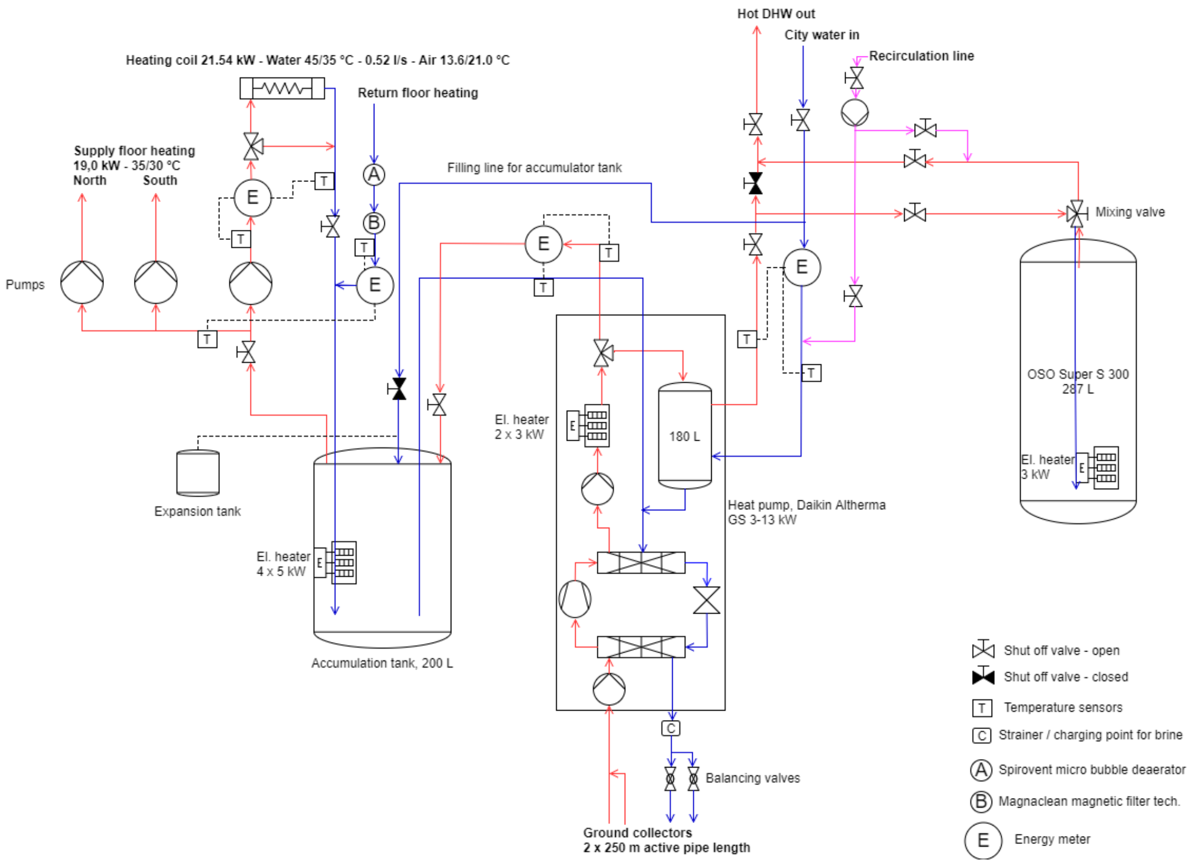


Figure 127: Principle sketch of the heat pump system at Medbroen Kindergarten (Rønneseth 2017).

Table 30: Specifications for the heat pump installation (Daikin Europe N.V., 2015).

Heating capacity	Minimum	3.1 kW (1) / 2.47 kW (2)
	Nominal	10.2 kW (1) / 9.29 kW (2)
	Maximum	13 kW (1) / 11.90 kW (2)
Input power	Nominal	2.3 kW (1) / 2.82 kW (2)
Nominal COP		4.35 (1) / 3.29 (2)
Dimensions	Height / width / length	1732 / 600 / 728 mm³
Weight		210 kg
Tank	Water volume	180 L
	Heat loss	1.4 kWh/24 h
Operating range	Space heating (min.-max.)	24-60 °C (hp.) 24-65 °C (hp.+ el.)
	DHW heating (min.-max.)	25-55 °C (hp.) 25-60 °C (hp. + el.)
Refrigerant	Type	R410A, 1.8 kg
	Control	Electronic expansion valve
Heating of DHW	Effectivity	93%
	Energy class	A
Space heating	Water outlet 55 °C	Seasonal space heating efficiency: 144% SPF: 3.79
		Energy class: A++
	Water outlet 35 °C	Seasonal space heating efficiency: 202% SPF: 5.26
		Energy class: A++

(1) 0 /35 °C (2) 0/45 °C

The heat pump was operated in "Reheating mode", which would be reasonable for residential buildings, but this proved to be unfortunate for a kindergarten as the space heating demand is by far the dominating heat load. This is discussed in chapter 4.4.4.

4.4.2.2 Heat Source – Horizontal Ground Collector System

The heat source system comprises a 2 x 250 m horizontal ground collectors (turbo collectors, OD40, PN10 SDR17 PE100) located next to a local river, Figure 126 middle. The river is so close to the ocean that it is affected by the tides, thus ensuring continuous heat exchange with a large thermal capacity close to the collectors. The brine (anti-freeze fluid) is 35% ethanol.

4.4.3 Monitoring

4.4.3.1 Description and Quality Assurance

The technical installations are monitored by a central control and monitoring system. With the exception of the electric input, it's not possible to monitor the heat pump, except for momentarily values read off from the display. The analysis of the heat pump installation is thus primarily based on the thermal/electric energy meters in the hydronic systems. This include:

- Heat supply from the heat pump to the accumulator tank
- Heat supply to the floor heating system from the accumulator tank
- Heat supply to the heating coil in the air handling unit from the accumulator tank
- Heat supply from the heat pump for DHW heating
- Input electric power for the electric heater in the accumulator tank
- Input electric power for the heat pump (compressor, pumps, el. heating coils)
- Input electric power for the DHW heater

Figure 128 displays a screenshot from the monitoring system showing energy meters and temperature sensors. Unfortunately, it was not possible to see the actual water flow rates in the system. This was suggested as an improvement of the monitoring system.

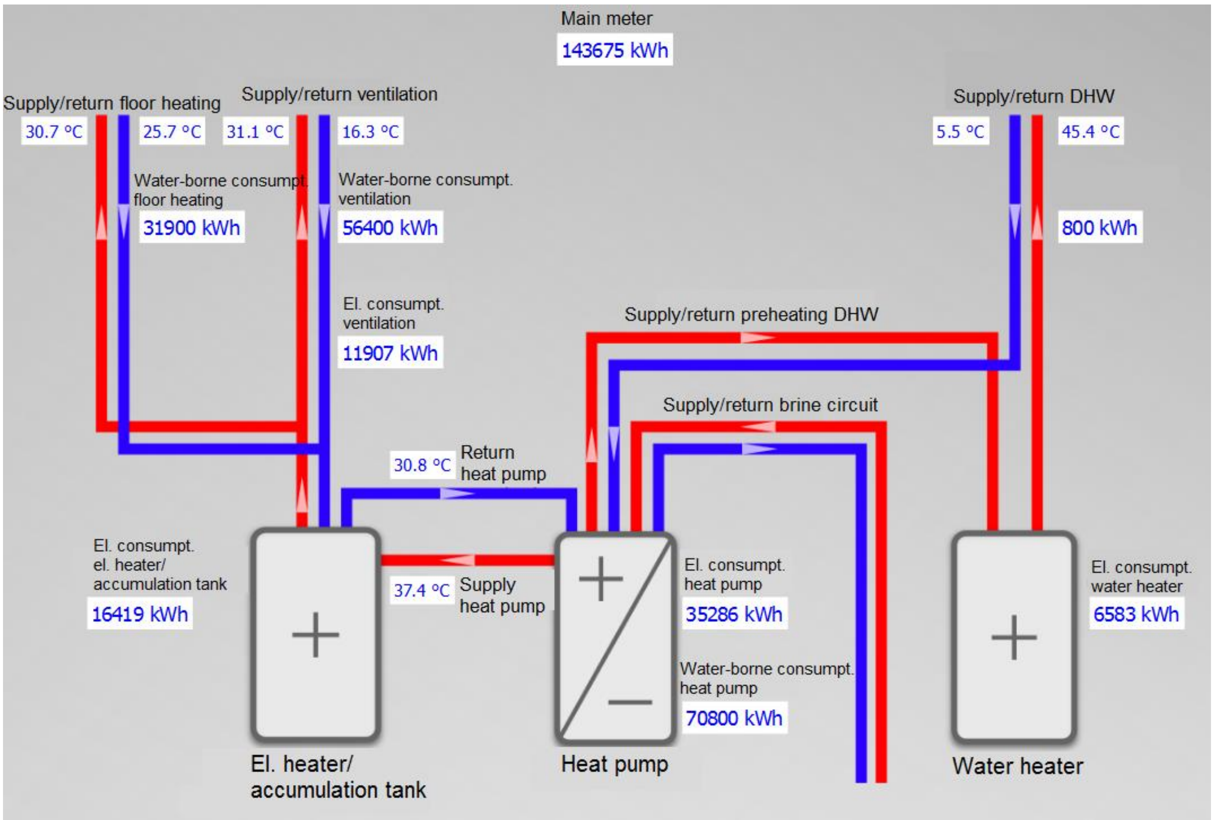


Figure 128: Screenshot from the control and monitoring system 28.02.2017 (Rønneseth, 2017).

Table 31 shows the specifications for the monitoring equipment.

Table 31: Overview of measuring equipment at Medbroen kindergarten (Rønneseth, 2017).

Meter	Type	Positioning	Accuracy
Thermal energy meters (4)	Kamstrup Multical 602	See Figure 127	Ec ± (0.5 + ΔΘmin/ΔΘ) %*
Temp. sensors connected to energy meters (8)	PT500	See Figure 127	Dependent on length and cable cross section
El. power heat pump **El. power air handling unit** **El. power el. heater**	Carlo Gavazzi EM24-DIN	-Heat pump -Air handling unit -Acc. tank	± 0.5 RDG (current/voltage)
El. power DHW heater	IME 1-phase meter	DHW tank	Not specified
Room temp. sensors	PT1000	Internal walls	Dependent on length and cable cross section
Temp. sensor, frost protection heating coil	PT1000	External sensor	Dependent on length and cable cross section
Temp. sensor, weather compensation	Not specified	Wall outside of technical room	Not specified
Temp. sensors in air handling unit (4 pcs.) **	PT 1000	Intake, exhaust, supply and extract	Dependent on length and cable cross section
CO_2–sensors (4 pcs.)	Jumo	Room 107, 109, 208 and 210.	±(50 ppm + 2 % of measured value) at the area 0-2000 ppm
Pressure transmitter	DPT-Dual-MOD og DPT-R8	Air handling unit	±1.5 % + 1 Pa

**ΔΘmin = 3 K. Ec is the uncertainty in the energy calculation.*
***An additional outdoor temp. sensor is also connected to the air handling unit, which is not used for control.*

The control and monitoring system monitors the input power for the electric heater, room temperatures, CO_2-levels, outdoor temperature, as well as air velocities, pressures and temperatures in the ventilation unit. This includes historical values, although the collected data are simplified after a period of 24 hours. This made it difficult to analyse the dynamics of historic events and errors in detail. A quality assurance of the measuring equipment was also performed to ensure that the measured values were reliable. Most of the equipment were correctly placed and functioning properly, but there were found some minor deviations that should be improved:

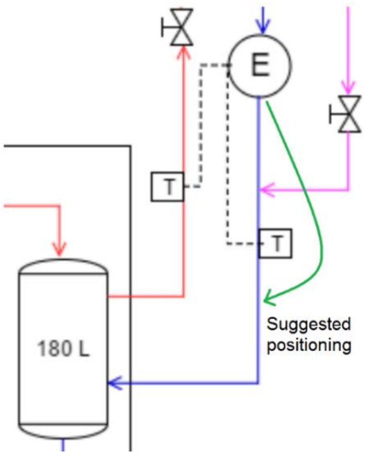


Figure 129: Suggested new placement of the energy meter for DHW (Rønneseth, 2017).

- The temperature sensors (and parts of the piping in the technical room) are not insulated. This could lead to some deviations for the energy use, but it is not considered a large problem as it is a low temperature system
- The temperature sensor measuring the supply temperature from the heat pump to the accumulator tank is placed too close to the heat pump. The shuttle valve switching between space heating and DHW mode is not completely sealed, and water leakage from DHW mode led to large temperature fluctuations
- The energy meter measuring the consumption of DHW is not including the water flow for DHW recirculation, and should be moved as illustrated in Figure 129

4.4.3.2 Monitoring Results (2017)

Due to problems with the heat pump installation, realistic measured energy consumption was not available for a full year during the work with the Master thesis. Table 32 presents calculated energy demand for heating for a full year compared with measured energy use for 4.5 months (1.1.2017 – 17.5.2017). The measured energy use could roughly be multiplied by two, to get a better basis for comparison. There is a large deviation between the calculated and measured parameters, where space heating and especially ventilation heating is underestimated, while the need for DHW heating is overestimated. The measured energy use (32.6 kWh/m^2) had already exceeded the calculated net energy need (31.4 kWh/m^2·a) in the Norwegian passive house standard (NS 3701). The total energy use could end up being over twice as high as calculated, which makes it crucial to optimize the function and efficiency of the heat pump installation to increase energy savings.

Table 32: Comparison between calculated energy demand and measured energy use for heating.

	Calculated energy demand		**Measured energy use***		**Deviation**
	Total [kWh/a]	Specific [kWh/m²]	Total [kWh]	Specific [kWh/m²]	[%]
Space heating	16 112	19.3	13 180	15.8	-18.1
Ventilation air heating	5 149	6.2	14 028	16.8	+171.0
DHW heating	8 347	10.0	1 147	1.4	-86
Total	29 608	35.5	28 355	34.0	-

**Only for the period 1.1.2017-17.5.2017, while calculated energy need is for a full year.*

Table 33 presents calculated heating power and two seasonal performance factors, SPF_{HP} and SPF_{gen}, for the heat pump during the same period (1.1.2017 – 17.5.2017), i.e. not a full year. As it was not possible to monitor the heat pump directly, the heating power and SPF's were calculated indirectly by using the energy meters installed in the heating system. SPF_{gen} incl. the electric peak load in the accumulator tank and is thus a form of system efficiency.

Table 33: Average, highest and lowest values for temperature, heating power and COP for the period 1.1.2017-17.5.2017 (Rønneseth, 2017).

	T_{out} [°C]	**Heating power [kW]**	**SPF_{HP} [-]**	**SPF_{gen} [-]**
Average	2.6	8.0	2.7	2.5
Highest value*	15	14.5	3.3	3.3
Lowest value*	-9.9	1.5	1.6	1.1

**Highest/lowest value are for each individual parameter, and the values for each line does not occur simultaneously.*

The highest heating power (14.5 kW) was measured on the coldest day (-9.9 °C), and for this day SPF_{gen} was also at its lowest (1.1), as the average power for peak load was at its highest (5.4 kW). The measured heating power of 14.5 kW is higher than the capacity of the heat pump (13.0 kW), and can be explained by that the peak load is placed in the lower part of the accumulator tank, which makes it possible *to heat the return water to the heat pump*. This is very unfortunate for the operation of the heat pump, as an increased return temperature makes the heat pump work with an increased condensation temperature, which reduces the COP. *The peak load should therefore have been placed at the top of the accumulator tank, as close as possible to the water outlet*. The lowest value for SPF_{HP} (1.6) was found on the warmest day (15 °C) and can be explained by part load and intermittent on/off operation, as the lowest capacity of the heat pump is 3.0 kW.

According to the specifications for the heat pump, the COP should be approx. 4.4 and 3.4 at 0/35 °C and 0/45 °C, respectively. This installation is somewhere in between the two, but closest to the latter one, so SPF_{HP} should have been close to 3.5. *The average measured SPF_{HP} of 2.7 is about 25% lower than the expected value, so there is a great potential for system improvement*.

4.4.4 Results and discussion – Improvement of the existing system

Several errors with the heating system at Medbroen kindergarten were identified through analysis and site visits. The main errors were connected to the ground collectors, design of the accumulator tank, control of the heat pump with regard to space heating and heating of DHW, and control of the peak load. These problems have led to low SCOP for the heat pump and significant use of peak load direct electric heating, which has increased energy consumption and operating costs. *Because of these significant errors, the performance of the heating system is considered to be very poor*.

Description of errors and recommended cost-effective improvements:

Clogging of the horizontal collector circuit

- Current system – The collector circuit was filled with dirt and grass during the installation! It was not properly cleaned afterwards, and even two years later, there were still problems with contaminants in the system. In 2016, there were severe problems with the collector circuit, and the peak load supplied the same amount of heat as the heat pump. Although the problems started already in January, they were first discovered in October as the heat pump did not communicate with the monitoring system. The filters were cleaned, but nothing was done with the balancing valves. This led to lower and unbalanced volume flow rates in the collector system, limiting the heat gain for the heat pump, which again increased the energy consumption for the heating system.
    - Improvement – The defect balancing valves were replaced in May 2017, and two extra filters were installed in front of them. Now, it is possible to clean one circuit at the time, while still operating the heat pump. The total flow rate for the two collector pipes was set at 50 litres/min, but this should be increased to 60-72 litres/min to ensure turbulent flow and maximum heat transfer. The collector circuit should have been properly cleaned immediately after the problems during installation.
    - Benefit – Maximizes the performance of the heat source system.

Missing screw in shuttle valve

Figure 130: Top of the heat pump, where the shuttle valve is mounted with a strip (left) and accumulator tank (middle) and segment from the principle sketch (right) (Rønneseth, 2017)

- Current system – The shuttle valve in the heat pump was missing a screw for the first two years, resulting in hot water leaking towards the space heating system, while the heat pump was in DHW mode (and probably the other way as well). This led to considerable temperature fluctuations in the control and monitoring system and complicated the analysis of the heating system until it was discovered and repaired. This was an error that happened during the installation and was solved by mounting the valve with a "strip" instead of replacing the screw (see Figure 130 left).
    - Improvement – A screw was inserted in May 2017, replacing the strip. This should have been done immediately during installation.
    - Benefit – Proper function of the shuttle valve.

Incorrect design of the accumulator tank

- Current system – Four junction points at the top of the tank and electric peak load placed in the lower/middle part of the tank (Figure 130 right). Mixing of supply and return water occurs and the tank fails in providing thermal stratification. The peak load heats the return water before the heat pump, which in turn increases the condensation temperature and lowers the COP.
    - Improvement – Replace the accumulator tank with a taller model with three junction points instead of four, and *peak load at the top of the tank* in conjunction with the supply pipe for the floor heating system and the heating coil.
    - Benefit – A taller tank will lead to better thermal stratification and the peak load unit will reheat the water from the heat pump (correct design).

Poor control of the electric peak load unit

- Current system – The peak load in the heat pump (2 x 3 kW) has a 15-20 min time delay, i.e. if the heat pump cannot meet the set-point temperature. Stage two of the internal peak load is directly connected to the peak load in the accumulator tank and will activate up to 20 kW simultaneously. This is a poor control method since the peak load is activated every time the heat pump runs its legionella protection programme in DHW mode (every Friday at 23:00). A maximum capacity guard was installed to limit the power peaks resulting in high energy costs.
    - Improvement measure – The peak load should only be used, when the heat pump is running at full capacity and cannot cover the entire heating demand
    - Benefit – Minimizing the use of peak load and reducing the operational costs

Poor control strategy for DHW heating

- Current system – The heat pump switches to DHW mode approx. every third hour, even though the heating demand for DHW constitutes only 5% of the total heating demand. Operation in “Reheating mode” led to periods where the accumulator tank could not deliver enough heat for space heating, and peak load was required when the heat pump switched back to space heating mode.
    - Improvement – “Scheduled heating” of DHW for the heat pump instead of “Reheating”. A heat pump with a desuperheater for DHW heating could also have been used, which would have made it possible to deliver heat to DHW and space heating simultaneously.
    - Benefit – Higher energy coverage factor for the heat pump system due to less use of peak load electric heater (lower peaks, lower energy consumption).

Frequent compressor start/stops

- Current system – Although the heat pump has variable speed drive (VSD) control of the compressor and is operated according to an outdoor temperature compensation curve, the compressor has been switched-on/off quite frequently (8900 start/stops during 20 month). In March 2017, there were 286 compressor starts alone, and the reason has not been fully investigated. Clogging of the collector circuit, the switching back-and-forth between space heating and DHW heating and the frequent power bursts from the peak load may all have triggered restarts of the heat pump.
    - Improvement – See the abovementioned improvement measures.
    - Benefit – Longer lifetime for the compressor and increased COP when the capacity is mainly controlled by VSD control of the compressor

No communication between the heat pump and the monitoring system

- Current system – Monitoring of the heat pump is only possible via the display on the heat pump unit. The level of details and history are also inadequate. An extra component was installed in the heat pump in May 2017 to make it possible to both monitor and control the heat pump, but it did not work.

- Improvement – Measures for making it possible to monitor and control the heat pump from the monitoring system should be further pursued. In the meantime, a separate energy meter should be installed in the collector system.
- Benefit – In order to optimize the operation of the heat pump, it should always be possible to monitor and control it from the monitoring system, including the collector circuit. With proper monitoring, the operational problems would also have been discovered and improved at a much earlier stage.

Limited utilization of the monitoring system:

- Current system – Monitoring of the temperatures in the heating system was only made possible from March 2017, as the building owner only required monitoring of the energy consumption. Although this is the building owner's choice, professionals should have recommended more detailed monitoring of the heating system.
  - Improvement – It is especially recommended to log the volume flow rates for the thermal energy meters in the heating system, and the temperature efficiency for the heat recovery unit in the air handling unit.
  - Benefit – Logging of the volume flow rates would make it easier to analyse and optimize the heating system, e.g. with regards to use of peak load and control of DHW heating. Due to substantially higher energy use for ventilation air heating than calculated, there might be an error with the system, and the temperature efficiency for the heat recovery unit might be lower than expected.

High GWP HFC working fluid (refrigerant)

- Current system – The heat pump is charged with R410A, which is controlled by the F-gas Directive. The Global Warming Potential (GWP) is 2 090 CO_2-equivalents.
- Improvement – Installation of e.g. a propane (R290, GWP=4) heat pump unit, air-source or ground-source.
- Benefit – Improve the eco-friendly profile of the unique building. The drawbacks are higher investment costs and requirement for safety measures due to flammability.

Many of the errors were connected, resulting in amplified problems with the system efficiency. When the suggested modifications are implemented, the heating system should be thoroughly monitored and evaluated to ensure everything is working properly.

4.4.5 Conclusions – Recommendation with regard to design and operation

Despite the issues with the heating system, Medbroen kindergarten is a unique project, as an over 100-year-old building has been refurbished to passive house standard. In order to reach the low emission society, refurbishment of existing buildings is necessary, and preferably to standards as high as nZEB. The heat pump system with horizontal collector circuits buried along a river at sea level, is also in principle a good solution that should achieve high performance. For future projects, the following recommendations should be pursued.

- Use qualified personnel for installation of the heat pump system – Get it right from the beginning, by using experienced professionals for the installation. Money saved on cheaper labour does not outweigh increased operational costs for a malfunctioning system. If an error is discovered, make sure to solve it properly immediately, instead of making minor improvements over multiple years. Insufficient fixes and reoccurring problems will lead to poor system efficiency.
- Function testing and adjustment after installation – Perform function tests and adjustments for the system during the first year of operation. Monitor and perform quality assurance with regards to the energy consumption. With this approach, potential errors will be discovered and improved at an early stage. It will also be possible to optimize the operation of the heat pump system.
- Use low temperature space heating system – Low-temperature heat distribution systems with maximum 30 to 50 °C supply temperature maximizes the energy coverage factor and the SCOP reduces wear and tear for the compressors.

- <u>Correct design of accumulator tanks for space heating</u> – The accumulator tank should be designed for thermal stratification – i.e. warm water at the top of the tank (where it is supplied) and cold water at the bottom of the tank where it is extracted and returned to the heat pump. The tank should have three junctions instead of four, as illustrated in Figure 131 to minimize mixing in the tank. *It's very important that the peak load is placed at the top of the accumulator and close to the supply pipeline for the heating system, to avoid heating the return water to the heat pump.*

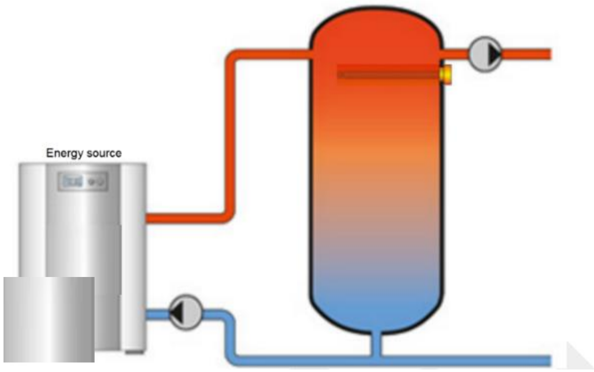


Figure 131: Parallel connected tank with three junction points, peak load at the top (VVSkunnskap, 2017).

- <u>Control of top load</u> – The heat pump should *always* control the peak load unit, and it should be in *serial connection* with the heat pump so that the peak load cannot be switched-on before the heat pump is running at full capacity.
- <u>Space heating vs DHW heating</u> – When using shuttle valves for prioritized DHW heating, the control method should be reasonable with regard to the heating demands for space heating and DHW heating, in order to achieve the highest possible energy coverage factor for the heat pump. For large DHW heating demands it would be better to use a separate CO_2 heat pump water heater (HPWH) or a heat pump with a desuperheater.
- <u>Natural working fluids</u> – Heat pumps and liquid chillers should preferably use natural working fluids, i.e. propane (R290), CO_2 (R744) or ammonia (R717).
    - Natural working fluids are, in contrary to the HFCs and HFOs, 100 % eco-friendly fluids since they have a zero or negligible GWP-value and do not have any negative impact on the global environment during manufacturing of the fluids or in case of unintentional leakages from the units.
- <u>Optimized instrumentation and monitoring system</u> – The instrumentation should enable measurements of important temperatures as well as electric and thermal power/energy for the heating and cooling systems. All sensors should be checked and calibrated before start-up, and the monitoring system should be tuned. Standardized historic graphs will simplify the monitoring of the heating and cooling system.

Advanced monitoring systems are of high importance to obtain optimized operation and minimum energy use for the heating and cooling systems and to detect operational problems at system and component level at an early stage.

4.5 Supermarket – Trondheim, NO

The Supermarket KIWI Dalgård in Trondheim, was finished in 2017, and was the fourth "green" KIWI store with an extra focus on sustainability. It has a heated floor area of 1250 m^2, is built according to the Norwegian passive house standard (NS3701, 2012), utilizes heat recovery from the refrigeration system and will during operation produce more energy than it uses due to the application of solar photovoltaic roof-mounted panels (PV) and a ground-source heat pump. Surplus heat is delivered to 60 apartments in three neighbouring buildings. The thermal energy system for KIWI Dalgård was analysed during 2018 in a project assignment for a Master student at NTNU (Aaberg, 2018). Main findings from the analysis are summarized here, including some additional analysis.

Figure 132: KIWI Dalgård, a high-efficiency supermarket in Trondheim (Mæhlen, 2017).

KIWI and NorgesGruppen have high ambitions of reducing their greenhouse gas emissions and are willing to test innovative solutions to succeed with their aim of becoming carbon neutral. Positive experiences from the first "green" supermarket led to the decision that all new KIWI-stores should have a higher environmental standard. This involves solutions such as an improved building envelope, using carbon dioxide CO_2 (R744) as the working fluid for the refrigeration systems (freezing and cooling), LED-lighting and simple and effective measures such as using doors on all refrigerators and display cabinets.

4.5.1 Calculated Energy Demand and Electricity Generation from PV

Table 34 summarizes the calculated net annual energy demand for the building, annual electricity generation from PV, annual heat supply from the ground-source heat pump as well as the potential for exported heat to the neighbouring apartment buildings (block of flats).

Table 34: Calculated/estimated net energy demand and other parameters for KIWI Dalgård (Aaberg, 2018).

Parameter	Value
Building, heated area	1,250 m^2
Total net energy demand	125,000 kWh/year
Specific net energy demand	100 kWh/(m^2·a)
Produced electricity from PV	55,000 kWh/year
Bought electricity	70,000 kWh/year
Heat production from borehole system	600,000 kWh/year
Exported heat to neighbouring apartments	350,000-400,000 kWh/year

The roof-top and parts of the façade of the building are covered with 560 m^2 of photovoltaic panels (PV), and the system has an estimated annual electricity production of 55,000 kWh/yr. This corresponds to approx. 45% of the total estimated electricity demand of the store (approx. 125,000 kWh). Both traditional crystalline solar cells and thin film solar cells are used, Figure 133.

Thin film solar cells are less energy demanding to produce and are expected to generate more electricity during clouded weather. The project received financial support from Enova SF for testing the thin film technology. The Institute for Energy Technology (IFE) will compare the two different types of solar cells in a research project. The solar cells are also connected to a battery pack for storage of surplus electricity. The batteries may also be charged with electricity from the grid during low load periods. Consequently, KIWI Dalgård is a good example on how to reach a near Zero Energy Building (nZEB).

Figure 133: PV on the roof-top of KIWI Dalgård, with thin film PV on the left and crystalline PV on the right (left, Aaberg, 2018) and Heat pump unit, Carrier Aqua Snap 61WG (right, AHI Carrier, 2018).

4.5.2 Thermal Energy System

Figure 133 shows a principle sketch of the thermal energy flow at KIWI Dalgård with:

1) CO_2 refrigeration plant – Cooling/freezing applications and utilization of gas cooler heat for heating of ventilation air in the supermarket as well as thermal charging of the BTES (bore-hole thermal energy storage – boreholes in bedrock) during May to September 2018.

2) Ground-source heat pump – Heat extraction from the BTES, reheating of ventilation air and space heating by means of radiators in the supermarket, snow melting outside the super-market as well as external heat supply to three neighbouring block of flats.

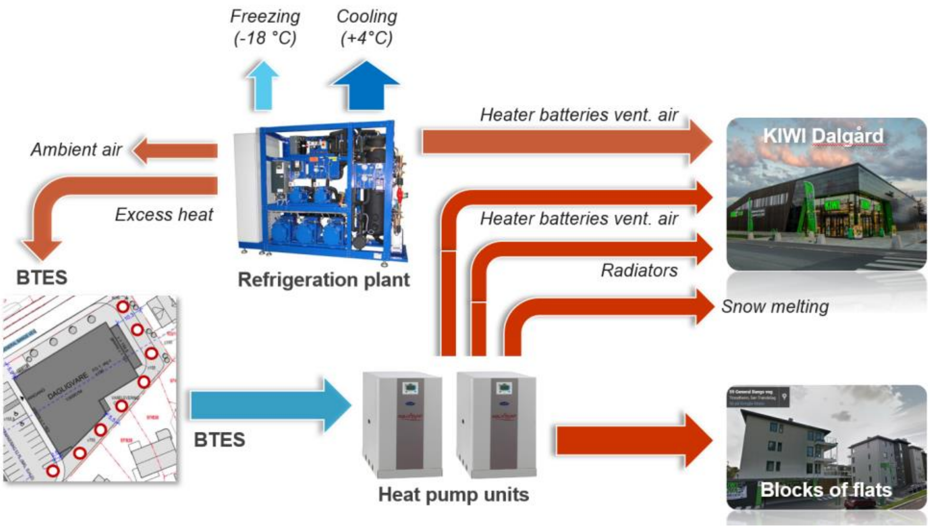


Figure 134: Energy flow for the thermal energy system at KIWI Dalgård (Stene, 2019).

Figure 134 shows a principle sketch of the heating system at KIWI Dalgård with 2 heat pump units connected to the BTES and the heat distribution system. The heat supply from the gas cooler in the CO_2 refrigeration system is also shown. The numbering in the sketch corresponds to the description of the main components in Table 35. The design supply and return tempera-tures for the heating system are also included in the table.

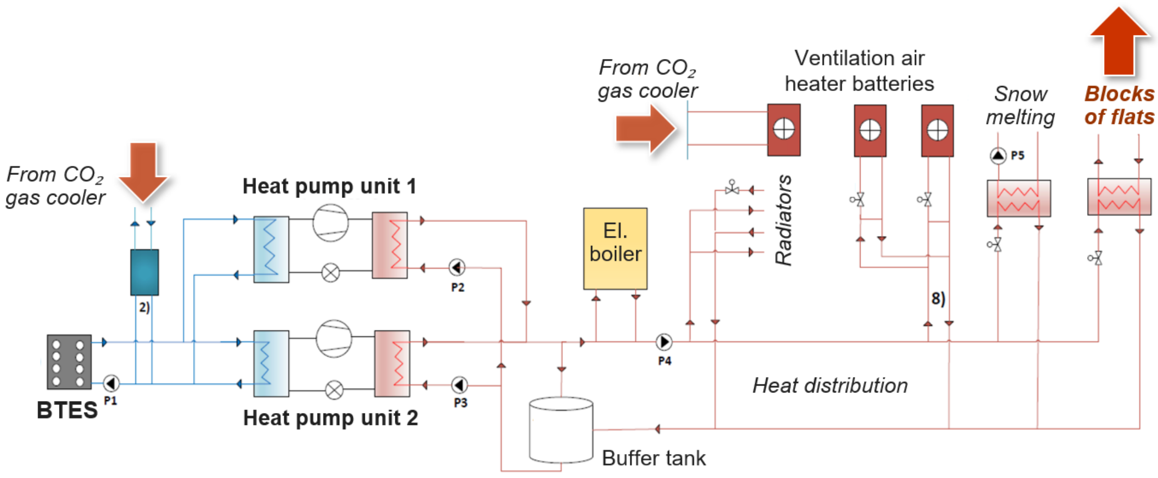


Figure 135: Energy flow for the thermal energy system at KIWI Dalgård (Stene, 2019).

The borehole thermal energy storage (BTES) consists of 8 vertical boreholes situated around the building, each 270 m deep and with approx. 14 m mutual distance. Two identical heat pump units with a total heating capacity of approx. 80 kW at B4/W50 are connected to the BTES.

Table 35: Thermal energy system at KIWI Dalgård summarized (Aaberg, 2018).

No.	Main components	Description	Supply/return temperatures
1)	Borehole system in bedrock (BTES)	• Eight boreholes with depth 270 m • Brine – ethanol (HXi-35)	1/4 °C
2)	Refrigeration plant	CO_2 as refrigerant	20/45 °C
3)	Recovered gas cooler heat from the refrigeration plant	Covers most of the demand for heating of ventilation air in the supermarket and provides thermal charging of the BTES (May-September)	20/45 °C
4)	Ground-source heat pump system	• Carrier Aqua Snap 61WG, R410A, one scroll-compressor with on/off control • Capacity 2 x 39.7 kW (4/50 °C), parallel • Reheats ventilation air in the supermarket and supplies heat to radiators in the super-market as well as to neighbouring buildings	4/50 °C
5)	Accumulator tank	• Volume 600 litres • Ensures constant flow on the condenser side • Reduces start/stop for compressors	N/A
6)	Electric boiler	Peak load, 70 kW (back-up only)	N/A
7)	Radiators/convector	Heats the storage area and staff area	50/30 °C
8)	Ventilation	Three heating coils for the AHU	50/30 °C
9)	Snow melting	Snow melting outside the supermarket during wintertime, capacity 70 kW	35/20 °C
10)	Heat to neighbouring buildings	Annual heat supply was (theoretically) estimated to 350 000-400 000 kWh/year – overestimated!	55/50 °C after HX

Originally, both heat pump units had scroll compressors with on/off control, but due to poor part load properties, one of the compressors was rebuilt to variable speed drive (VSD). The condensers are connected in parallel to a 600 litres accumulation tank. Both evaporators and condensers are brazed plate heat exchangers. A 70 kW electric boiler is installed as back-up in the heating system. The set-point room temperature in the supermarket is 21 °C. Due to internal loads from refrigerators, freezers, and lighting heated ventilation air is sufficient to cover the space heating demand. The ventilation system is VAV, and the airflow rate is controlled to reach the set-point temperature. The staff area in the building is heated by a hydronic radiator system (1.1 kW), while the storage area is heated by a hydronic convector (18 kW) mounted in the ceiling.

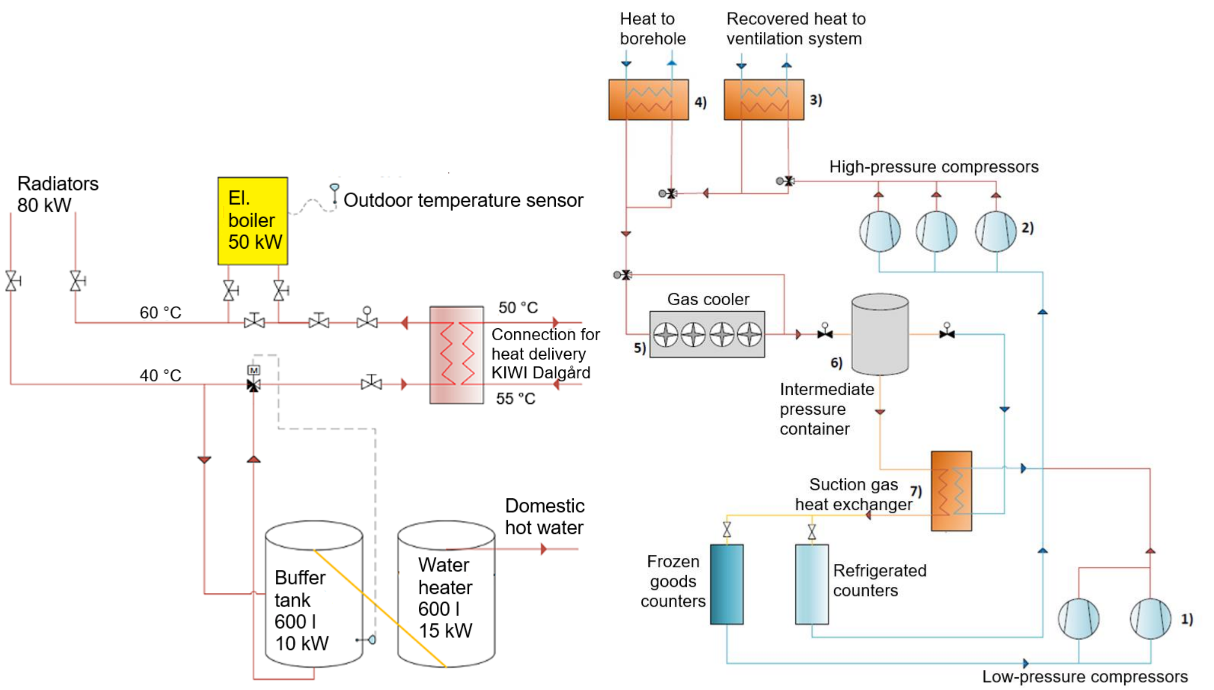


Figure 136: Principle sketch of the heating system in the apartment buildings (left) and sketch of the refrigeration system (Aaberg, 2018).

The design supply and return temperatures for the heating battery in the air handling unit and radiator/convector system is 50/30 °C. Recovered gas cooler heat from the CO_2 refrigeration system is primarily used for heating of ventilation air, while excess heat is rejected to the BTES for thermal charging during May to September. The recovered heat covers most of the heating demand for heating of ventilation air, and when it is not sufficient, hydronic heating coils connected to the heat pump system covers the remaining temperature lift for the supply air. Heat is also supplied from the ground-source heat pump to 3 neighbouring apartment buildings and used both for space heating and preheating of domestic hot water (DHW). Figure 136 shows a principle sketch of the thermal energy system at the neighbouring apartment buildings. Water at 50 °C from the KIWI heat pump rejects heat via a heat exchanger and an electric boiler reheats the water to 60 °C for the radiators (design conditions). The return water from the radiators flows through a buffer tank for preheating of DHW. To maximise the heat supply and SCOP for the ground-source heat pump, the design temperature level 40/25 °C was re-commended. The R410A heat pump units have a maximum supply temperature of about 50 °C. Using 60/40 °C leads to lower energy coverage factor and SCOP for the heat pump due to increased temperature level and higher energy consumption for the electric boiler. This is further discussed in chapter 4.5.3.2.

Table 36: Main components in the refrigeration system at KIWI Dalgård (Aaberg, 2018).

Nr	Component	Description
1)	Low-pressure compressors	2 compressors for display cabinets (freezing), one has variable speed drive control. Design evaporation temperature is -35 °C.
2)	High-pressure compressors	3 compressors for display cabinets (cooling), one has variable speed drive control. Design evaporation temperature is -10 °C.
3)	Heat exchanger connected to the ventilation system	Recovered heat is used to heat ventilation air. Capacity **65 kW** and design temperature levels 25/10 °C and 10/20 °C at primary and secondary side, respectively.
4)	Heat exchanger connected to the BTES	Recovered heat is given off to BTES for thermal charging (reduces the required number of boreholes)
5)	Gas cooler	Cools the CO_2 and rejects heat to the ventilation air or the borehole
6)	Intermediate pressure vessel	Contains fluid which is sent to the evaporators. Design temperature is -3 °C.
7)	Suction gas HX	Ensures dry suction gas to the compressor

The thermal energy system at KIWI Dalgård also provides snow melting outside the supermarket entrance, with a capacity of 70 kW and a design temperature level of 35/20 °C. Temperature and humidity sensors control the system, which is operated between 0 °C and -10 °C. The refrigeration plant for cooling and freezing uses CO_2 as refrigerant, which is a highly efficient and environmentally friendly refrigerant for this kind of application. The model is a "Carrier MiniCO_2OL Compact" with a cooling capacity of approx. 60 kW (+4 °C) and a freezing capacity of 20 kW (-18 °C). An important measure for reducing the energy use is to recover as much as possible of the gas cooler heat and use it to heat the ventilation air in the building. The system is also connected to the BTES for storage of surplus heat (thermal charging).
Figure 136 right shows a principle sketch of the refrigeration system used at KIWI Dalgård. The numbering in the sketch corresponds to the description of the main components in Table 36.
The lighting system at KIWI Dalgård uses LED (light emitting diodes). The lighting system is controlled for daylight in addition to DALI (Digital Addressable Lighting Interface) in the store areas, while other rooms have presence-based control (Sundlisæter et al., 2015). DALI is an international standard that ensures the building owner/installer free choice of dimmers, relay modules, transformers, control panels and converters (Micro Matic, 2016).

4.5.3 Monitoring

4.5.3.1 Description of Monitoring System

The heating system at KIWI Dalgård is monitored by means of eight thermal energy meters (Kamstrup Multical 602), an electric energy meter (Saia ALE3D5FD10) and six temperature sensors (Siemens QAP21.2) to optimize the operation of the system as well as to control for errors. The central control and monitoring system (IWMAC Basic) provide continuous monitoring and automatically sends alarms if any errors or deviations occur. The heat pump units are controlled based on an ambient temperature compensation curve and by a temperature sensor to maintain the supply temperature between **50-55 °C** to activate the thermal storage in the accumulator tank. The peak load direct electric heater should never be used unless the heat pumps are not already running at full capacity. Unfortunately, the central control and monitoring system does not include the thermal energy system for the apartment buildings. This is a separate system operated by another building owner, and there is no control of the heat transfer from the KIWI store based on the demand in the apartment buildings. The CO_2 refrigeration system will not be analysed in detail in this report.

4.5.3.2 Measured Energy Use 2018

The total net annual energy demand at KIWI Dalgård was estimated to be approx. 125 MWh/year.

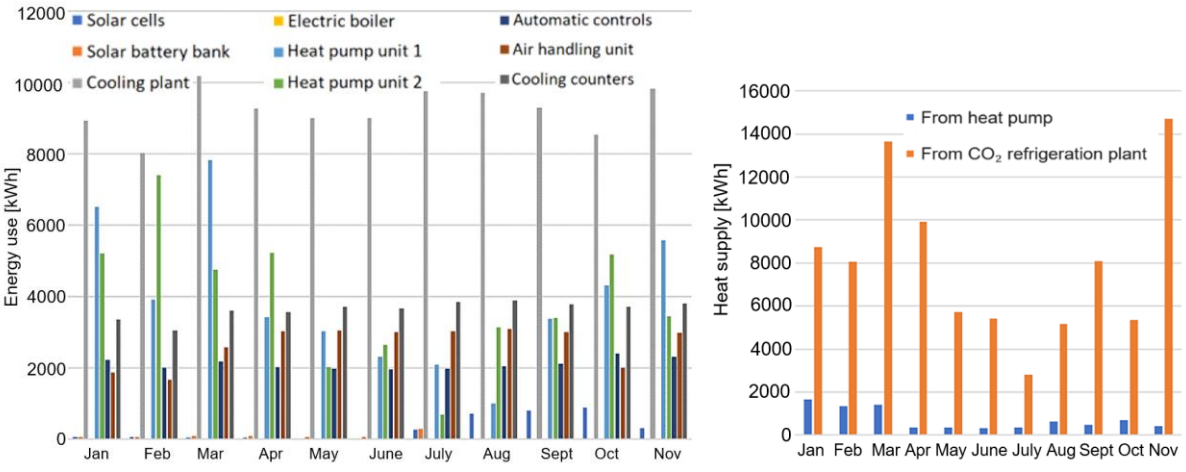


Figure 137: Measured energy production and use at KIWI Dalgård 01.01.2018 – 30.11.2018 (left, Aaberg, 2018) and ventilation air heating covered by heat from the CO_2 refrigeration system (orange bars) and the heat pump (blue bars) (right, Aaberg, 2018).

During the first 11 months of 2018, the measured energy use was 284 723 kWh, i.e. more than twice as high. The energy production for PV and energy use for the different sub-systems is shown in Figure 137 left.

The CO_2 refrigeration (cooling plant) is the largest single consumer of energy, using approx. 100 MWh, close to the estimated total energy demand for a full year. If "Cooling counters plug-in" are included, i.e. free-standing display cabinets in the supermarket, the refrigeration system alone amounts to approx. 140 MWh.

4.5.3.3 Utilization of Surplus Heat

Surplus heat from the CO_2 refrigeration plant is utilized for heating of ventilation air in the KIWI supermarket. During the measurement period 01.01.2018 – 30.11.2018, recovered heat from the plant was approx. 90 000 kWh, corresponding to an energy coverage factor of **92 %** (Figure 137 right). This is close to the design coverage factor of 90%. The heat pump covers the remaining 8%. In addition, 70 000 kWh of recovered heat from the CO_2 plant was rejected to the BTES, mostly during the summer months. This is however much lower than the design value. It is crucial to maintain an annual thermal energy balance for the borehole systems, to avoid permanent reduction in the ground temperature and possible freezing of the ground water which will reduce both the SCOP and heating capacity of the heat pump.

4.5.3.4 Borehole Thermal Energy Storage (BTES) System

As previously mentioned, 70,000 kWh of recovered heat from the CO_2 refrigeration plant was transferred to the BTES. Extracted heat from the BTES by the heat pump was 60 000 kWh.

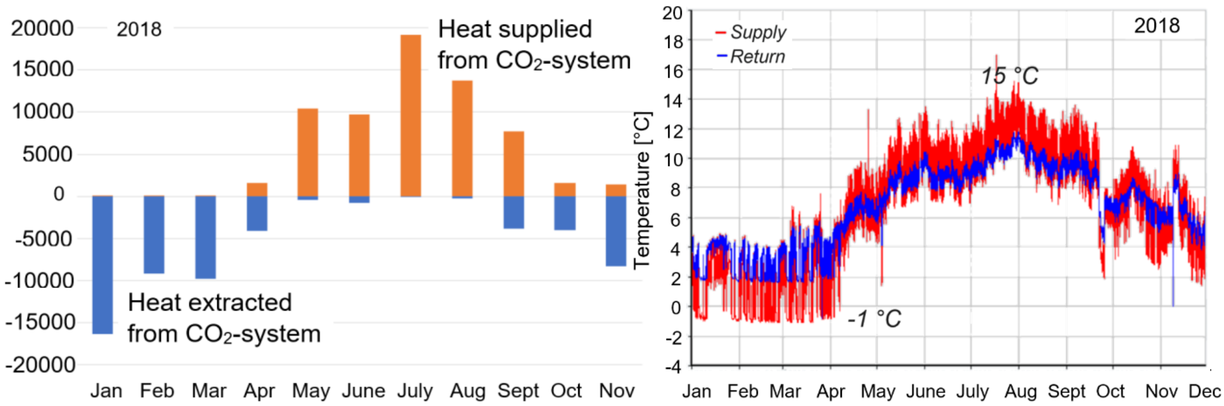


Figure 138: Annual heat balance for the BTES (left) and temperature levels in the BTES during the measuring period (right, Aaberg, 2018)

Figure 138 shows both the thermal balance of the BTES (left) and measured supply and return temperatures (right) for the measuring period. The minimum brine temperature was -1 °C. The BTES was found to be undersized compared to the heating demand of the apartment buildings. Simulations in Earth Energy Designer over a 25-year period showed that the potential heat production would be 100,000 kWh/yr, if no heat is transferred back to the BTES, and 130,000 kWh/yr if 20,000 kWh is transferred to the BTES. This is significantly lower than the potential heat production of 600,000 kWh/yr (highly overestimated). At low outdoor temperatures the return temperature from the BTES has been lower than 0 °C, which is another indication of an undersized BTES.
The temperature of the brine circulating in the borehole heat exchangers (BHE) should not drop below approx. -2 °C, as this might lead to freezing of the clay. Freezing and consequent thawing will damage the BHE. Suggested improvements include increasing the number of boreholes or installing temperature sensors on each borehole for improved control. The measured heat transfer to/from the BTES does however indicate that there is a good thermal energy balance in the system.

4.5.3.5 Export of Heat to Neighbouring Apartment Buildings

During the first 11 months of 2018, the heat pump supplied 160,000 kWh to the neighbouring apartment buildings, as shown in Figure 139. As the design value was 350,000 kWh/yr, this is a considerable deviation. However, the design value was probably highly overestimated.

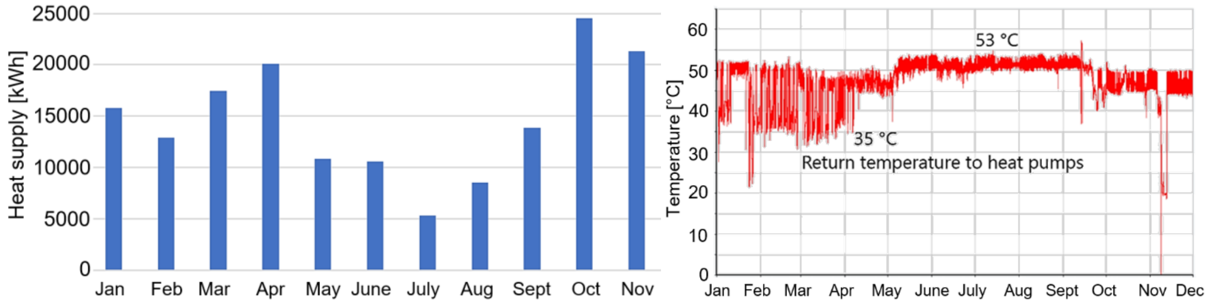


Figure 139: Supplied heat from heat pumps to the apartment blocks (left) and measured return temperature to the heat pump (right), Measuring period 1.1.2018 – 30.11.2018 (Aaberg, 2018).

As the KIWI store and neighbouring apartment buildings had two different building owners and was constructed by different contractors, the solutions were not properly matched, especially with regards to temperature levels for the heat distribution system. The possibility of exporting heat from KIWI Dalgård to the apartment buildings is limited by a higher temperature requirement for the radiators (**60/40 °C**) than what was recommended (floor heating system, 40/25 °C). The higher temperature level reduces both the SCOP as well as the heat supply from the heat pump since the heat pump units have a maximum supply temperature of **55 °C**.

4.5.3.6 The Heat Pump System

The measured average COP (SPF_{HP}) for the two heat pump units was **3.0** and **2.9** during the 11 months in 2018. This corresponds to an energy saving of approximately 65 % compared to a direct electric heating system. The SPF_{HP} is considered to be moderate, but *with a low-temperature floor heating system in the apartment buildings and more energy efficient heat pump units (from prevailing B to e.g. A^{++}) the system performance would have been highly improved*. The two heat pump units were originally controlled on/off. This led to frequent starts and stops, approximately 4-5 per hour. The compressor for one of the heat pump units was rebuilt to variable speed drive (VSD), which in addition to reducing wear and tear also leads to higher SPF and considerably improved controllability at low heating demands. In addition, the accumulator tank for the heating system has been rebuilt to improve thermal stratification.

4.5.3.7 Central Control and Monitoring system

The central control and monitoring system at KIWI Dalgård does not include the heating system at the apartment buildings. It would be easier to identify errors and optimization possibilities, if everything was monitored in the same system. This is a challenge at the neighbourhood scale that needs to be solved, probably by introducing new business models on how and by whom such interconnected systems should be operated. The CO_2 refrigeration system at KIWI Dalgård is controlled by Carrier, while Caverion, who operates the rest of the thermal energy system, would like to have full overview and control of this in addition to the ground-source heat pump to optimize the operation of the thermal energy system.

4.5.3.8 CO_2 Refrigeration System

The temperatures in the cooling and freezing display cabinets should be +4 °C and -18 °C, respectively (Mattilsynet, 2018). The most energy-efficient refrigeration plants can maintain these temperatures with evaporation temperatures/pressures at -2 °C/33 bar and -26 °C/ 16 bar for cooling and freezing counters, respectively. The energy use increases, if the evaporation temperature is reduced in order to maintain the temperature levels in the cabinets. Measured evaporation temperatures during a week in November 2018 is shown in Figure 140. For this time period, the refrigeration plant at KIWI Dalgård operated at -4 °C/31 bar and -28 to -31 °C/13 to 14 bar. There is thus an improvement potential to increase the energy efficiency of the system. By implementing a low-pressure receiver or a suction gas heat exchanger after the evaporators, the entire heat exchanger area can be utilized, and no superheating is needed. The refrigerant can be safely controlled based on the air temperature in the cabinets and the evaporator temperature increased to -2 and -26 °C. The temperature peaks in the graph occur during defrosting. It is good practice to distribute the defrost cycles of the freezing and cooling systems, so they do not overlap, as simultaneous start of the compressors after the defrost period would require a high power input to reduce the temperature levels in the display cabinets.

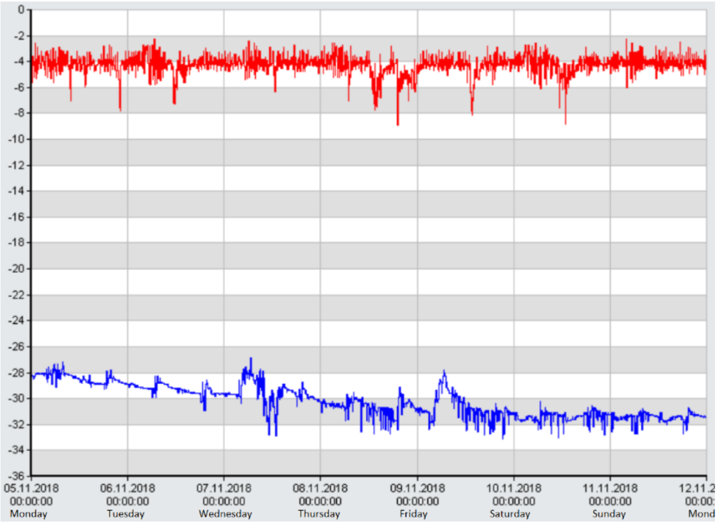


Figure 140: Evaporation temperatures for the CO_2 refrigeration plant (cooling and freezing) at KIWI Dalgård during a week in November 2018 (Aaberg, 2018).

4.5.4 Results and Discussion – Improvement of the Existing Systems

KIWI Dalgård is designed to be a very environmentally friendly supermarket and should be considered a role model for supermarkets, albeit still having a potential for improvement. The design of the building and technical installations is very good, and the CO_2 refrigeration system including heat recovery for heating of ventilation air is working well. The largest challenge or problem is the relatively high temperature requirement for the radiators in the apartment buildings that receive heat from the ground-source heat pump. This limits the potential for exporting heat and also reduces the SPF_{HP} of the heat pump. In addition, the measured energy use at KIWI Dalgård was over twice as high as the calculated net energy need. It is however still early to properly evaluate the thermal energy system at KIWI Dalgård, as the first operating year of buildings usually involves higher energy use and some modifications and adjustments on the system to optimize it.
Recommended improvement measures that can be implemented at KIWI Dalgård:

4.5.4.1 Borehole thermal energy storage (BTES)

- Current system – Fully utilized BTES in the measurement year 2018 and potentially undersized compared to the heating demand of the apartment buildings. The potential heat production was simulated to be 100,000-130,000 kWh/year which is significantly lower than the most likely highly overestimated potential of 600,000 kWh/year. The measured minimum brine temperature of -1 °C is close to the minimum acceptable limit of -2 °C.
  - Improvement – Increase the number of boreholes or install temperature sensors on each borehole for improved temperature control.
  - Benefit – Higher heat production from the BTES and reduced risk of damage for the borehole heat exchangers (BHE).

4.5.4.2 Heat pumps & central control and monitoring system

- Current system – Different building owners (KIWI Dalgård vs. apartment buildings) with minimum coordination has led to suboptimal design and operation of the thermal energy systems.
  - Improvement – A) Replace the R410A heat pumps with new heat pump units that are able to supply heat at minimum 65 °C (no temperature limitation). The heat pump units with minimum A^{++} energy rating should use propane as working fluid and have compressors with variable speed drive (VSD). This presupposes increased number of boreholes (larger BTES). In future projects with similar system design the apartments should have a low-temperature heat distribution system, e.g. a floor heating system, instead of standard radiators with a relatively high temperature requirement. B). Install

a common monitoring system for the thermal energy system in both the supermarket and the apartment buildings.

- Benefit – A) New heat pump units without a temperature limitation will be able to supply more heat to the radiator systems in the apartment buildings, despite the relative high temperature requirement. A^{++} energy rating would lead to increased SCOP. B) Optimal control of the heating system which will maximise the utilization of the heat pump and minimize the utilization of the electric peak load. It would also be easier to identify errors and optimization possibilities.

4.5.4.3 Choice of working fluid/refrigerant

- Current system – The refrigeration system is using CO_2 as refrigerant which is a good choice since it is a natural fluid that is highly efficient for refrigeration purposes. The heat pump units are, however, using the synthetic refrigerant R410A, which is not ideal, as HFCs with large GWPs will be phased out by 2030. This might lead to difficulties for service and maintenance of the heat pump units at KIWI Dalgård.
  - Improvement – Install new heat pump units with propane (R290) as working fluid, compressors with VSD and outlet temperature of min. 60 °C. In general, propane heat pumps achieve higher COP and longer lifetime than R410A heat pumps, but have higher investment cost. Propane is also a very flammable fluid (safety class A3) and additional safety measures are required.
  - Benefit – CO_2 has excellent thermophysical properties for refrigeration, is environment-tally friendly (GWP of 1) and is also non-toxic and non-flammable, which is beneficial with regard to safety. Propane is environmentally friendly (GWP of 3) and the heat pump units may achieve higher SCOP and longer lifetime than R410A units.

4.5.5 Conclusions – Recommendation with regard to design and operation

4.5.5.1 Recommendations for future projects:

- Buildings with connected heating systems for export/import should have an integrated design process and common monitoring of the entire thermal energy system. A lack of co-operation between the building owners and designers/contractors at KIWI Dalgård and the neighbouring apartment buildings led to a mismatch of the temperature levels and sub-optimal operation of the thermal energy systems. This is related to both the export of surplus heat from the ground-source heat pump to the apartment buildings, the operation of the electric peak load in the apartment buildings and monitoring/control of the thermal energy system. These issues should be solved for future projects with energy/heat exchange at neighbourhood scale.

- Low-temperature space heating system – Low-temperature heat distribution systems with maximum 30 to 40 °C supply temperature maximizes the energy coverage factor and the COP in heating mode and reduces wear and tear for the compressors.

- Highly efficient refrigeration plants and heat pumps with natural working fluids – Heat pumps and liquid chillers should preferably use natural working fluids, i.e. propane (R290), CO_2 (R744) and ammonia (R717 – larger systems).

- Available surplus thermal energy (heat) should always be utilized, either directly through heat recovery or as a heat source for heat pump systems. It is important to identify the thermal demands, as well as temperature requirements, for space heating and cooling, heating of ventilation air, heating of DHW and process cooling. This should be considered in the design phase and taken into account before designing the heating and cooling systems. The surplus energy can either be used within the same building or in neighbouring buildings. A good match between the source of surplus heat and the heat load is important. If there is a poor match, storage can be an option through accumulation tanks, BTES or phase-changing materials (PCM). Duration curves are a good tool for designing heating and cooling systems and to visualize the potential of utilizing surplus heat sources.

4.7 School – Kristiansand, NO

Justvik skole, which was completed in 2017, is a primary school in Kristiansand in the Southern part of Norway, designed according to the Norwegian passive house standard (NS3701, 2012). The total heated area is 3,480 m², incl. 535 m² for a sports building. A CO_2 ground-source heat pump covers the heating and cooling demands. The contractor for Justvik skole (Veidekke ASA) received the Norwegian Heat Pump Award 2018 due to the unique design of the CO_2 ground-source heat pump system.

Figure 141: Justvik school (primary school) in Kristiansand (Photo – Jeanette Hoff/NAL)

4.7.1 Heating and Cooling Demands

Table 37 summarizes the calculated total heating and cooling demands for the school building and sports building including space heating, heating of ventilation air, DHW heating and cooling of ventilation air (Moe, 2018). The table also shows the design temperature levels.

Table 37: Calculated heating and cooling demands and design temperature levels for the hydronic heat distribution system at Justvik skole (Moe, 2018).

		Temp. level	Value
Buildings, total heated area			3,480 m²
Heating demand	**- Total energy demand**		170,000 kWh/year
	- Radiators	45/40 °C	
	- Floor heating	35/30 °C	
	- Ventilation air heating	30/18 °C	
	- DHW heating	70 °C	*95,000 kWh/year (55 %)*
Cooling demand	**- Total energy demand**	9/22 °C	7,000 kWh/year

Figure 142 shows the calculated monthly thermal and electrical energy demand for Justvik skole (Moe, 2018). Space heating, heating of ventilation air and domestic hot water (DHW) heating are the dominating loads. DHW heating accounts for about 55 % of the total annual heating demand, and includes both DHW consumption and reheating of circulating DHW.

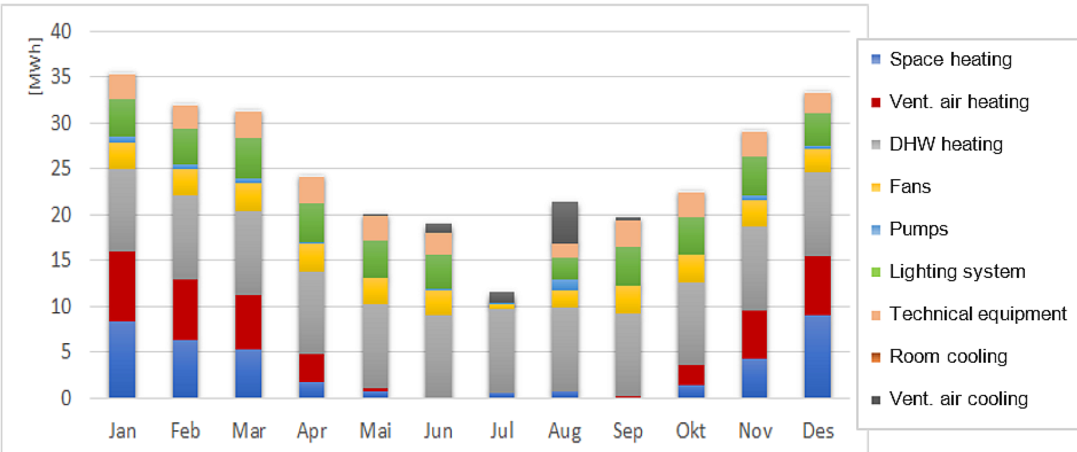


Figure 142: Calculated monthly thermal and electrical energy demand for Justvik skole (Moe, 2018).

4.7.2 System for Thermal Energy Supply

Justvik skole has a ground-source heat pump system for space heating, heating of ventilation air, DHW heating and space cooling. The heat pump unit uses CO_2 (R744) as working fluid, and the systems for DHW heating and heat distribution have been designed to provide the best operating conditions for the CO_2 heat pump in order to maximize the performance.

4.7.2.1 CO_2 Heat Pump System

A CO_2 heat pump rejects heat at supercritical pressure ($p > p_C$) by cooling of high-pressure CO_2 gas in a heat exchanger named "gas cooler" (no condensation). The CO_2 temperature difference between the inlet and outlet of the gas cooler is the "temperature glide" ($t_2 - t_3$), Figure 143. Both the heating capacity (Q_{gc}, kW) and the COP are strongly affected by the temperature glide, i.e. the CO_2 outlet temperature from the gas cooler (t_3). The lower the CO_2 outlet temperature (t_3), the higher the heating capacity and the higher the COP. The outlet CO_2 temperature is to a large extent determined by the inlet water temperature.

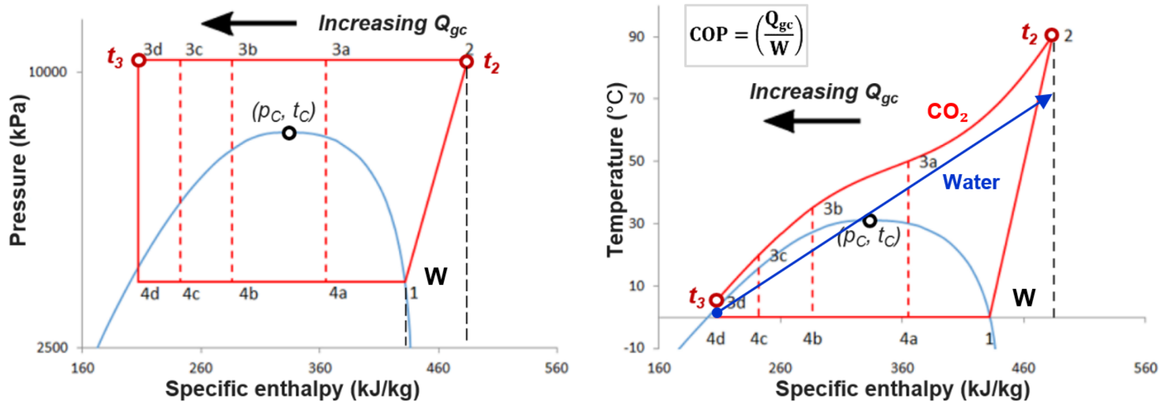


Figure 143: Principle illustration of a single-stage CO_2 heat pump cycle in pressure/enthalpy and temperature/-enthalpy diagrams (Moe, 2018/Stene, 2019). Q_{gc} – gas cooler capacity, W – input compressor power. Gas cooler heating capacity (Q_{gc}) 2 – 3, Input compressor power (W), 1 – 2.

The main application for CO_2 heat pumps has been DHW heating since the low city water temperature leads to excellent performance compared to competing DHW heating systems. If a CO_2 heat pump is used for combined space heating, heating of ventilation air and DHW heating, it is crucial that the return temperature in the heat distribution system is as low as possible, preferably lower than 25 °C.

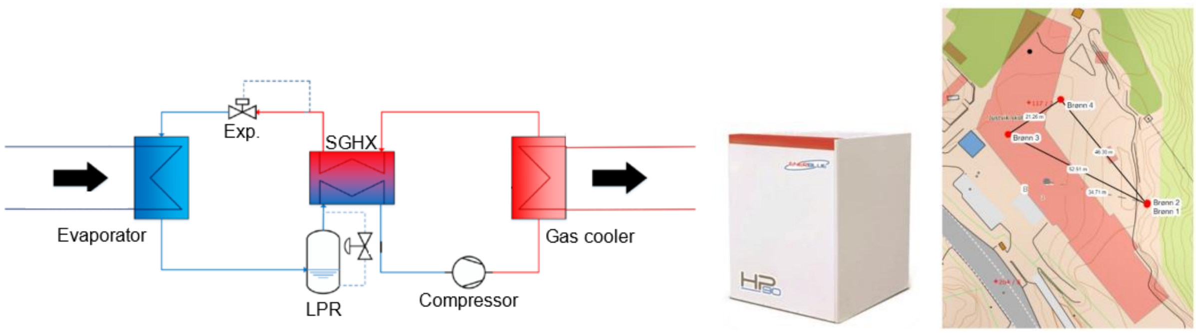


Figure 144: Principle sketch of the CO_2 heat pump unit (left, Moe, 2018) and Enerblue CO_2 heat pump unit (middle) as well as overview of the borehole configuration for the ground-source heat pump (right)

The heating capacity of the CO_2 brine-to-water heat pump unit at Justvik skole unit is 35 kW at 3/-2 °C and 30/70 °C. In the design phase it was estimated that the heat pump would cover about 94 % of the total heating demand and achieve an SCOP of 3.4 (approx. 65 % net energy saving, peak load incl.). The standard heat pump unit, EnerBlue HP90W48, is equipped with brazed plate heat exchangers as evaporator (80 bar) and gas cooler (120 bar), a semi-hermetic piston compressor with on/off control, an electronic expansion valve, a suction gas heat exchanger (SGHX) and a low-pressure receiver (LPR), Figure 144. The brine-to-water heat pump is connected to a ground-source system with 4 vertical boreholes, each 200 m deep.

The borehole heat exchangers (BHE) are smooth collectors with specifications OD 40/2.3, PN10, PE100, SDR17, and the BHE are connected in parallel. The anti-freeze fluid (brine) is 24% ethanol (HXi-24) with a freezing point of approx. -10 °C. Borehole 1 and 2 are drilled from the same starting point with 8 ° inclination. The groundwater flow at a depth below -100 m is estimated at 1000 litres per hour. A 75 kW electro boiler is used for peak load heating.

4.7.2.2 Design and Operation of the Heating and Cooling System

In order to achieve the lowest possible return temperature in the heat distribution system at all operating conditions, the radiators, the floor heating system and the heating coils for heating of ventilation air are connected in series with decreasing temperature level. The DHW system is connected in parallel to the heat distribution system and can be operated independently.

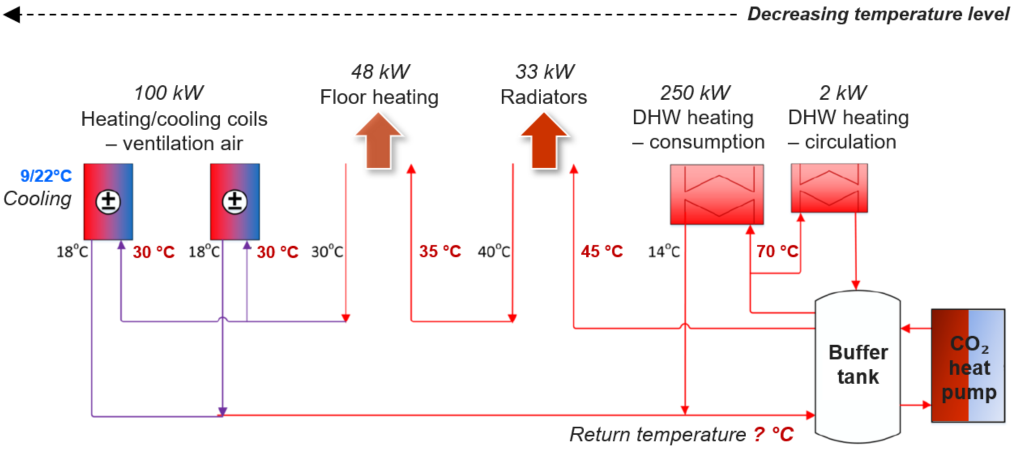


Figure 145: Principle illustration of serial connection of heat loads with decreasing temperature level (Moe, 2018)

The temperature levels at design conditions for the different sub-systems are as follows:

- 70 °C – DHW circulation
- 70 °C – DHW consumption
- 45/40 °C – radiators (space heating)
- 35/30 °C – floor heating system (space heating)
- 30/18 °C – heating coils (heating of ventilation air)

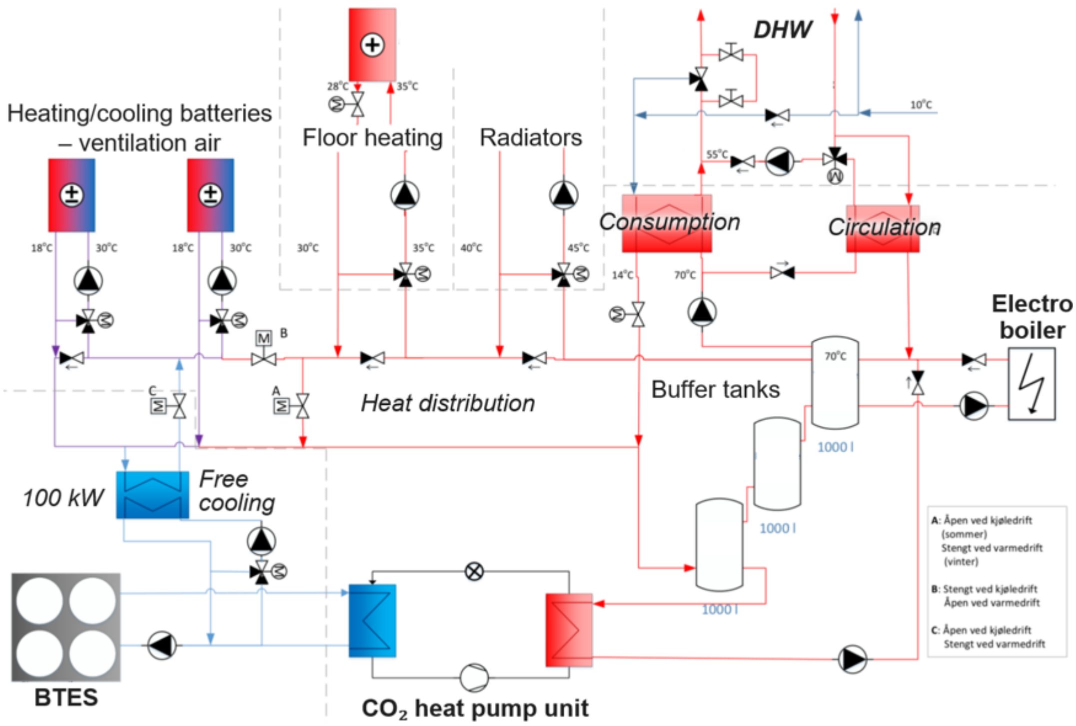


Figure 146: Illustration of the thermal energy system with CO_2 heat pump/BTES and electro boiler (peak load) as well as the hydronic distribution systems for heating and cooling (Moe, 2018).

Figure 145 shows a principle illustration of the serial connection of the different heat loads in the heat distribution system (radiators, floor heating, heating coils), the parallel connection of the DHW system as well as the temperature level and calculated heating capacity at design conditions (Moe, 2018). The coils in the ventilation system are used during "overall heating mode" and for cooling during "overall cooling mode". Cooling is provided by cold brine from the BTES, and it is not possible to operate the heat pump as a liquid chiller for peak load cooling. The maximum cooling capacity is about 115 kW.
Figure 146 shows an illustration of the thermal energy system incl. the CO_2 heat pump/BTES and electro boiler (peak load) as well as the hydronic distribution systems for heating and cooling (Moe, 2018). The CO_2 heat pump and the electro boiler are connected in series and parallel, respectively, to three 1000 litres accumulator/buffer tanks. Each of the two circuits are equipped with a circulation pump. Since the CO_2 heat pump is operated on/off, the accumulator tanks are used as a thermal energy storage.

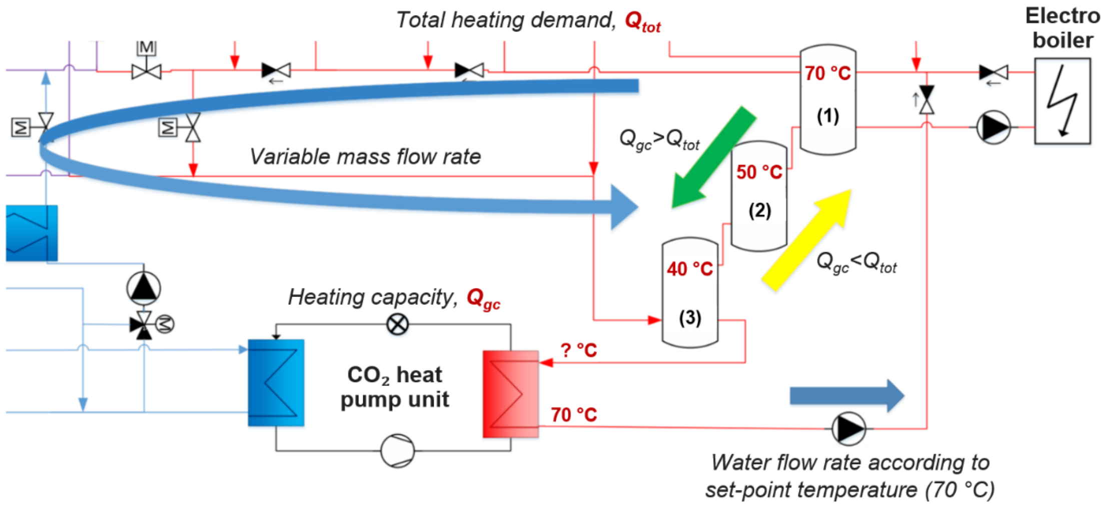


Figure 147: Principle illustration of the control strategy for the thermal energy system with thermal charging and discharging of the three accumulator tanks (Moe, 2018/Stene, 2019).

Figure 147 illustrates the control strategy for the thermal energy system depending on the heating demands and operation of the CO_2 heat pump unit and the electro boiler, i.e. the water flow rates in the heat distribution circuit (blue arrow) and heating circuit (green/yellow arrow).
The main strategy behind the design and operation of the thermal energy system with CO_2 heat pump, electro boiler, DHW system and heat distribution system, is to cover the actual heating demands and at the same time achieve the lowest possible return water temperature to the CO_2 heat pump in order to achieve a high annual energy coverage factor for the CO_2 heat pump and high SCOP. CO_2 heat pump – The CO_2 heat pump is operated on/off and the pump in the heat pump circuit adjusts the water flow rate to achieve a constant outlet water temperature of 70 °C when the heat pump is running.
The heat pump starts when the temperature at the top of Tank (1) drops below 70 °C and stops when temperature at the bottom of the tank reaches 70 °C. DHW system – There is a constant water flow through the heat exchanger for heating of DHW in the circulation system ("Circulation") and the DHW is reheated to about 55 °C. When there is a DHW draw-off, motor valve for the "Consumption" heat exchanger opens, and water from Tank (1) at 70 °C heats the cold city water to about 55 °C. The DHW heating systems are connected in parallel with the heat distribution system. Heat distribution system – The heat distribution system has three different heat loads connected in series – radiators, floor heating system and heating coils in the air handling units. Each circuit has a separate pump, i.e. the water flow rate and the resulting return temperature in the heating system will depend on the heating demand for each of the loads/circuits. Non-return valves ensure that the return water from the different heating circuits do not flow to the supply pipelines. Accumulator tanks, charging – If the heating demand in the DHW system and the heat distribution system is lower than the heating capacity of the CO_2 heat pump, the water flow rate through the heat pump will be higher than in the heat distribution system.

70 °C water from the heat pump will then partly go to the heat distribution system and the remaining flow will go to the top of Tank (1), through Tank (2) and finally to Tank (3) – green arrow in Figure 147. When the temperature at the bottom of Tank (3) reaches 35 °C the heat pump stops. When the temperature drops below 30 °C the heat pump starts again. Accumulator tanks, discharging – If the heating demand in the DHW system and the heat distribution system is higher than the heating capacity of the CO_2 heat pump, the water flow rate through the heat pump will be lower than in the heat distribution system. 70 °C water from the heat pump and water from the accumulator tanks will flow to the DHW system and the heat distribution system – yellow arrow in Figure 147. Peak load (electro boiler) – At low ambient temperatures the heating demand will be higher than the capacity of the CO_2 heat pump and accumulator tanks, and the pump in the peak load circuit will start when the temperature at the top of Tank (1) drops below 63 °C. The electro boiler supplies heat to Tank (1) with a 70 °C set-point. Cooling – The thermal energy system operates in “overall heating mode” at ambient temperatures below 9 °C and in “overall cooling mode” at ambient temperatures above 20 °C. The entire cooling demand for the school is covered by free cooling (direct cooling) from the boreholes. The cold brine cools the water in the ventilation coils via a plate heat exchanger, and the set-point for the room temperature is 26 °C.

4.7.3 Monitoring Results

The thermal energy system is equipped with a large number of temperature sensors, volume flow meters, thermal energy meters for the CO_2 heat pump circuit, the DHW “circulation” system, the DHW “consumption” system and the heat distribution system as well as electric energy meters for the CO_2 heat pump, the electro boiler and main pumps. The measuring equipment is connected to a monitoring system that controls the controllable components and monitors the thermal energy system.

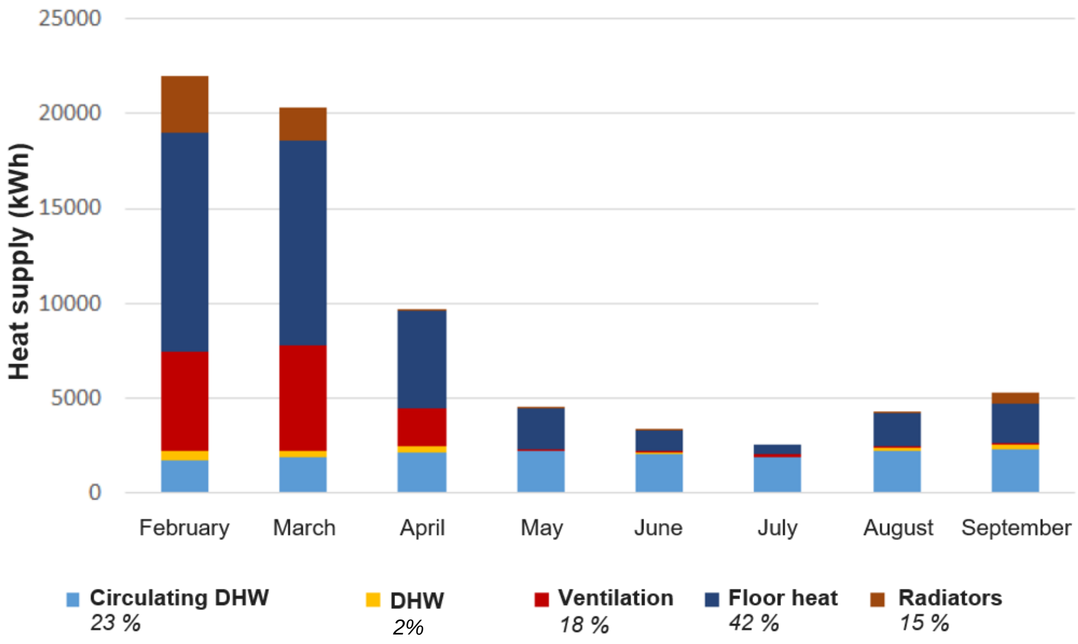


Figure 148: Measured monthly heating demands from February to September 2018 (Moe, 2018).

Figure 148 shows the measured monthly heating demands for February to September 2018, approx. 72,000 kWh. Space heating (floor heating, radiators) and heating of ventilation air accounted for 57 % and 18 % of the heating demand, respectively (Moe, 2018). Since the measuring period was only 8 out of 12 months, the heating demand was extrapolated for an entire year. The measured extrapolated heating demand was higher than the simulated value according to the Norwegian passive house standard NS3701 (2012). This is probably due to “drying out” of the building, higher room temperature and longer operating time for the ventilation system, lower heat recovery efficiency for the ventilation system, higher U-values for the building envelope and non-optimised operation of the thermal energy system.

The deviation is expected to be lower the second year of operation. Figure 148 shows that the heating demand for DHW “consumption” and DHW “circulation” accounted for 2 % (1,800 kWh) and 23 % (16,000 kWh), respectively. The low DHW consumption may be due to a measuring error for the energy meter caused by a large number of small draw-offs but it also indicates that rel. few pupils shower after exercising in the sports hall. The measured cooling demand was almost 5 times higher than the calculated value. This can be explained by a much higher ambient temperature than that of a “normal year” from April to September. Insufficient solar shading can also be an explanation. The entire cooling demand was used to charge the BTES and increase the ground temperature, which in turn increases the heating capacity and SCOP of the CO_2 heat pump. Figure 149 shows the measured monthly heat supply from the CO_2 heat pump and the electro boiler from February to September 2018 (Moe, 2018). The average energy coverage factor and SCOP for the CO_2 heat pump was 78% and 3.05, respectively, which gives a net energy saving (ΔE) of about 52%. This is much lower than the calculated energy coverage of approx. 94 % and SCOP of 3.4, which gives an energy saving of 66%. The relatively low energy coverage factor and moderate SCOP for the CO_2 heat pump were partly due to a relatively high average return temperature, which was caused by a much lower DHW heating demand and more heat supply from the radiators than estimated/calculated. The CO_2 heat pump also had a number of unexpected stops during the measuring period.

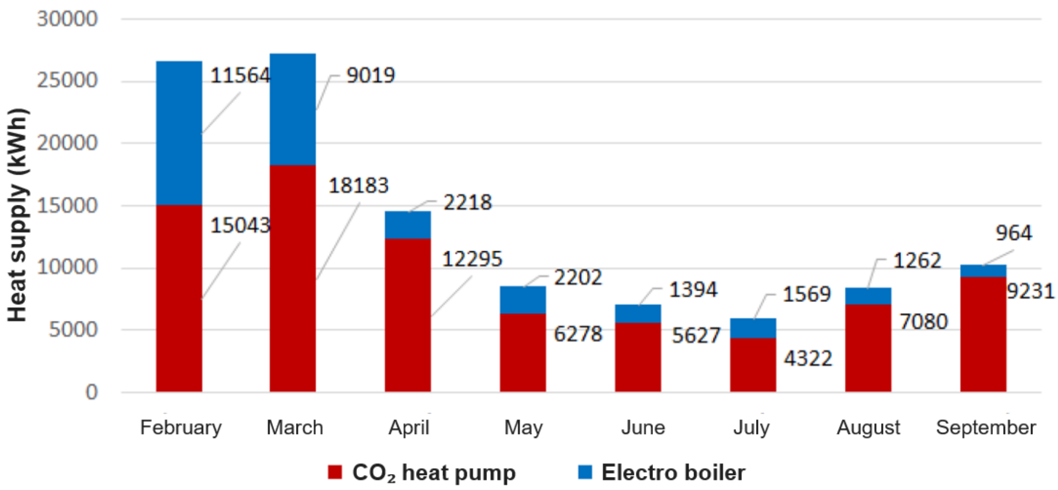


Figure 149: Measured monthly heat supply from the CO_2 heat pump and the electro boiler from February to September 2018 (Moe, 2018).

Figure 150 shows the measured monthly COP (-) as well as energy coverage factor (%) and energy saving (%) for the CO_2 heat pump system (Moe, 2018).

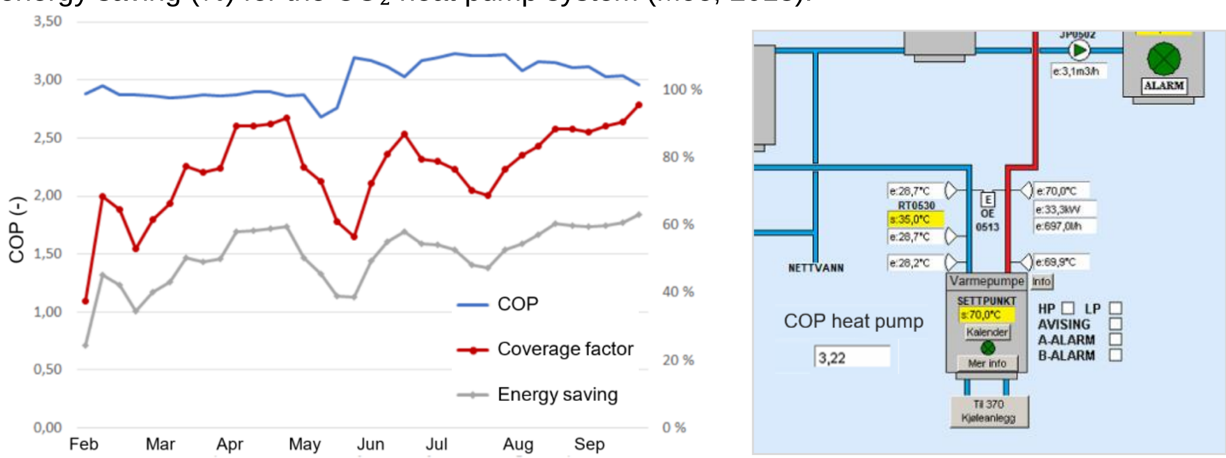


Figure 150: Measured monthly COP (-) as well as energy coverage factor (%) and energy saving (%) for the CO_2 heat pump from February to September 2018 (Moe, 2018) and Snap shot from the monitoring system showing the CO_2 heat pump unit with 70 °C set-point temperature.

After the measuring period was completed the heat pump supplier discovered that the temperature sensor for the CO_2 heat pump had a measuring error of 9 °C., i.e. the supply temperature from the heat pump had been 79 °C instead of 70 °C, which consequently resulted in a higher return temperature in the heat distribution system. After the temperature sensor was replaced in March 2019, the average COP increased by 10-15% and the heating capacity by 20%.
The borehole system was simulated in Earth Energy Designer (EED). Figure 151 shows the simulated development of the minimum and maximum brine temperatures for the 4 boreholes over 20 years (Moe, 2018). The simulation model does not take into account ground water flow. The temperature level decreases gradually, but the temperature drop for the simulation period is not more than 2 °C, i.e. if ground water flow is taken into account the lowest temperature will probably not fall below -2 to -3 °C, which is the minimum accepted brine temperature. However, drilling of one extra borehole to increase the capacity would be beneficial.

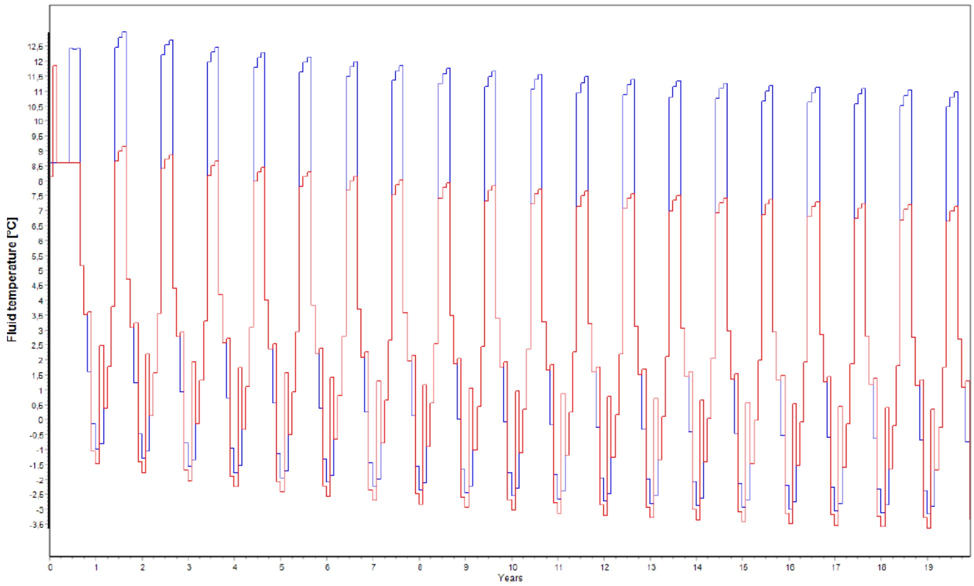


Figure 151: Simulated development of the minimum and maximum brine temperatures in the borehole system over 20 years (Moe, 2018).

4.7.4 Results and Discussion – Improvement of the Existing Systems

The in-depth analysis of the thermal energy system at Justvik skole, which includes a ground-source CO_2 heat pump, an electro boiler, a DHW heating system, a heat distribution system (radiators, floor heating, heating of ventilation air) and a system for space cooling, showed that the system performance in terms of SCOP, energy coverage factor and annual energy saving for the heat pump was lower than estimated. However, *after replacing the temperature sensor for the CO_2 heat pump unit the performance has been considerably improved*.
Possible measures to improve the performance:

- The SCOP and heating capacity of the CO_2 heat pump was calculated on the basis of typical DHW demands in schools with a sports hall. However, the measured DHW usage was very low. If the DHW usage increases, e.g. with mandatory showering for the pupils, the performance of the CO_2 heat pump system will be further improved.
- The CO_2 heat pump is not currently connected to the main monitoring system of the building. If the heat pump is connected to the monitoring system, the operation of the heat pump could be improved by means of optimized gas cooler pressure control.
- If the DHW circulation system is shut-down during the summer the heating demand for circulation of DHW would be reduced
- If possible, the supply water temperature for the radiator circuit should be reduced. This would result in a lower return temperature to the CO_2 heat pump and higher COP.

4.8 Conclusion monitoring nZEB with non-residential use

Monitoring of nZEB in Annex 49 had also different non-residential application apart from office use, among these educational buildings with two schools and a kindergarden, commercial buildings with a supermarket and a hotel. Some of the projects are also quite particular projects, e. g. the 100-year-old retrofitted building to passive house of the Modbroen Kindergarden and Justvik Skole with and innovative CO_2-heat pump system with adapted space heating emissions system in order to optimally use the characteristic of the CO2-heat pumps.

Compared to the other buildings uses the general experience of these nZEB buildings is that there are larger deviations between the monitoring and the design values regarding the measured building energy consumption, which is partly significantly higher than the design values.

Heat pump performance is rather moderate in the range of seasonal performance factors of SPF = 3 despite ground-source heat pumps with low supply temperature. Moreover, also linked to the moderate performance of the heat pump, respective optimisation potentials could be identified, so it can be expected that a further performance increase in the future should be possible.

All the applications monitored are rather newer applications for heat pumps, so there may have been a lack of experience, which may explain the lower average performance values. However, also with moderate performance factors in the range of 3 can yield significant energy savings compared to alternatives and all systems show optimisation potentials.

The seasonal performance can also be much higher which is shown in the results of the Willibald Gluck secondary school. Despite a high seasonal performance factor in the range of 5, the planned energy plus balance was not achieved. In this project, also interesting experience with new heat sources like the agrothermal field have been gained.

5 Monitoring results of neighbourhoods

In this chapter monitoring results of groups of buildings connected by thermal grids are considered. Thereby, the step from balancing each single building to a group of buildings is made, which is a step to future consideration of zero energy/emission neighbourhoods or positive energy districts. The extension of the system boundary to multiple buildings can have advantages regarding load balancing among the buildings in case that different load profiles of the different building uses, e.g. residential and office are combined which may offer better conditions both for on-site electricity self-consumption as well as for the recovery of waste heat.

However, the extension of the system boundary to neighbourhoods is also a quite new topic and therefore, also in this case the zero energy balance and performance characterisation of the applied system concepts is one of the main evaluations of the monitoring. Thereby, also synergies by the consideration of a group of buildings as well as the evaluation of different thermal grid concepts and load management options by the connection of buildings are investigated. In particular the monitoring evaluation comprises the following particular aspects:

- Optimisation of self-consumption and grid supportive operation by advanced control and storage application
- Integration of multiple heat source for low and high temperature grids
- Heat export between buildings
- Use of sewer as heat source and sink for the heating and cooling of office buildings
- Technical options and economic feasibility for nearly/net Zero Energy neighbourhoods

5.1 Overview

In Herzo Base project, Herzogenaurach, Germany 8 terraced single family houses of a total energy reference area of 1,200 m^2 are connected by the heating grid to two central capacity-controlled ground source heat pumps of 17 kW$_{th}$ each connected to 7 boreholes of 100 m each. The buildings are designed for plus energy and have a high performance building envelope with U-values in the range of 0.13–0.18 W/(m^{2}K) for outer walls, roof and basement and 0.7-0.8 for the triple glazed windows, leading to a calculated space heating demand of 9.6 kWh/(m^{2}a), which is also supported by the mechanical ventilation of max. air flow rate of 1760 m^3/h and a heat recovery of 86%. To reach a plus balance a 88 kW$_p$ solar PV-system is integrated on the roof of the buildings. The DHW is produced decentrally in the houses using the return of the heating systems as heat source for the 2 kW DHW booster heat pumps installed in the 200 l DHW storages. As also an optimised self-consumption by storage and advanced control is a topic to be investigated in the project, a thermally storage cascade of 2,800 l and an electric battery storage of 40 kWh are integrated at the two central heat pumps.

The **residential building "D12"** is a block of 7 buildings with 4-6 storeys each, commercial use on the ground-floor with 8 shops on 900 m² and 213 flats on the upper levels. The gross (conditioned) floor area is about 20,600 (19,080) m² and the buildings are integrated in the **Smart City Demonstration project Aspern, Vienna**. The buildings are supplied with 7 heat pumps, which are connected to the different users by a low temperature at 35 °C and high temperature at 65 °C heating grid. The heat pumps are connected to different heat source, which comprise 4 groudn water heat pumps of 144 kW$_{th}$ (W10/W55), 2 ground-source heat pumps of 65 kW$_{th}$ (B5/W40) and a 58 kW$_{th}$ (A5/W60) exhaust air from the underground parking. Moreover, 90 kW$_{th}$ are contributed by solar thermal and 60 kW$_{th}$ by PV/T collectors, which generate 16 kW$_{p,el.}$, which is added by a 20 kW$_{p,el.}$ solar PV. The main focus of the monitoring is the energy balance and the integration and interaction of the different heat sources.

The group of the 5 **office buildings at Otto-Nielsens Vei12E in Trondheim, Norway** was completed in June 2017 as an extension of 9,100 m² of several other buildings, Otto Nielsens vei 12 A-D, completed in 1990 and 2000. The new building is designed and constructed according to the Norwegian passive house standard NS 3701 (2012) and certified as Breeam-Nor "Excellent". The tenant is Nordic Semiconductor (https://www.nordicsemi.com/), a Norwegian company that is world-leading in advanced electronics, including low-energy Bluetooth technology. The company has large server installations as well as testing facilities that require cooling.

5.2 HerzoBase– Herzogenaurach, DE

5.2.1 Introduction/outline

The terraced houses are located in Herzogenaurach in the new district Herzo Base and built in 2017. The total energy reference area is 1,200 m². Each terraced house consists of three floors and an unheated cellar. The building is integrated in a suburban surrounding characterized by residential buildings. In the planning phase, a plus energy balance has been envisaged, and henceforth the building is equipped with a large photovoltaic (PV)-system, which is integrated on the roof, orientated to the east and west. Figure 152 shows a view of the terraced houses.

Figure 152: View of the Herzo Base - energy storage terraced houses

The idea of small neighbourhoods creating an energy community and share energy systems enables higher potential for increase the PV self-consumption. Furthermore, synergies between different electrical loads lead to an even electrical profile and reduces electrical load peaks.
The objectives of the monitoring were thus

- Comparison of the real operating data with planning data
- Approval of the detailed overall energy balance regarding the plus energy balance
- Test and evaluation of control strategies for increasing PV self-consumption and efficiency

5.2.2 Concept building envelope

The concept of the building planers were the creation of a highly insulated building envelope in order to minimize the heating energy as well as use and evaluate insulating material, which is recyclable. In this building the highly insulating material CALOSTAT is used in 4 of the 8 terraced houses.
The architecture of the building is based on simplicity and efficiency of the building envelope, so that the fraction of envelope area to volume is low and the thermal energy demand is as little as possible. On the other hand, the saddle roof opens up wide areas to install PV modules and produce as much energy as possible.
The design and material of the outer wall differs for each terraced house. Different insulating materials, Perlite and CALOSTAT, is used and analysed. Thus, the compact thermal building envelope reaches U-values of the outer wall from 0.18 until 0.13 W/(m^{2}K) respectively, which corresponds nearly to ultra-low energy houses or passive house. The windows were also planned better than the standard requirements with an U-value of the windows of U_g = 0.7 and 0.8 W/(m^{2}K). All windows have outer sun shield for the summerly heat protection.

5.2.3 Concept building technology system

The energy concept is orientated to increase energy efficiency, reduce load peaks and increase PV self-consumption. The terraced houses share a central heat pump system with a two buffer storage tanks, a PV plant on the roof and a battery which is installed in a shared installation room in the cellar of the building.

Domestic hot water (DHW) production is decentralized in each building. The advantage of this energy system is to make use of temporal different energy consumption through different user behaviour that leads to a reduction of electrical load peaks and a higher PV self-consumption. Beside the energy advantages, the share of the energy system enables to reduce investment and operating costs for each terraced house.

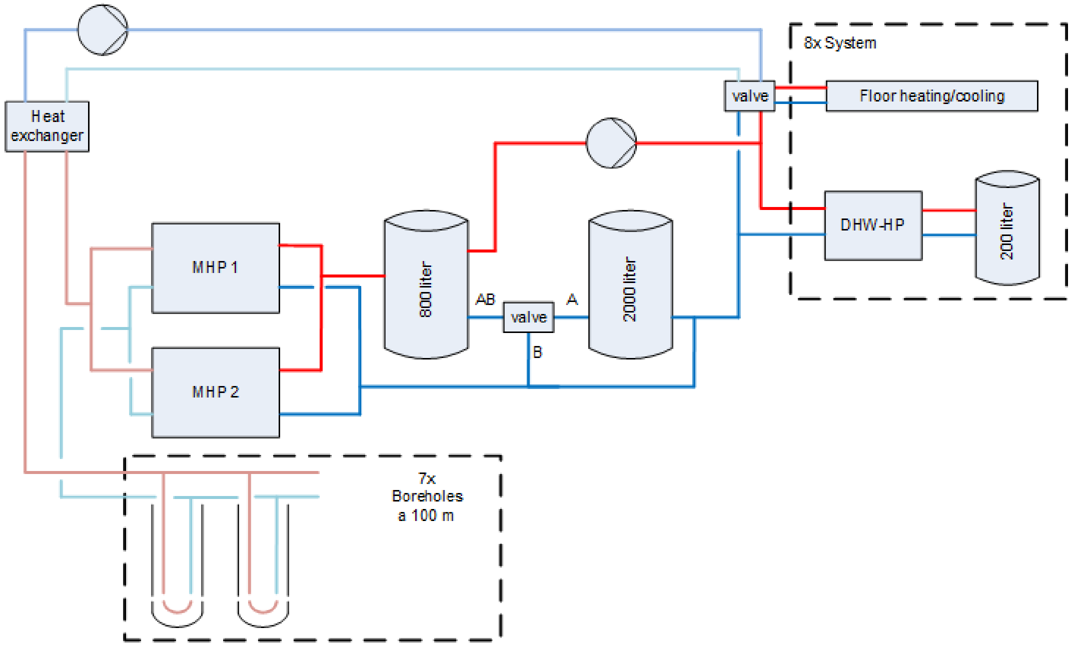


Figure 153: Building technology of the Herzo Base - houses with ground-coupled heat pump and DHW-HPs

The two modulating heat pumps (MHP) are coupled to 7 boreholes with a depth of each 100 m, which provides an efficient MHP operation, but is also integrated in the cooling concept. Beside the buffer storage of 800 litres an additional surplus buffer storage of 2000 litres is installed in order to charge during PV production (Power to heat). An increase of the coefficient of performance (COP) is reached by the MHPs providing a low temperature level of 35 °C as well as preferred part load operation by parallel installation. Part load operation also contributes to reduce the maximal electrical load peak.

The supply of domestic hot water is decentralized in each terraced house via a DHW-HP and a 200 litre water storage unit. As the DHW volume is small, the water will be renewed daily and high temperature levels in the storage units are not necessary. The risk of a legionella contamination in the DHW system is prevented. Regarding the advantages of energy efficiency, the water-water-HPs use the thermal buffer storage cascade as a heat source. The higher source temperature increases the Seasonal Performance Factor (SPF) of the DHW system. The low electrical power consumption of each DHW-HP contributes to a reduction of electrical load peaks as the temporal loading process is varying due to different user behaviour.

All 8 terraced houses equipped with floor heating. The high insulated building enables to provide low supply temperatures of 27 °C to 32 °C depending on the outdoor temperature. In summer, cooling is provided by the boreholes and is also realized by the floor. In addition, 4 terraced houses are equipped with ceiling heating/cooling. Both systems are used in defined periods separately in order to evaluate the thermal comfort. Therefore, actual and set temperature in each room as well as moisture in each floor is measured. These measurements as well as a survey of the dwellers is used for the evaluation of both heating/cooling systems.

5.2.4 Control strategies

The targeted modulation of the MHPs as well as the targeted operation during PV production are focused. The full capacity of the two buffer storages should be used during PV production by charging the second storage. The main target of the DHW production is to adapt to the PV power in a row during PV production as well as increase the DHW storage capacity due to increase the temperature level. The high number of storages (thermal, DHW and electrical storage) enables to store the PV surplus.

For exploiting the full potential of PV self-consumption, smart controls for MHPs are needed. The PV optimized control (PVC), aiming an increase of PV self-consumption and a reduction of grid consumption, has the function of a rule based control. First, as there is a surplus of PV power after fulfilling the electricity needs of the household, the main focus of the PVC is on the adaption of the compressor speed of the MHPs to PV surplus power. During grid consumption, the MHPs operate in part load because of the higher efficiency. Second, during surplus PV production the DHW-HPs can be switched-on in a row for using the available amount of PV surplus and during grid consumption the DHW-HPs can be switched-on temporally shifted to avoid electrical load peaks. If there is still PV surplus left after the heat pumps, the battery is charged. The PVC offers an approach to control heat pumps in order to increase the PV self-consumption.
Another control strategy, which is developed and tested for the energy system, is a model predictive control (MPC). On basis of weather and load prediction, the model predictive control creates an operation plan for each heat pump and the battery. In this case, the target and thus, the operation depends on the defined cost function.

5.2.5 Monitoring concept

All relevant data of the energy system for creating energy balances are registered. Temperature and energy consumption is measured before and after every energy component and storage unit. As well, set and actual room temperatures and moisture in each floor is measured. The monitoring concept with balance boundaries are depicted in Figure 154.
The building has been operated since 2018 and continuously measured in the operation. The evaluation of the monitoring data refers to the annual measurement period of April 1, 2018 to March 31, 2019.

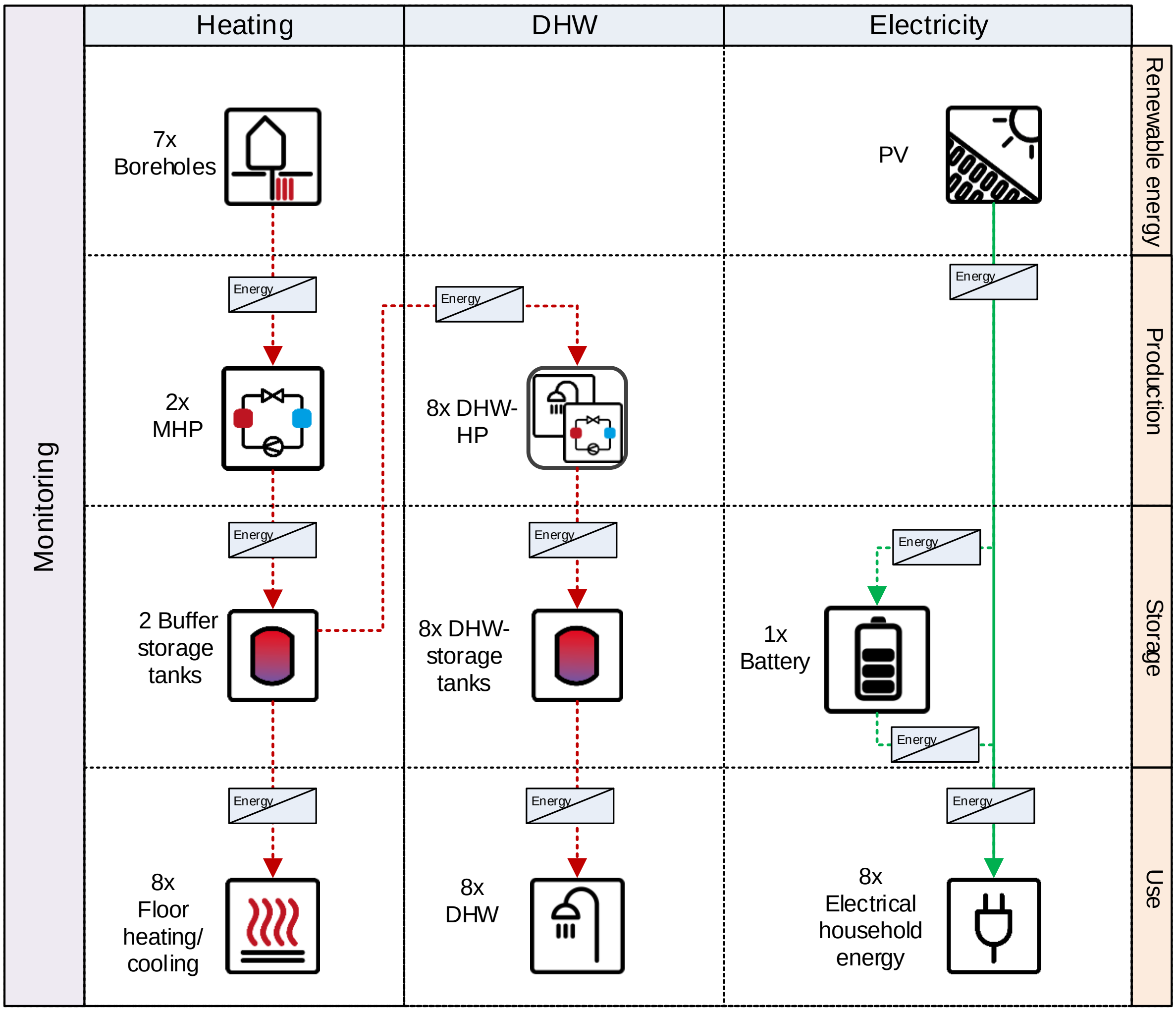


Figure 154: Installed measurement sensors and measurement concept with balance boundary of Herzo Base

5.2.6 Monitoring results

In the following the different results for the energy consumption and energy production are discussed. The monitored period is from 01. April 2018 until 31. March 2019. Figure 155 shows an overview of the thermal and electric energy consumption. It becomes clear that space heating energy makes up more than half of the thermal total energy consumption. Regarding the electrical consumption, the main part is household electricity. However, all heat pumps, two MHPs and eight DHW-HPs, nearly reach the same value.

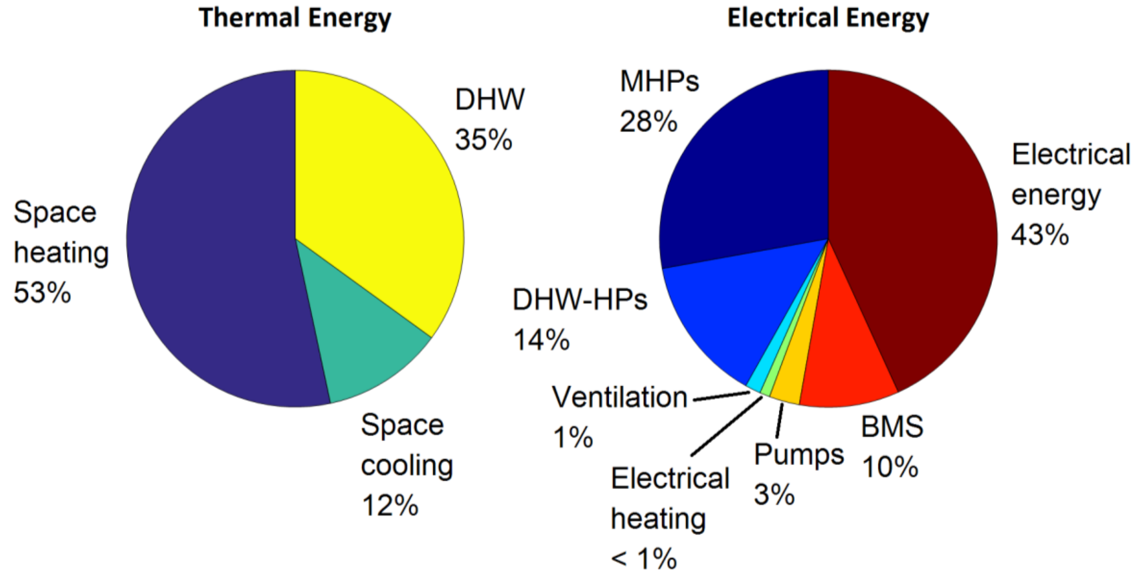


Figure 155: Shares of the thermal and electric energy in Herzo Base

As main component of the energy system, the MHPs are in the focus of the efficiency assessment. Regarding the overall amount of heat including the use of the ground source by free-cooling the MHPs deliver an energy amount of 9,900 kWh. The boreholes are designed only for delivering the heat source to provide heating and heat source for DHW. The positive effect of heating up the soil during free-cooling is beneficial for the efficiency of the MHPs. The MHPs reach good overall seasonal performance factor of all operation modes is 5.6.

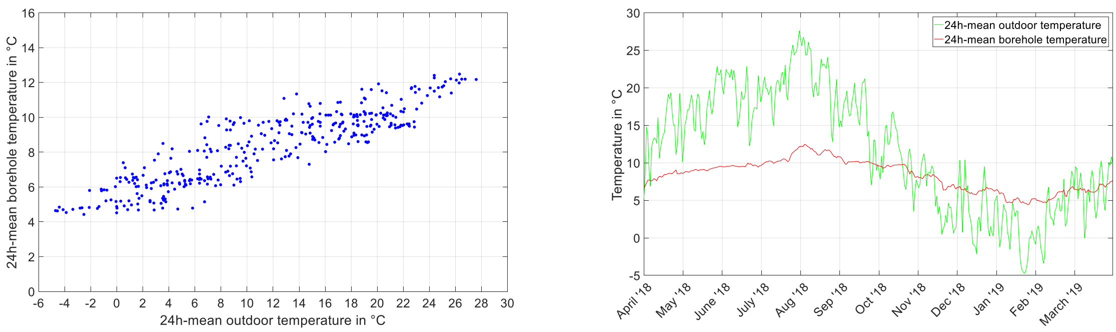


Figure 156: Annual evolution of 24-h-average values of the source temperature in 100 m depth in dependency of outdoor temperature (left) and annual curve of 24-h-average values of the source and outdoor temperature (right)

The good seasonal performance factor depends on the ground source temperature. The borehole temperature is measured by temperature sensors which are fixed next to the pipe. Thus, the temperature sensors are in the backfilling material between the pipe and the soil. Figure 156 shows the 24h-mean borehole temperature dependent on the 24h-mean outdoor temperature (left) and the course of the 24h-mean borehole temperature dependent on the 24h-mean outdoor temperature from April 2018 until March 2019. In wintertime, the 24-hour-averaged values of the borehole temperature are only slightly below 5 °C, which guarantees a good source temperature. The maximum 1h (24h)-mean heat extraction power is around 49 (28) W/m, which corresponds to the recommended thermal power extraction of 35 – 50 W/m for the regional soil (sand, clay) (VDI 4640).

Also at maximum supply temperatures of 35 °C or rather 40 °C during PV production in the space heating storage, of which the heating and source (for DHW) circuits with design supply/return temperatures of 27 °C/23 °C are supplied, the favourable source temperatures lead to high performance values of the heat.

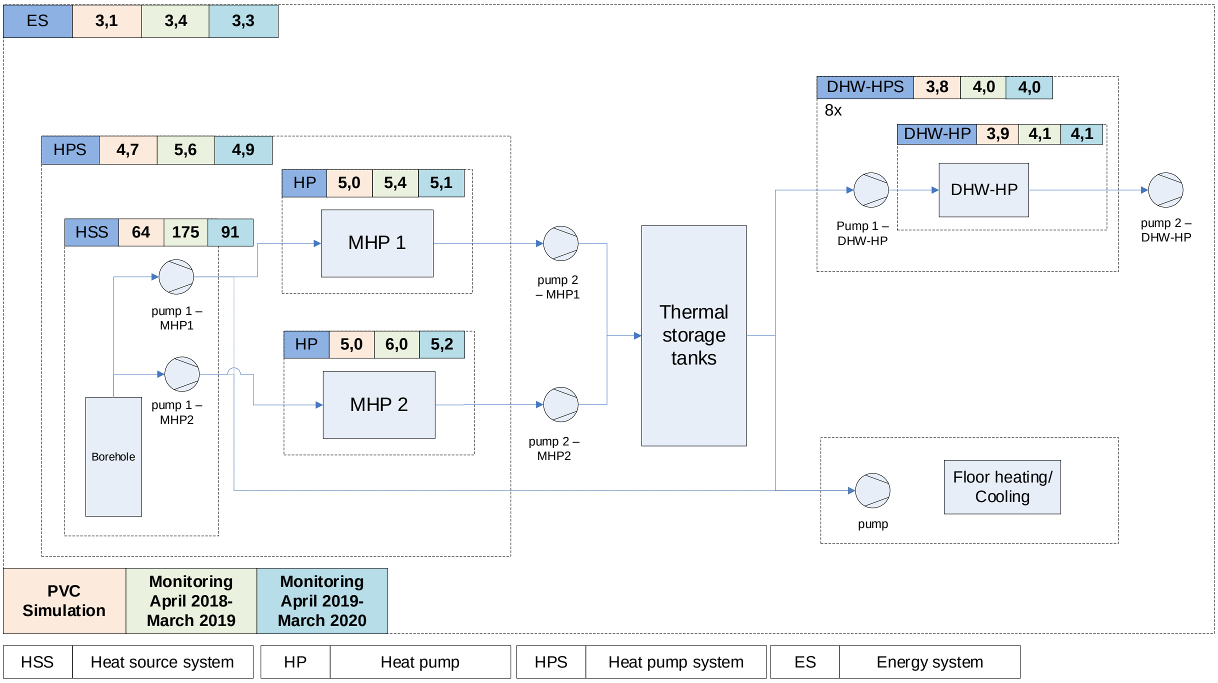


Figure 157: SPF for different energy balances

The seasonal performance factors are separated according the different energy balances (see Figure 157), the MHPS have a SPF of 5.4 and 6.0, and the HPS, including pumps for heat source energy, has a SPF of 5.6. The very good values are influenced by the operation in summer when the storage tanks are charged to low temperature levels of 25 °C and 27 °C and the evaporator temperatures are higher due to the heat exchanger for free cooling. The evaporator inlet temperatures are between 17 °C and 22 °C during summer. Mainly one MHP was in heating mode and has a very high SPF while the other was in free cooling mode and has a good but lower SPF. The DHW-HPs have a SPF of 4.1 and 4.0, including pumps for heat source energy. The SPF of the energy system is 3.4, which is composed of a SPF of 4.6 for space heating and 2.5 for DHW. Moreover, Figure 157 shows the results for the PVC simulation (orange) and the second monitoring period from April 2019 until March 2020 (cyan). For the energy production side, the solar PV-system has an annual energy of 76.9 kWh_{el}. Thereby, the solar PV-system produces more than the total electricity consumption in the annual balance. Figure 159 shows a comparison of the monthly consumption of the total electrical consumption and the solar PV production.

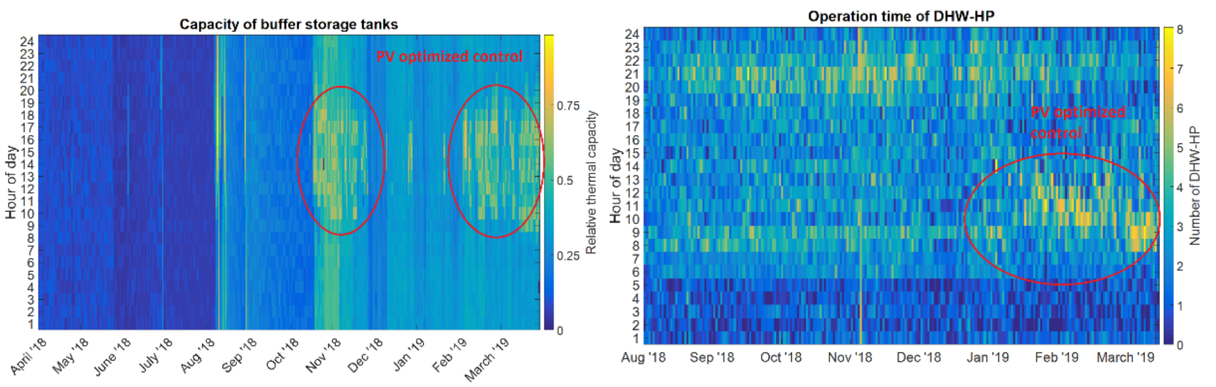


Figure 158: Influence of PV optimized control on relative thermal capacity of buffer storage tanks (left) and on operation times of DHW-HPs (right)

Figure 159 shows the well-known picture of a surplus in summer and a deficit in wintertime. Over the annual period about 38% of the produced PV electricity are used on-site, and 64% are fed into the grid. The commissioning of PV optimized control for the MHPs was in October 2018 and for the DHW-HPs in January 2019. Figure 158 shows the relative thermal capacity of the 2 buffer storage tanks (left) as well as the number of the DHW-HP in operation (right) dependent on the hour of day and day of month. During PV production in winter, the relative thermal capacity is higher between 9 am and 6 pm. It is also visible that in December 2018 and January 2019 the buffer storage tanks was not charged to its maximum as there was hardly any PV production. The monitoring of the DHW-HPS in the period August 2018 until March 2019 shows that the operation time of the DHW-HP moved from 8 am to 10 pm in February 2019 as the PV optimized control was activated. It is also visible that in the morning the number of DHW-HPs in parallel operation is higher and in the evening the number of DHW-HPs in parallel operation reduced.

5.2.7 Seasonal behaviour and self-consumption of produced PV electricity

Typical PV production in Germany is characterized by high production in summer and low production in winter, and in opposite of the electrical consumption. The PV self-consumption is expressed by the supply cover factor (SCF), which relates the PV electricity consumed on-site to the total PV-production, and self-sufficiency expressed by the load cover factor (LCF), which relates the PV electricity consumed on-site to the total building electricity consumption.
Figure 159 shows the load cover factor and supply cover factor, which course is typical for a plus energy building. In wintertime, the PV production is low, so the supply cover factor rises, since a high fraction of the PV production can be consumed on-site. The load cover factor or self-sufficiency, however, is low, since only a small fraction of the total consumption can be covered by on-site PV electricity. On contrary, in summertime there is a high PV surplus, so the load cover factor rises and almost the entire electricity consumption can be covered by PV, but the supply cover factor is low, since only a fraction of the PV production can be consumed on-site.
The annual value of the on-site PV consumption is 27.9 MWh (including direct PV and battery) and thereby about 32% of the total annual yield of 87.1 MWh/a. The supply cover factor and load cover factor sum up to 32% and 61%, respectively, in the annual balance.

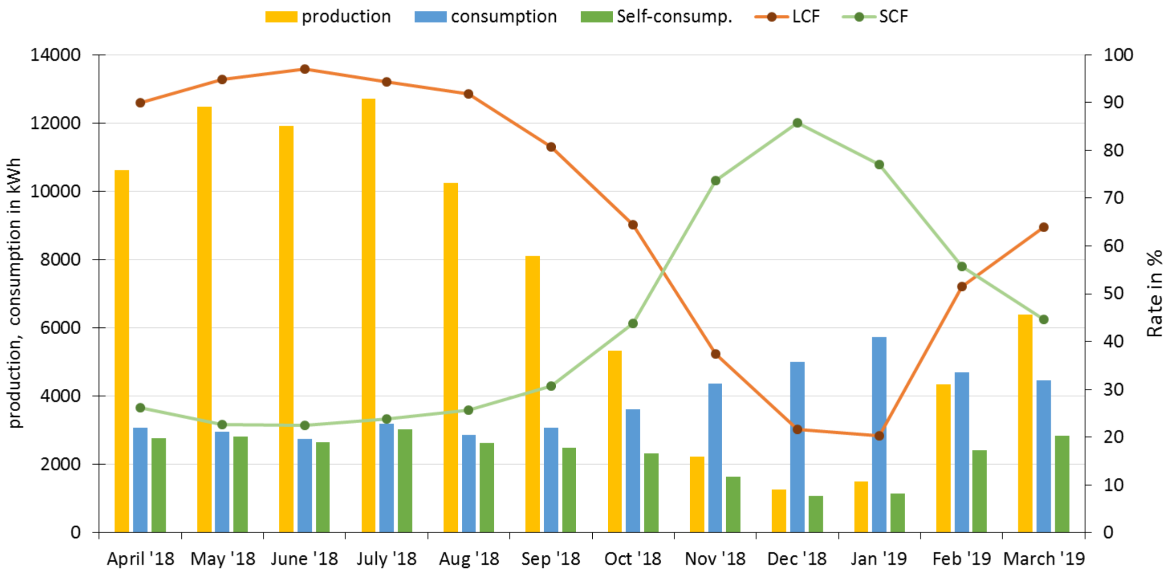


Figure 159: Monthly PV-production, total electrical consumption and self-consumption as well as load- and supply cover factor on the basis of 15-min monitoring values

For all operation modes and building services the total thermal energy for space heating and DHW of 66,851 kWh_{th}/a is supplied. Figure 160 contrasts the total thermal energy and the single fractions of the production of the thermal energy supply.

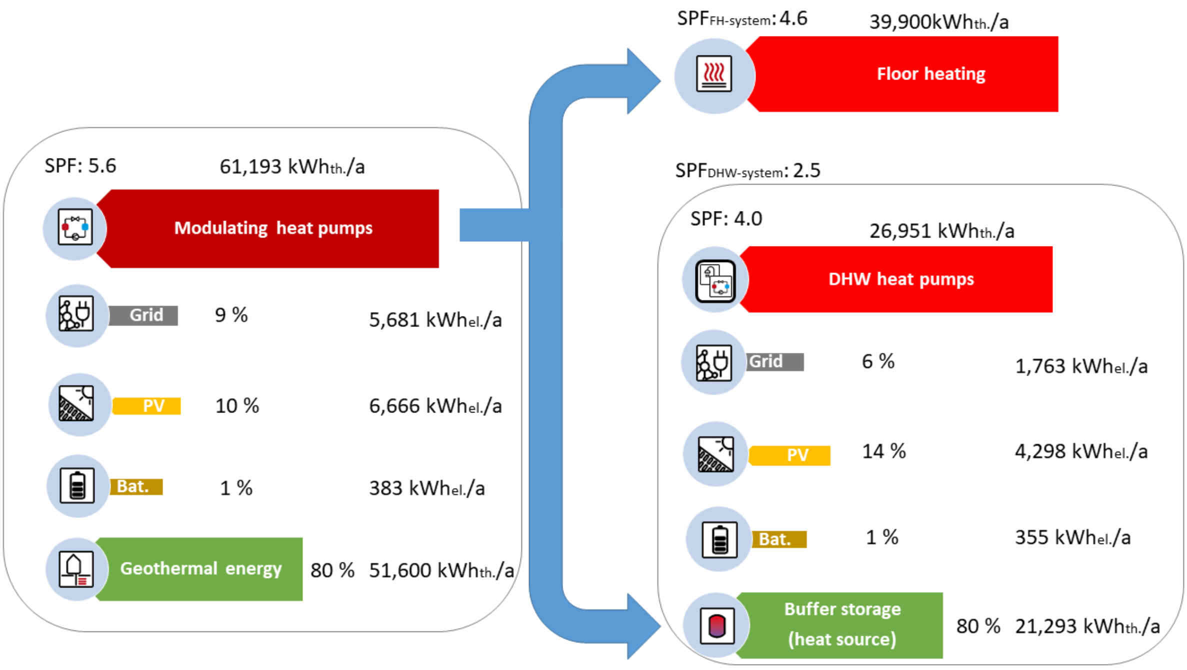


Figure 160: Comparison of thermal energy and renewable energy for the balance boundary building technology (based on monthly balance)

Regarding the MHP system, with 80% or 51,600 kWh_{th}/a the major part of the space heating and providing the heat source for DHW-HPs stems from the ground. Balancing the electrical consumption on a monthly basis, 9% stems from the public grid, 10% from PV and 1% from battery. Regarding the DHW-HP system, with 80% or 21,293 kWh_{th}/a the major part of providing DHW stems from the buffer storage. Balancing the electrical consumption on a monthly basis, 6% stems from the public grid, 14% from PV and 1% from the battery.

5.2.8 Comparison with design data

Table 38 shows a comparison of the electrical monitoring data with the design data from the simulation in TRNSYS.

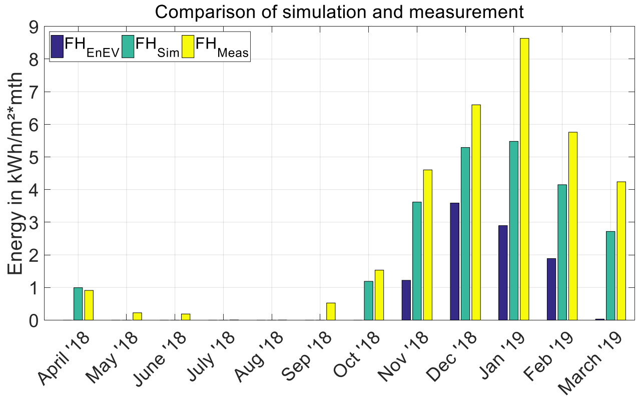
Table 38: Comparison of the design data with the results of the Monitoring

	Calculation (simulation)	Monitoring	Deviation
Space heating + DHW	12.3 $kWh_{el.}/(m^2a)$	16.8 $kWh_{el.}/(m^2a)$	+ 37%
Ventilation	1.2 $kWh_{el.}/(m^2a)$	0.6 $kWh_{el.}/(m^2a)$	- 50%
Electricity consumption	27.8 $kWh_{el.}/(m^2a)$	16.6 $kWh_{el.}/(m^2a)$	- 40%
Electricity production PV	51.4 $kWh_{el.}/(m^2a)$	64.1 $kWh_{el.}/(m^2a)$	+ 25%
SPF of energy system	3.1	3.4	+ 10%

In comparison to the design data the monitoring data have quite high deviations. The electricity consumption for space heating and DHW is up to 37% higher than calculated. The ventilation value of monitored 0.6 kWh/(m²a) and calculated 1.2 kWh/(m²a), which is a deviation of 50%. The total monitored value of the electricity use of 16.6 kWh/(m²a) including the building technology is also significantly lower than the estimated value in the simulation of 27.8 kWh/(m²a). In the simulation, an electrical consumption of 4,175 kWh/a for each terraced house was estimated. The PV yield delivered about 25% more electrical energy than calculated.

5.2.8.1 Heating energy demand/consumption

The heating energy demand was calculated by the German EnEV 2016 as well as by a building simulation in the software TRNSYS 17. The results from the calculation and the simulation are compared to the heating energy consumption from April 2018 until March 2019. Simulation as well as monitoring results differ significantly from the results of the EnEV 2016. This is mainly an effect of the calculation method of the EnEV 2016.



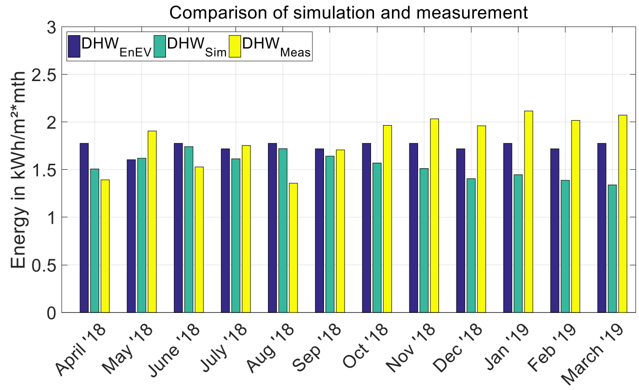
Method	Energy demand/consumption	Relative demand to EnEV 2016
EnEV 2016	9.6 kWh/m²a	
Simulation	23.4 kWh/m²a	144%
Measurement	33.2 kWh/m²a	246%

Figure 161: Comparison of the design data with the results of the monitoring and EnEV 2016 for the space heating demand in monthly balance (right) and in yearly balance (left)

But also, the simulation results are 42% lower than the monitoring data. Mainly, different user behaviour by setting higher room set temperatures and using windows airing are identified, but also the decentralized ventilation causes higher thermal losses than in the simulation. As well, the drying process in the first year influences the heating demand.

5.2.8.2 DHW energy demand/consumption

The German EnEV 2016 calculates 12.5 kWh/(m²a) for DHW consumption. The area is related to a calculation method of the EnEV 2016. In this comparison the area is related to net area of the terraced houses. The DHW consumption in the simulation depends on a DHW profile, created in the tool "DHW calc" by the University of Kassel. The DHW profile basis of a daily load of 120 - 200 litres and different tapping times, varying for each house. Simulation as well as monitoring results correspond to the results of the EnEV 2016. But also, the simulation results are 16% lower than the monitoring data.



Method	Energy demand/consumption	Relative demand to EnEV 2016
EnEV 2016	20.9 kWh/m²a	
Simulation	18.5 kWh/m²a	-11%
Measurement	21.8 kWh/m²a	4%

Figure 162: Comparison of the design data with the results of the monitoring and EnEV 2016 for the DHW demand in monthly balance (right) and in yearly balance (left)

5.2.9 Comparison of two monitoring periods

The Herzo Base terraced houses are continued to be monitored until May 2022. The presented monitoring results are compared to the new 12-month monitoring period from 01. April 2019 until 31. March 2020. In general, the monitoring results in the two periods are quite similar. There are some differences between the supply cover factor and load cover factor as well as between SPF of the MHPs.

The PV yield in the second period is 85.2 MWh/a and is about 2.2% less compared to the first period. In general, the total electrical energy consumption increased by 6.9% to 48.9 MWh/a. This is mainly an effect of the addition of two electrical cars in the energy community. The annual value of the on-site PV consumption in the second period is 31.4 MWh (including direct PV and battery) and 12.5% higher. This also results in a higher supply cover factor of 37% and load cover factor of 65%, compared to the first period of 32% and 61% (see Figure 163). The main effect for the higher on-site PV consumption is the use of PVC over all 12 months.

In the first monitoring period, the PVC was active for about five months for the MHPs and for about 2 months for the DHW-HPs in the wintertime. The shares of the thermal and electric energy mainly differs from few percent points (1-3%), but the electrical energy is higher up to 5% because of the electrical cars.

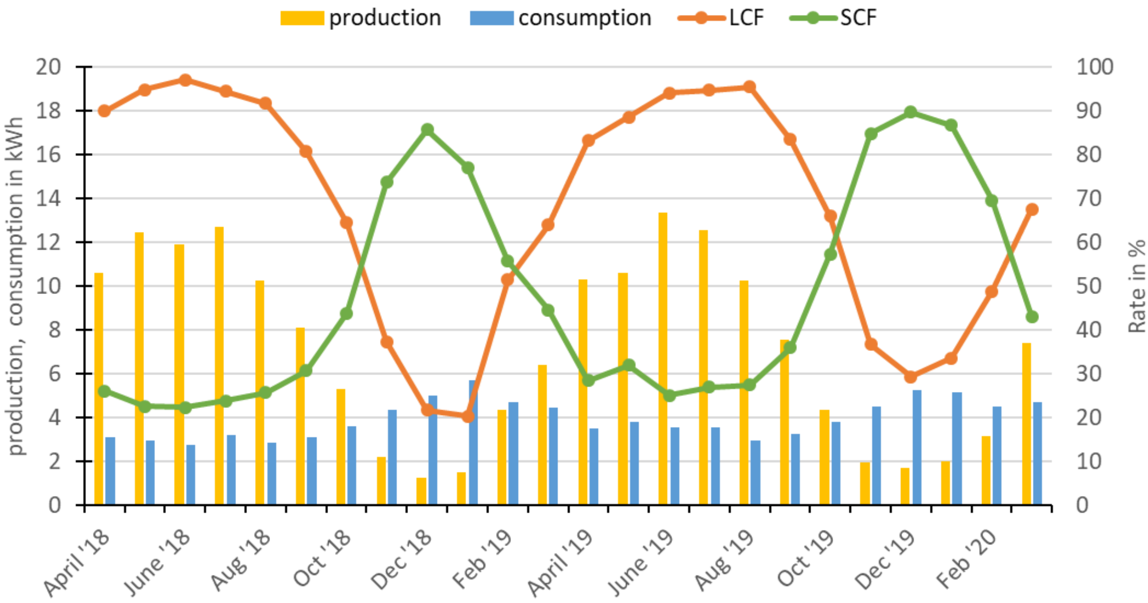


Figure 163: Monthly total electrical consumption as well as load- and supply cover factor on the basis of 15-min monitoring values in comparison to two monitoring periods

SPF for the MHPs and the MHP system is different in the two monitoring periods (see Figure 164 right). In the second period, the SPF for the MHP is 5.2 and 5.1, and the SPF for the MHP system is 4.9. This is an effect of the full year PVC operation that leads to higher temperatures levels in the storage tanks, especially in summer the temperatures are higher between 31 °C and 35 °C. In the first monitoring period the temperatures levels in the storage tanks were between 25 °C and 27 °C.
Figure 164 left shows that the heating energy consumption decreased in the second period by 10.2% from 33.2 kWh/m²a to 29.8 kWh/m²a. This is still 6.4 kWh/m²a higher than the simulation results, but in praxis, the room set temperatures are higher and windows airing is used.

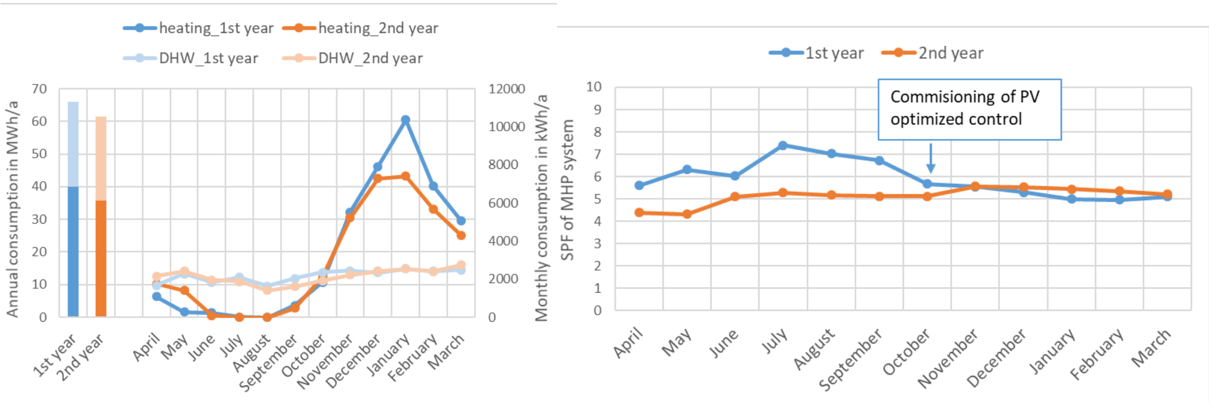


Figure 164: Annual and monthly heat consumption in the two years (left) and monthly SPF of the MHP system in the two years (right)

5.2.10 Discussion and conclusion of the monitoring results

The Herzo Base energy storing terraced houses in Herzogenaurach, Germany offer 8 terraced houses for residential use in a suburban area. Creating an energy community, a shared energy systems of geothermal heat pumps, PV and battery is installed. In combination with highly insulating materials in the building envelope, the building reaches a positive energy balance in an annual observation period.

The geothermal heat pumps have a very good overall balance, in which 91 % (on monthly balance) of the annually used thermal energy are covered by the use of the ground, PV energy production or battery unload energy.
The decentralized DHW-HPs even reach a value of 94 % (on monthly balance) for delivering the annually used DHW energy by the use of the buffer storage tanks (heat source), PV energy production or battery unload energy.
By the detailed monitoring the operation and control strategies of the building technology and the energy demand of the building could be approved. The thermal energy consumption is higher than calculated in the national tool EnEV 2016 and the building simulation in TRNSYS 17. Mainly, different user behaviour by setting higher room set temperatures and using windows airing are identified, but also the decentralized ventilation causes higher thermal losses than in the simulation. As well, the drying process in the first year influences the heating demand. The second monitoring period show a reduction of the thermal energy consumption by 10%, but still the value is 27% higher than the simulation result.
In the planning phase, a plus energy balance has been envisaged, and the monitoring demonstrates a clear positive energy balance on an annual observation period. The PV production was 87.1 MWh and 42% higher than the total energy consumption in the terraced houses. According to the monitoring results the PV system can even be designed smaller for a positive energy balance. However, in the planning phase, the electrical household demand was estimated to be higher.
The targeted operation of the MHP compressor speed could not be implemented, because the manufacturer just offers the possibility to set the set temperature of the return flow. Thus, the internal control operates the compressor speed in order to reach the same temperature for actual and set temperature of the return flow. Under this conditions, two set temperatures were defined for grid/battery mode and PV mode.
Comparing to the simulation results, the SPF of the MHP is higher in real application. The internal control is already optimized to operate the compressor speed in the best operation point (high COP). The targeted operation lead to a lower SPF and is not supposed to be used in grid and battery mode. But nevertheless, the MHP system reach a high SPF of 5.6 and the DHW-HP system have an overall SPF of 4.0. Comparing two monitoring periods, the monitoring results shows that the PVC leads to lower SPF of the MHPs as temperature levels in the storage tanks are higher, especially in summer. The SPF of MHP system reduced from 5.6 in the first period to 4.9 in the second period. The DHW-HPs have slightly higher SPF comparing to the simulation results. This is the influence of higher source temperatures than in the simulation. In summer, the source was 25 °C and in winter, mainly 32 °C. In simulation, the temperatures was 20 °C in summer and 27 °C in winter. The PVC has hardly any influence on the SPF of the DHW-HPs as the boundary conditions were nearly the same in the two monitoring periods. In the first monitoring period without PVC, the set temperatures were mainly set by default to 55 °C and the source temperatures are minimal 27 °C. Nevertheless, the SPF of the energy system is quite low of 3.4/3.3. Thermal distribution losses is a certain problem in the energy system as the distribution pump is running all the time. The distribution pump is integrated in the building automation management and thus can be controlled. But as the communication to three boosters is missing due to user settings the distribution pump must be on all the time (in winter as well as in summer) to guarantee the function of the three missing boosters. In addition, circulation losses of DHW due to user settings also cause further losses which burden the system efficiency.
The results of two monitoring periods are quite similar. There are few differences between the supply cover factor and load cover factor. This is mainly an effect of the PVC, which was active for about five months for the MHPs and for about 2 months for the DHW-HPs in the wintertime. The second monitoring period, the supply cover factor is 37% and load cover factor is 65%, compared to the first period of 32% and 61%, respectively. As well, the PVC influences the SPF, because the storage tanks are charged up to 45 °C that lead to lower values of COP. In the second monitoring period, the SPF for MHP reduced from 5.4/6.0 down to 5.2/5.1, and the SPF for the MHP system reduced from 5.9 to 4.9.

5.3 Smart City Demo Aspern – Residential Building – D12 - Vienna, AT

5.3.1 Aspern Smart City Research GmbH & Co KG

Aspern Smart City Research GmbH & Co KG (ASCR) is a joint venture between a network operator, an international technology company, an energy generation and supply company, and the City of Vienna. The testbed Aspern Smart City Research, located in the urban development area "Seestadt Aspern" outside Vienna, focuses on energy management, smart buildings, smart grids, smart ICT and smart users.

Figure 165: Photos of the D12 building ((c) Hertha Hurnaus).

The residential building "D12" is a block of 7 buildings with 4-6 floors each, with commercial use on the ground-floor with 8 shops and 213 flats from the ground to the upper levels. The gross floor area is about 20,600 m² and the conditioned gross area is 19,080 m², where 900 m² are foreseen as non-residential area. Under the ground level two levels of underground car parking have been constructed whereas the exhaust air of this parking is used as the source for one of the 7 heat pumps. The flats are heated with floor heating allowing for rather low heating powers and temperatures. The domestic warm water is heated to 60 °C by fresh-water-modules which are supplied by the high-temperature (HT) ring, which is supplied by HT-heat pumps up to 70 °C.

Table 39: Building facts of Aspern Seestadt EBG D12 [OGNB]

Type of building	Multi-family - Residential & Commercial
Location	Vienna – Seestadt Aspern
Construction finished	2016
Architect	querkraft architekten zt GmbH gemeinsam mit Berger+Parkkinen
Number of Storeys / Use Unit	6 / 213
Conditioned gross (useful) area	19,080 m² (15,689 m²)
Heating demand (HWB)	15,6 kWh/($m^2_{gross\ area}$ a)
Primary Energy demand (PEB)	87,4 kWh/m² gross area a
CO2-Emission	13,9 kgCO_2/($m^2_{gross\ area}$ a)
Solar technology	solar thermal (90 kW_{th})+hybrid (60kW_{th}), PV (20 kW_p)+Hybrid (16 kW_{pel})
Storages	*Earth storage (40 MWh_{th}), hot water storages as backup for DHW*
Heating and domestic hot water	*Solar thermal collector system; Heat pump, renewable district heating*
Air-handling unit	*The central air-handling unit with heat recovery system*
Other innovation	*Designed to support demand response with a multitude of different*
Certificates	*ÖGNB*

The buildings' heating and domestic hot water system was specifically designed to support demand response with a multitude of different sources, namely thermal-, photovoltaic- and hybrid-solar collectors as well as seven heat pumps using ground water, waste air and shallow-surface geothermal heat storage. Hot water tanks are the short-term heat storage, while the long-term ground storage is loaded by excess solar thermal energy.

A dynamic-thermal simulation study was performed using TRNSYS to get an estimation for the demand response potential of the building. The model was further used to develop and test control strategies and also to verify the demand response potential once validated with monitored data. The buildings are in operation since March 2016.

5.3.2 Calculated energy demand in the planning/design

The building envelope is constructed in a high-quality design combined with a heat recovery ventilation system with a sensible efficiency of 80%. This resulted in a yearly heating energy demand of 15.29 kWh per m² gross area and year based on the calculations of Austrian regulations for the energy certificate (20 °C room temperature). The limit in the planning phase was 23.42 kWh/(m² a).

5.3.3 System for thermal energy supply and distribution

The implemented innovative energy supply system of the building complex is using several heat pump technologies combined with various sources (air, soil, groundwater, solar) and storage technologies – see Table 1.
The control strategy operates the heat pump system (or combinations of heat pumps) with the most efficient heat source (depending on the demand and the external boundary conditions) and loads the thermal storage system. The connection between those plant components of the heat supply systems and the heat consumers is realized with two loops for high temperature and low temperature supply correlating with the set-point temperatures for domestic hot water (DHW: 65°C), and room heating (RH: 40°C). Using a so called 'stratifier lance module' the solar heat can be fed into three different temperature level storages - high, middle, low - meaning that operating time and performance of the collector is maximized. A schematic overview of the used Heating, Ventilation and Air Conditioning (HVAC) components is shown in Figure 166.

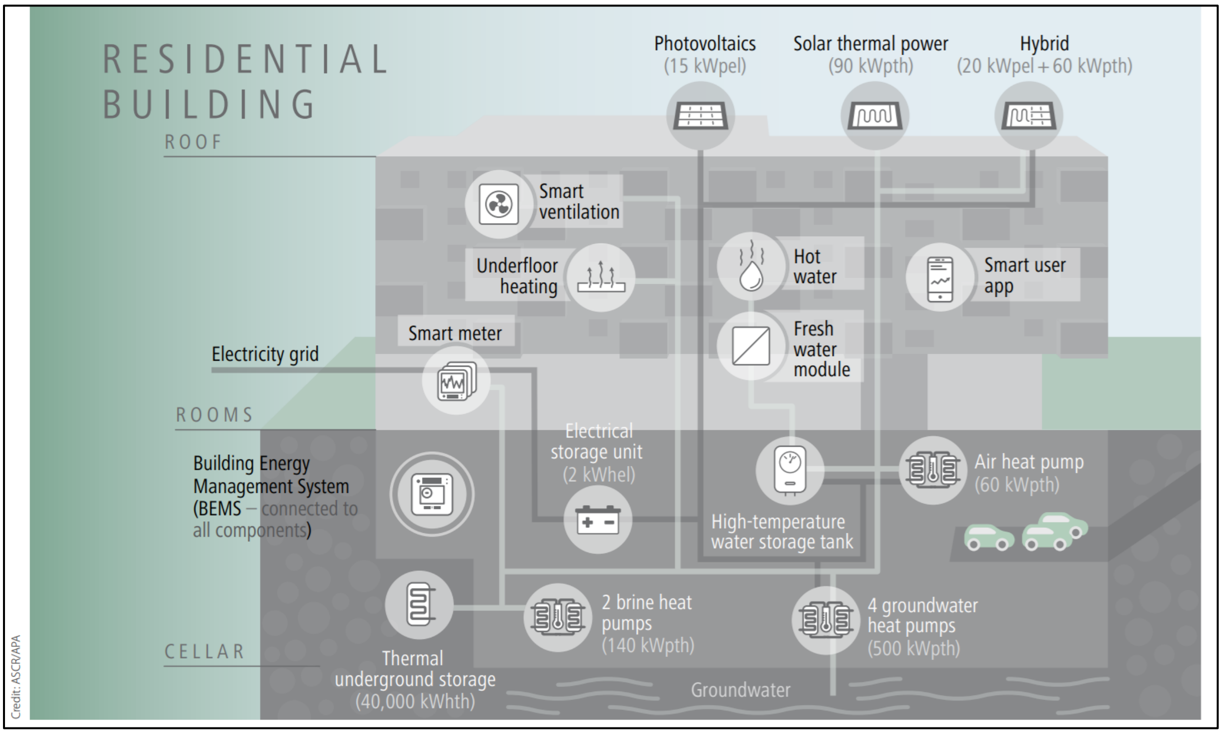


Figure 166: Schematic overview of the D12 building concept (Note: the low temperature storage tank is not shown).

The heat generation systems are located in 6 building service rooms, each with two buffer storages (6x2,000 l), each one for SH and DHW, connected by the two loops, see Figure 2.
The electrical energy demand of the HVAC system is foreseen to supplied by the PV panels, hybrid collectors and the battery storage and if not available, from the public electricity grid.
As heating delivery system, a floor heating system is installed. The floor heating system is connected to the low temperature water loop and consists of 228 heating circuits, 17 main

pumps circulate water to the ascending major distribution pipes with a total mass flow rate of 95 m^3/h. The domestic hot water production is provided by 5 freshwater modules connected to the high temperature loop. Each of these plate heat exchangers has a maximum heat transfer capacity of 315 kW$_{th}$. The building complex is as well connected to the local district heating network with a capacity of 1.5 MW$_{th}$.
The heat system is operated in a holistic approach and the required/delivered energy is exchanged homogeneously over the hydraulic rings. However, the current water flow direction/ frequency of the changes of direction cannot be determined explicitly. There are basically two different operational modes depending on the pressure difference:

a) Two or more active components operate the water network: The pumps produce the required pressure to direct the water flow, the pumps supply heat to the heating circuit and load the buffer tanks.
b) No heat generators running: The thermal water tanks are discharged and supply heat to the heating circuit.

The total thermal power demand for the domestic hot water is 461 kW$_{th}$ (electrical power: 119 kW$_{el}$). The total heat power for room heating is calculated to 306 kW (electrical power is 66 kW$_{el}$). The energy performance data of the heat pumps are summarized in Table 40.

Table 40: The energy performance data of the heat pumps [ASCR]

Number and type of heat pump	Standard for design and development according to EN14511	Thermal power [kW$_{th}$]	Electric power [kW$_{el}$]	COPHP
2 ground sources	Cold 5°C / Hot 40°C	65.1	14.6	4.47
1 waste heat	Cold 5°C / Hot 60°C	57.8	19.3	3.00
2 ground water	Cold 10°C / Hot 55°C	144.1	40.4	3.57

5.3.4 Monitoring results

An extensive monitoring campaign on the energy system and room level was conducted to study mainly the load shifting potential and occupant behaviour. Figure 167 shows the monitoring concept of the heat generation and distribution system.

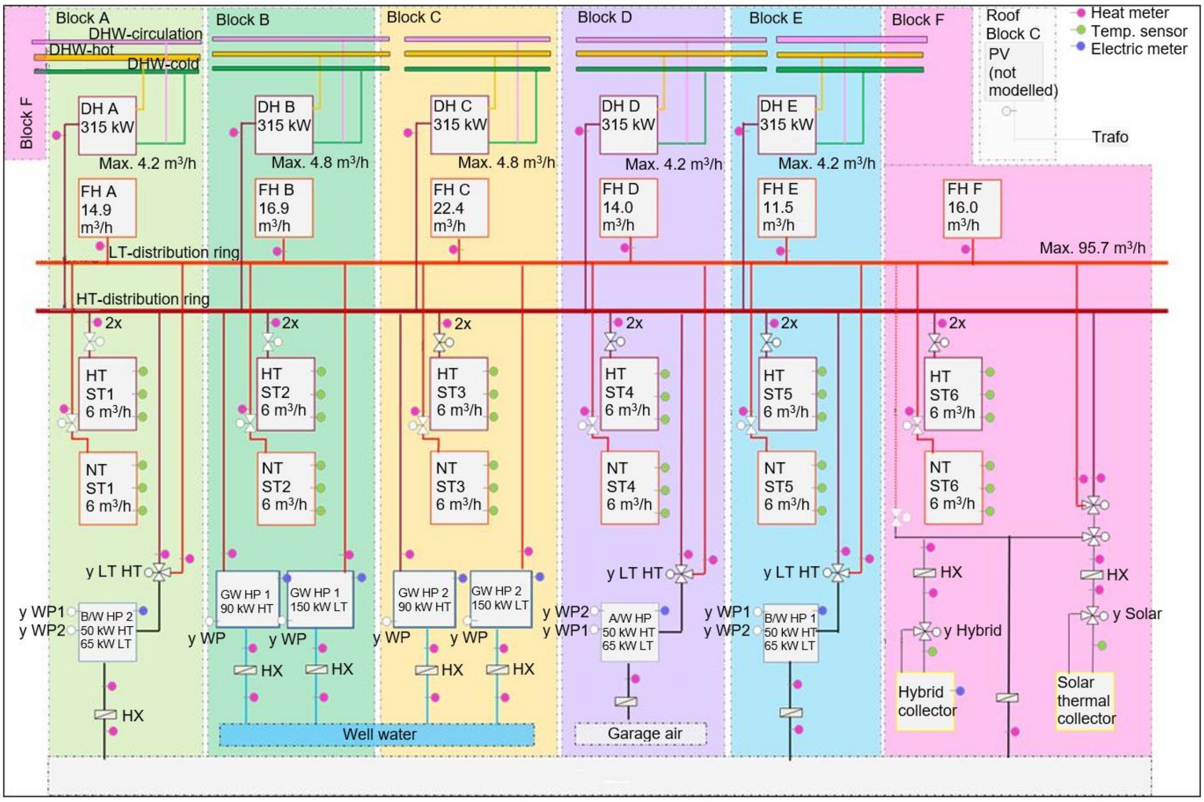


Figure 167: Monitoring concept (ASCR).

Recorded and visualized monitoring data have been used to validate and to calibrate simulation models (building and system), see Figure 170.
The measured delivered heating (measured on room level, i.e. without distribution losses) is accounted to 26.73 kWh/m^2 (conditioned area) and higher than the target value. The increased window ventilation (rather than using the heat recovery forced ventilation) lead to higher heating demand above the heating limit temperature ($T_{ambient}$ < 12 °C) and more occupied hours than planned.
Figure 168 shows the split of delivered heat between the different heat sources for the first year of operation. The ground-water heat pumps delivered 52% of the required heat, the solar thermal system includes heat for the regeneration of the geothermal storage.

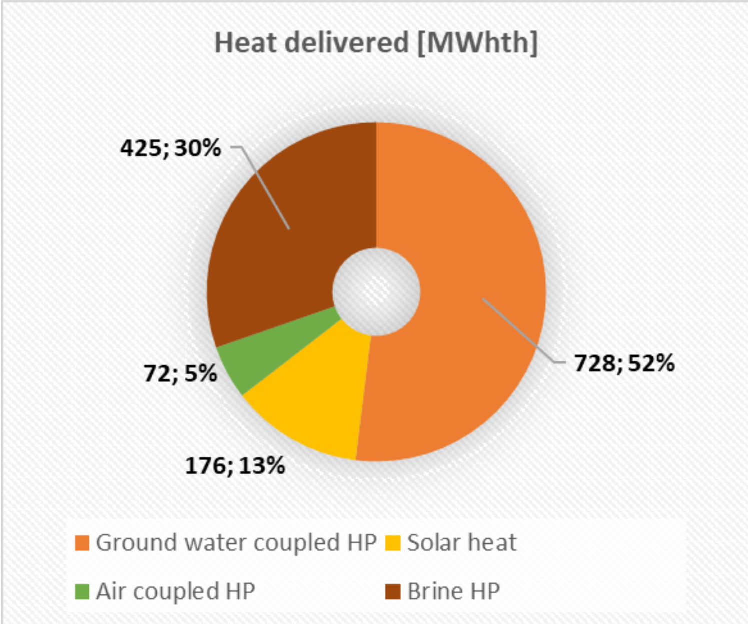


Figure 168: Share of heat generation between solar thermal, groundwater-, brine- and air- heat pump

Due to both a) operation of various heat delivering systems and b) feeding delivered heat to two distribution water networks (Low and High temperature level), insufficient circulations and erroneous flows appeared in the beginning. This malfunctioning could be resolved by using non-return flaps and shut-off valves. Initially, it was expected that the system would suffer from relatively high distribution losses due to the complex hydraulic scheme. In fact, it was observed that the thermal losses are in the normal range.
In order to check the operational performance of the heat delivering and distribution system on the low temperature level, modelling and simulation work were carried out.
Figure 169 display the instantaneous heat fluxes (simulated and measured) on the low temperature level of the observation period from 02.02.2017 00:00 till 04.02.2017 00:00. Displayed heat fluxes are a) delivered heat from all heat pumps on low temperature level, b) heat taken and fed to the water storages and c) heat transferred to the floor heating system. By comparing heat capacity provided by the LT heat pump system, simulated values are lower the measured numbers – see dark blue line of Figure 169. As long as the first heat pump is sufficient to cover the heating load, only this heat pump is operated, and the residual heat is taken from the storage tanks (red line). If the water storage tanks are discharged, the second heat pump started up and heat surpluses are used to recharge the storage tanks (green line). In case the hot water tanks are fully charged, the heat pumps are switched-off and the hot water tanks are discharged (red line). In the considered period, no heat generated by solar collector system was transferred into the LT circuit, neither in the results of the simulation nor in the recorded values of the measurement equipment.

[3] With a variation between 12 and 35 kWh/ m^2

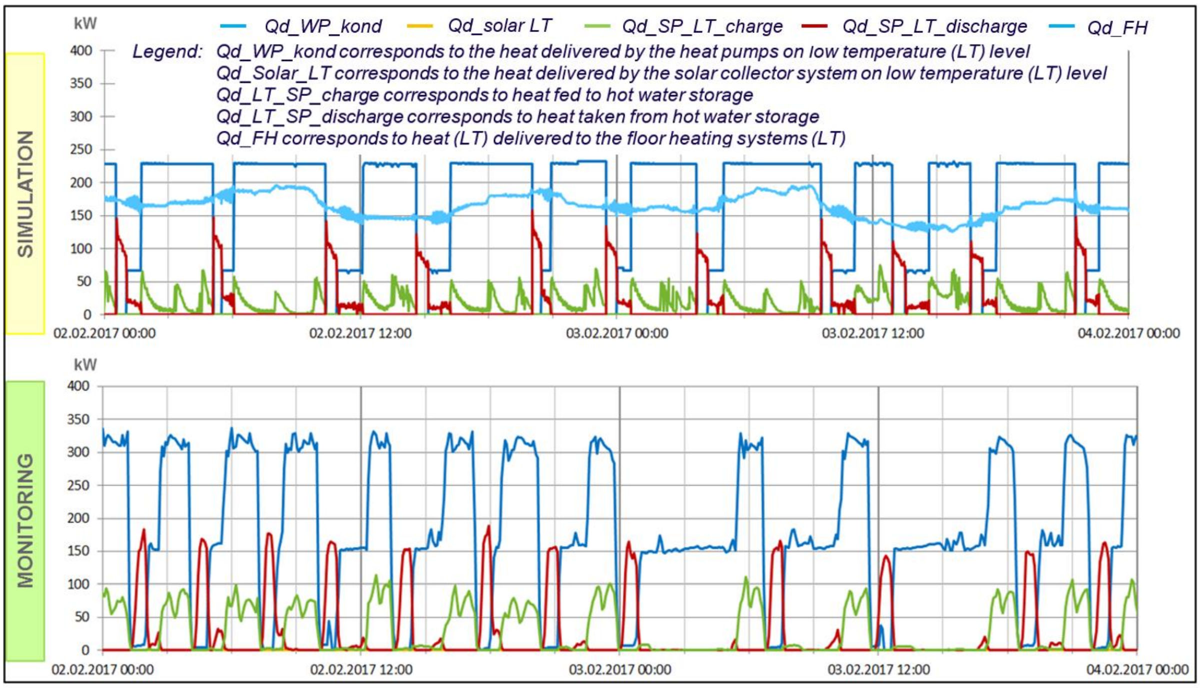


Figure 169: Comparison of simulation and monitoring data of heat delivered by heat pumps, as well as storage tank charging and discharging on the low temperature level, Observation period is from 02.02.2017 00:00 till 04.02.2017 00:00 (ASCR).

Energy performance data of the heat pump manufacturer for different flow and source temperatures were implemented in the heat pump models. Subsequently, the simulation results were compared with the monitoring data by taking the target parameter T_out_load. Figure 170 displays a table of relevant manufacturer data and a scatterplot of simulated and measured values of the parameter T_out_load. Based on the results of the scatterplot in Figure 170, it can be stated, that the defined heat pump model calculates the energy performance of the heat pump very well.

Vorlauf tVL (°C)	Wärmequelle Medium t1	(°C)	Q kW	P kW	COP
30	Brine (Sole)	-5	27,36	6,52	4,20
		-2	30,52	6,58	4,64
		0	32,89	6,64	4,95
		2	35,26	6,69	5,27
		5	39,31	6,80	5,78
	Groundwater (Wasser)	8	43,04	7,03	6,12
		10	45,34	7,07	6,41
		12	46,87	7,12	6,59
		15	48,52	7,16	6,78
35	Brine (Sole)	-5	26,77	7,29	3,67
		-2	29,83	7,36	4,05
		0	32,00	7,40	4,32
		2	34,37	7,44	4,62
		5	38,22	7,53	5,08
	Groundwater (Wasser)	8	41,68	7,76	5,37
		10	44,00	7,80	5,64
		12	45,57	7,82	5,83
		15	46,95	7,84	5,99
40	Brine (Sole)	-5	26,27	8,13	3,23
		-2	29,14	8,20	3,55
		0	31,21	8,24	3,79
		2	33,48	8,28	4,04
		5	37,14	8,37	4,44
	Groundwater (Wasser)	8	40,51	8,59	4,71
		10	42,66	8,64	4,94
		12	44,08	8,66	5,09
		15	45,55	8,64	5,27
		-5	25,78	9,04	2,85

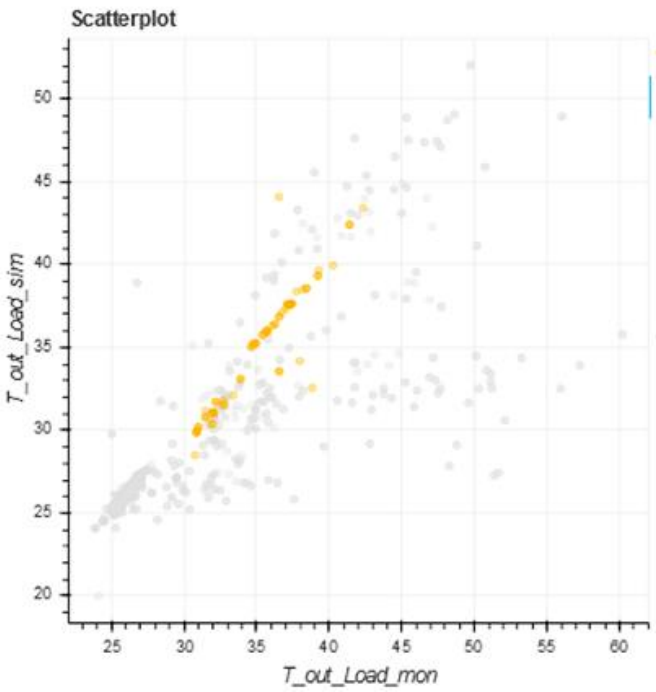


Figure 170: Scatterplot of the heat pumps sending temperature (monitoring vs. simulation) in part load operation (right) and manufacturers' performance data on the left.

5.3.5 Key Findings

- One central technical room rather than 6 would save costs. Enough space for such a large room should be planned.
- High thermal insulation of the water pipes to reduce thermal losses is important.
- Air-source heat pump (parking garage) could be used mainly during summer to provide high temperature heat, whereas ground-source heat pump mainly during winter (highest source temperature)
- The “multiple-heat source concept” of the overall energy system is approved to deliver a high redundancy and availability.
- The district heating network represents the thermal backup and guarantees high thermal comfort during heating season.
- Achieving high solar fraction and avoiding stagnation of the solar collectors, solar heat basically always charge/feed the earth storage or the high/low temperature loop. Legionella-risk is not an issue due to the use of freshwater stations.
- Hybrid solar collectors should be well designed and chosen to regenerate the geothermal storage.
- Pressure management for high and low temperature water circuit is recommended, but difficult to manage and very tight dampers/valves are needed.
- Complex control strategies provoke to overburden the service and facility management personal.

5.4 Otto Nielsens vei 12 - Trondheim, NO

Otto Nielsens vei 12E, which is a 9,100 m² office building located in Trondheim, was completed in June 2017. The building is an extension of several other buildings, Otto Nielsens vei 12 A-D, completed in 1990 and 2000, Figure 171. The new building is designed and constructed according to the Norwegian passive house standard (NS3701, 2012), and certified as Breeam-Nor "Excellent" (second highest classification level in Breeam).

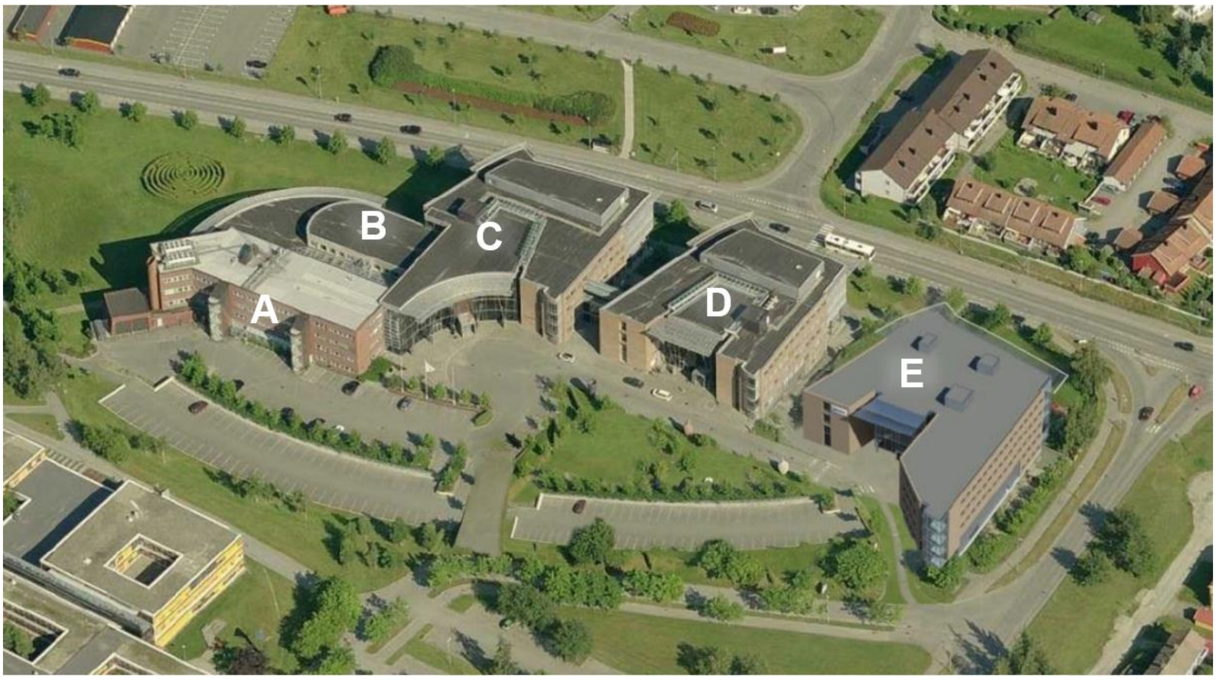


Figure 171: Otto Nielsens vei 12 A-E (office buildings) in Trondheim (source: Ketend Eiendom AS)

The tenant is Nordic Semiconductor, a Norwegian company that is world-leading in advanced electronics, including low-energy Bluetooth technology (https://www.nordicsemi.com/). The company has large server installations as well as testing facilities that require cooling.

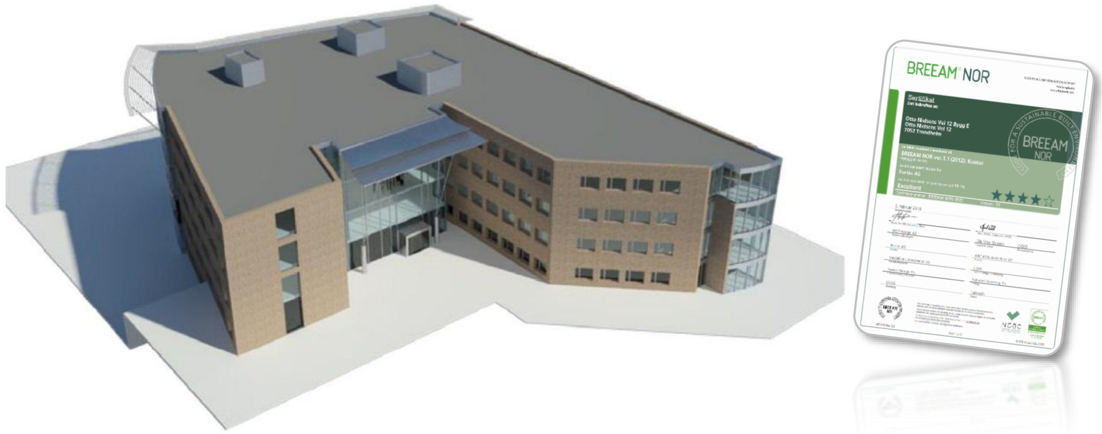


Figure 172: Otto Nielsens vei 12 E, office building (Koteng Eiendom AS).

5.4.1 Heating and Cooling Demands

Table 41 summarizes the calculated heating and cooling demands for the building including space heating, heating of ventilation air, DHW heating, snow melting, cooling of ventilation air, local room (space) cooling and process cooling for Otto Nielsens vei 12 E as well as the measured average annual heating demand for Otto Nielsens vei 12 A-D. The maximum power demand for cooling for Otto Nielsens vei 12 E (290 kW) is almost 50% higher than the maximum power demand for heating (160 kW).

Table 41: *Calculated heating and cooling demands (power, energy) and design temperature levels for the different hydronic distribution systems at Otto Nielsens vei 12 E (COWI AS) as well as measured annual heating demand and temperature level for the hydronic heat distribution at Otto Nielsens vei 12 A-D.*

OTTO NIELSENS VEI 12 E – new building	**Temp. level**	**Value**
Building, heated area		9,100 m^2
Heating demand - Total energy demand		250,000 kWh/yr
- Space/ventilation air	60/50 °C	155 kW
- Domestic hot water (DHW)	75 °C	5 kW
- Snow melting	35/20 °C	40 kW
Cooling demand - Total energy demand		600,000 kWh/yr
- Ventilation air	10/16 °C	220 kW
- Local room cooling	14/18 °C	20 kW
- Process cooling	10/16 °C	50 kW
OTTO NIELSENS VEI 12 A-D – old buildings	**Temp. level**	**Value**
Heating demand - Total energy demand		1,700,000 kWh/yr
- Space heating	80/60 °C	
- Ventilation air	60/40 °C	

Moreover, the estimated annual cooling demand (600,000 kWh/year), where process cooling accounts for almost the entire demand, is about 2.5 times higher than the annual heating demand (250,000 kWh/year). This is due to the considerable process cooling demand for the unique tenant Nordic Semiconductor as well as the airtight and super-insulated building envelope. Figure 173 shows the estimated power duration curves for heating and cooling (Alfstad, 2018).

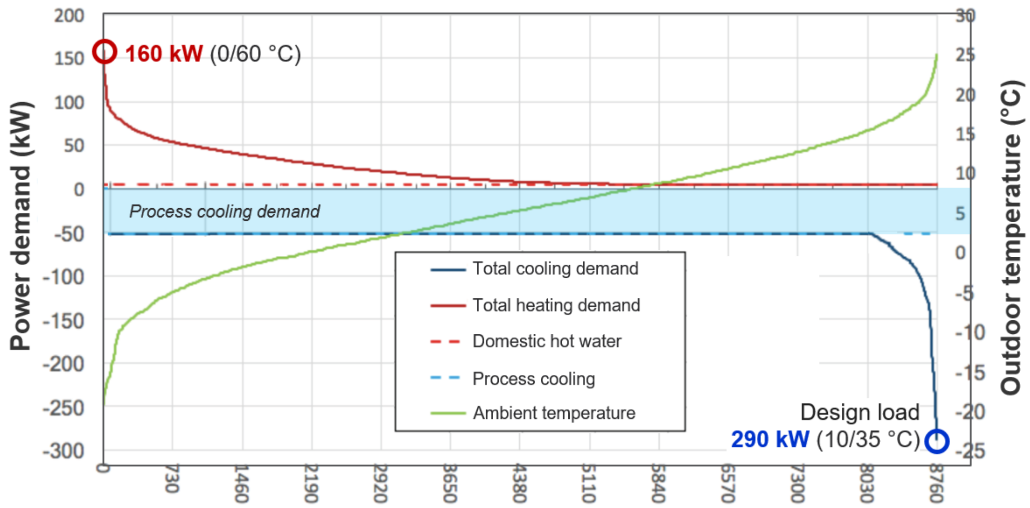


Figure 173: *Estimated power duration curves for heating (space heating, heating of ventilation air, DHW heating) and cooling (cooling of ventilation air, space cooling, process cooling) (Alfstad, 2018).*

5.4.2 System for Thermal Energy Supply

5.4.2.1 Overall Concept/Design and Control

Heating and cooling of the building is provided by a ground-source heat pump system connected to a borehole thermal energy storage (BTES). The maximum power demand for cooling of ventilation air (290 kW) determined the design capacity of the heat pump. According to the power duration curves in Figure 173, the heat pump may be operated as a liquid chiller to cover the process cooling demand during most of the year, and the surplus condenser heat is transferred to the existing buildings in Otto Nielsens vei 12 A-D. Figure 174 shows a principle sketch of the thermal energy flow for the thermal energy system. The BTES is used as a heat source when the heat pump system is operated in “overall heating mode” (dominating heating demand in the building). In “overall cooling mode” (dominating cooling demand in the building) the excess heat from the condenser is transferred to Otto Nielsens vei 12 A-D most of the year.

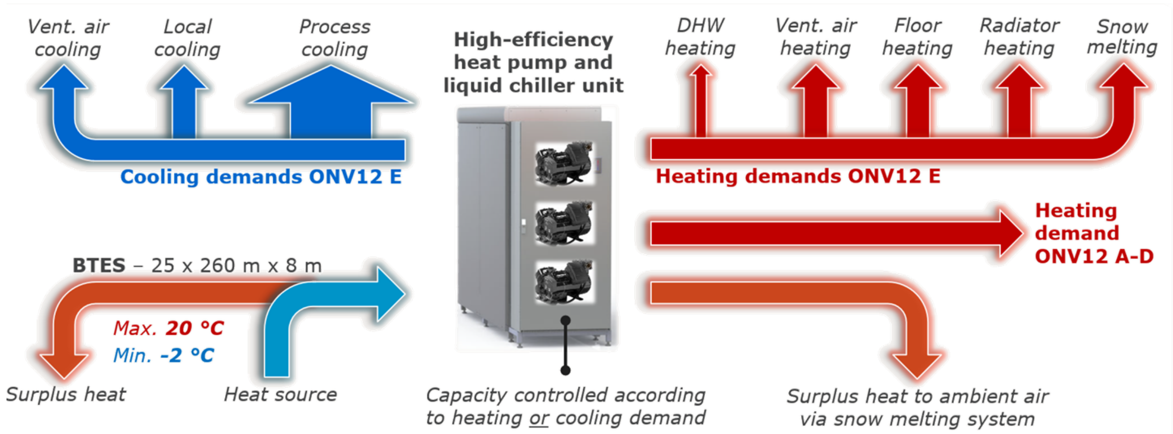


Figure 174: Energy flow for the thermal energy system at Otto Nielsens vei 12 E (Stene, 2019).

When the available excess heat exceeds the heating demand the heat is transferred to the BTES. If the temperature in the BTES for some reason reach a temperature of 20-25 °C, the excess heat is rejected to the ambient via the ground heat exchanger for the snow melting system. *Due to the utilization of multiple heat sources (BTES, process cooling) and heat sinks (BTES, ambient) the heat pump system has high flexibility*.

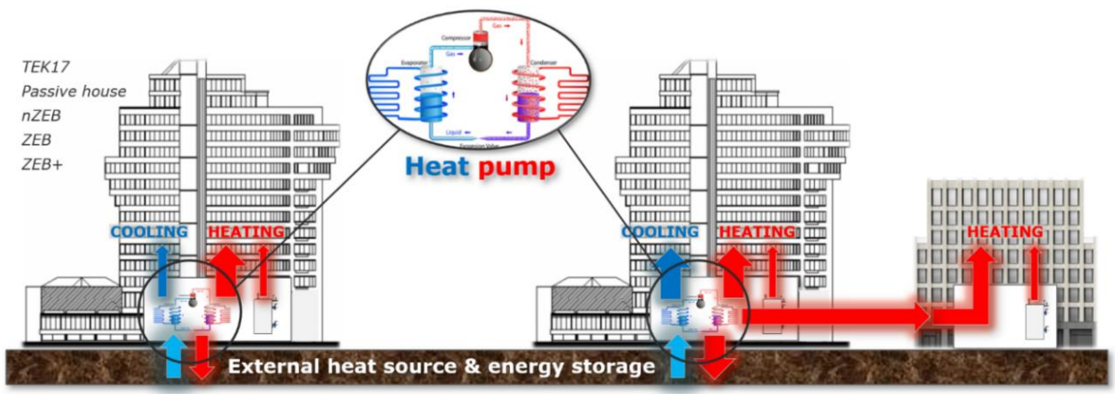


Figure 175: Principle illustration of heating/cooling in e.g. an individual passive house building vs. heating/cooling with exchange of surplus heat to adjacent buildings (neighborhood) (Stene, 2019).

5.4.2.2 Selection of the High-Quality Heat Pump Unit

In order to transfer heat from the heat pump to the existing heat distribution system a 200 m pipeline system was installed between the new machinery room in 12 E and the common machinery room for the existing buildings (12 A-D). The design temperature level for the radiators in the existing buildings is 80/60 °C. In order to maximize the COP of the heat pump when rejecting excess heat, the heat supplied to the return pipeline where the temperature is lowest. Since the heat pump should be able to supply heat at minimum 65 °C and preferably 70 °C, an ammonia heat pump would become too expensive since high-pressure (40-50 bar) technology had to be used. In 2016 propane and HFO heat pump units with the required capacity were hardly available on the market, and a CO_2 heat pump was regarded an inefficient solution due to the relatively high return temperature in the heat distribution system. Consequently, a high-temperature heat pump unit with R134a was selected. Due to large variations in the heating and cooling loads it was important to select a unit with excellent part load properties. The installed high-quality heat pump unit has a cooling capacity of 290 kW at 10/35 °C (heating capacity of approx. 200 kW at 0/65 °C), has two independent working fluid circuits and is equipped with three reciprocating (piston) compressors (2 with variable speed drive, 1 with on/off control), electronic expansion valve and brazed plate heat exchangers as evaporator/condenser. Reciprocating compressors with VSD control were selected since they achieve higher SCOP than reciprocating compressors with cylinder unloading, screw compressors with VSD control and scroll compressors with on/off control. The unit is also equipped with sub-coolers that increases the COP and desuperheaters for heating of domestic hot water (DHW).

The application of the latter is the most energy efficient solution for this installation, since the DHW demand in an office building is quite moderate (< 5 kWh/m²year), and the heat pump unit will be running continuously throughout the year due to the process cooling demand. The heat pump unit from Oilon Scancool is able to supply heat at maximum 75 °C, i.e. the unit will never have a temperature limitation. Figure 176 shows a principle sketch of the heat pump unit with the main components.

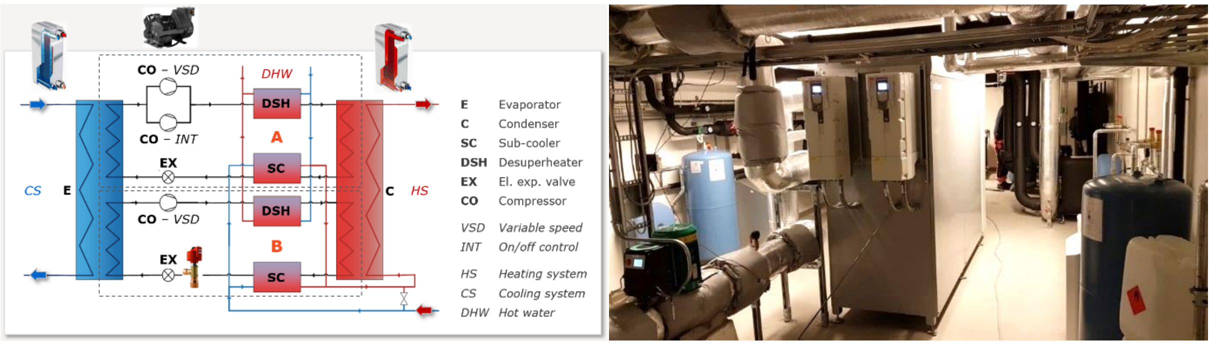


Figure 176: Principle sketch of the R134a heat pump unit with two independent working fluid circuits A and B with common evaporator and condenser, sub-coolers, desuperheaters, reciprocating compressors, and electronic expansion valves (left, Alfstad, 2018/Stene, 2019) and high-quality R134a heat pump unit with two independent working fluid circuits with three reciprocating compressors, two with variable speed drive (VSD), one with on/off control (right, Stene, 2018)

5.4.2.3 Borehole Thermal Energy Storage (BTES)

The borehole thermal energy storage (BTES) comprises 25 vertical boreholes with 7 m mutual distance, each approx. 260 m deep – 6500 m in total. The ground water level is at approx. -16 m (requires 18 m steel casing). Thermal Response Testing (TRT) and simulations with the software Earth Energy Designer (EED) were used to optimize the BTES. The BTES is located under the floor of the basement parking facility on the same level as and quite close to the machinery room, where the heat pump unit is installed, see Figure 177.

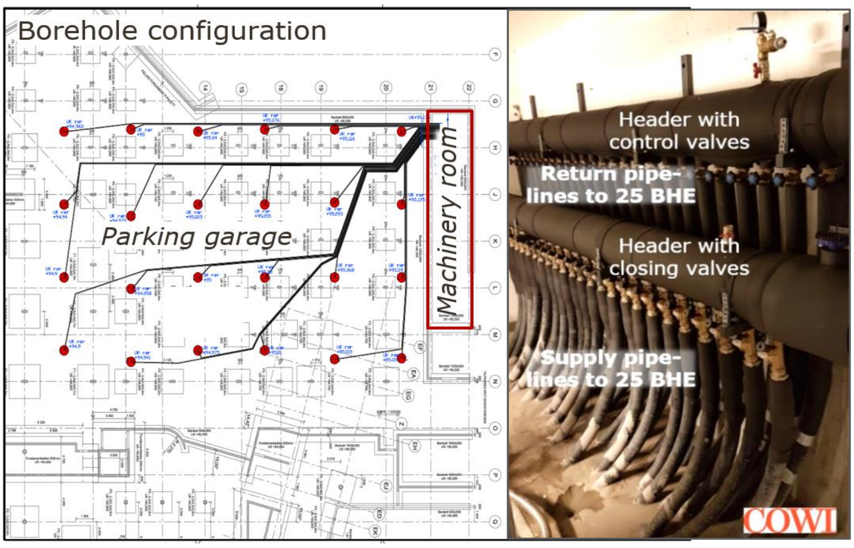


Figure 177: Location of the boreholes for the borehole thermal energy storage (Asplan Viak AS, 2016) and photo of supply/return headers and valves for the borehole heat exchangers (Stene, 2019).

The specifications for the borehole heat exchangers (BHE) are as follows – OD40/2.3, PE100, SDR17, PN10 – turbo collectors. The anti-freeze fluid (brine) is 24% ethanol (HXi-24). The flash-point of the fluid is 33 °C, and the maximum allowed temperature in the BTES is therefore set to approx. 25 °C.

5.4.2.4 System Design and Operational Strategy

Figure 178 shows an "as built" system sketch for the thermal energy system (COWI AS, 2017). Since the heat pump unit has always sufficient capacity to cover the entire heating demand in the building (200 kW vs. approx. 160 kW), district heating is only used as back-up. The existing buildings (12 A-D) are heated by district heating.

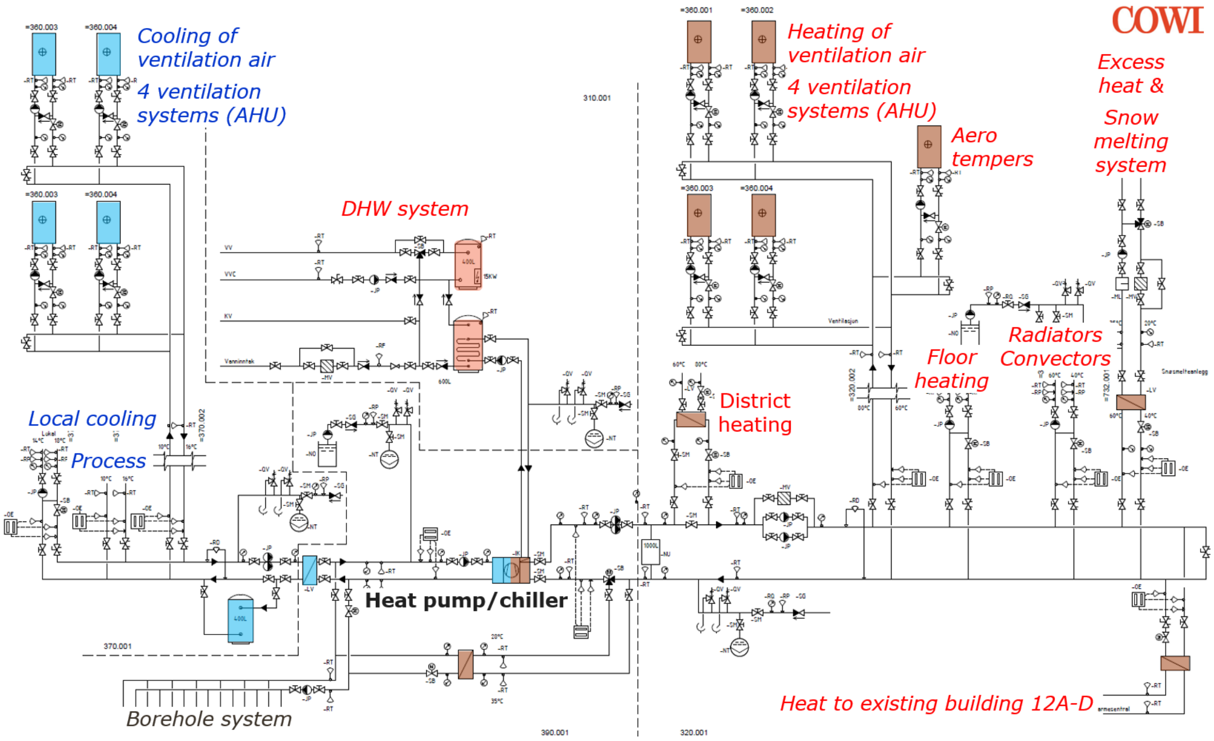


Figure 178: "As built" system sketch for the thermal energy system at Otto Nielsens vei 12 E including the heat pump and liquid chiller unit, BTES (borehole system) and distribution systems (COWI AS, 2017).

The thermal energy system is operated in "overall heating mode" (dominating heating demand) or "overall cooling mode" (dominating cooling demand), see Figure 179 and Figure 180.

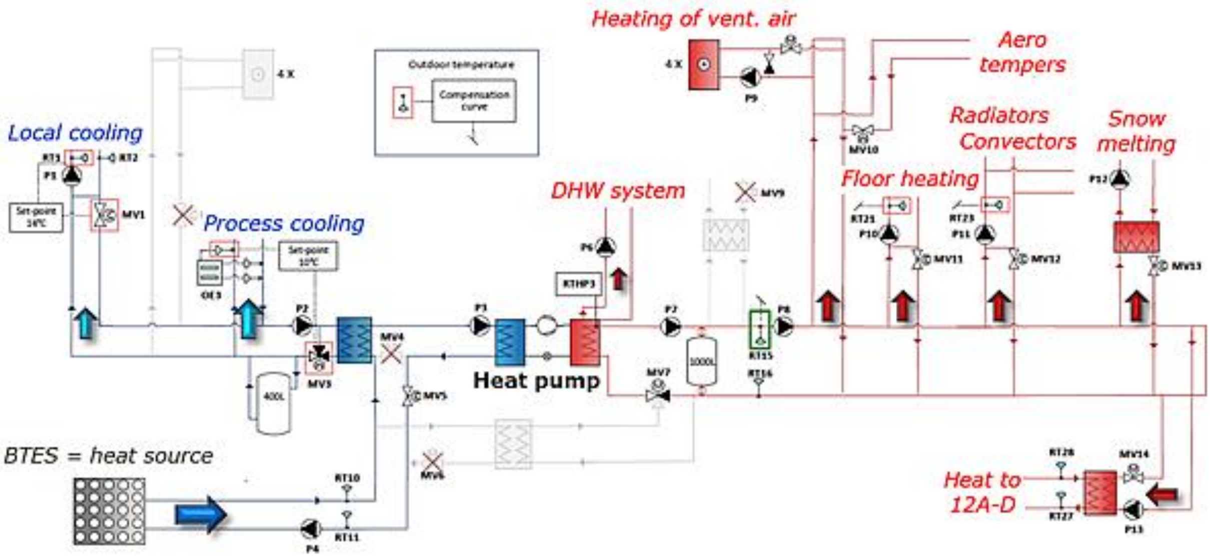


Figure 179: Principle sketch of the thermal energy system in "Overall heating mode" (Alfstad, 2018).

Since it is very profitable to supply heat to both the new building 12 E and the existing buildings (12 A-D), the heat pump has mainly been operated in "overall heating mode". Due to the Breeam-Nor Excellent classification, the thermal energy system in the building has extended instrumentation including a large number of thermal energy meters. For the heat pump and liquid chiller unit the heating/cooling capacity for the evaporator, condenser and desuper-heaters are measured as well as the input electric power to the compressors.

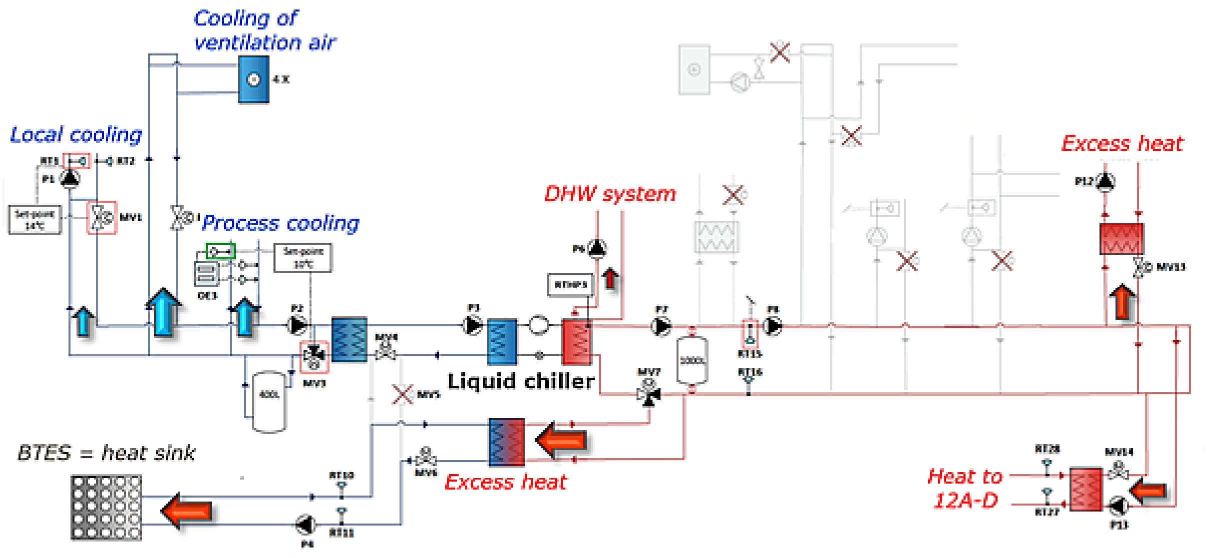


Figure 180: Principle sketch of the thermal energy system in "Overall cooling mode" (Alfstad, 2018).

Figure 181 shows a principle sketch of the thermal energy system incl. instrumentation (energy meters/OE, flow meters, temperature/pressure sensors) (Alfstad, 2018).

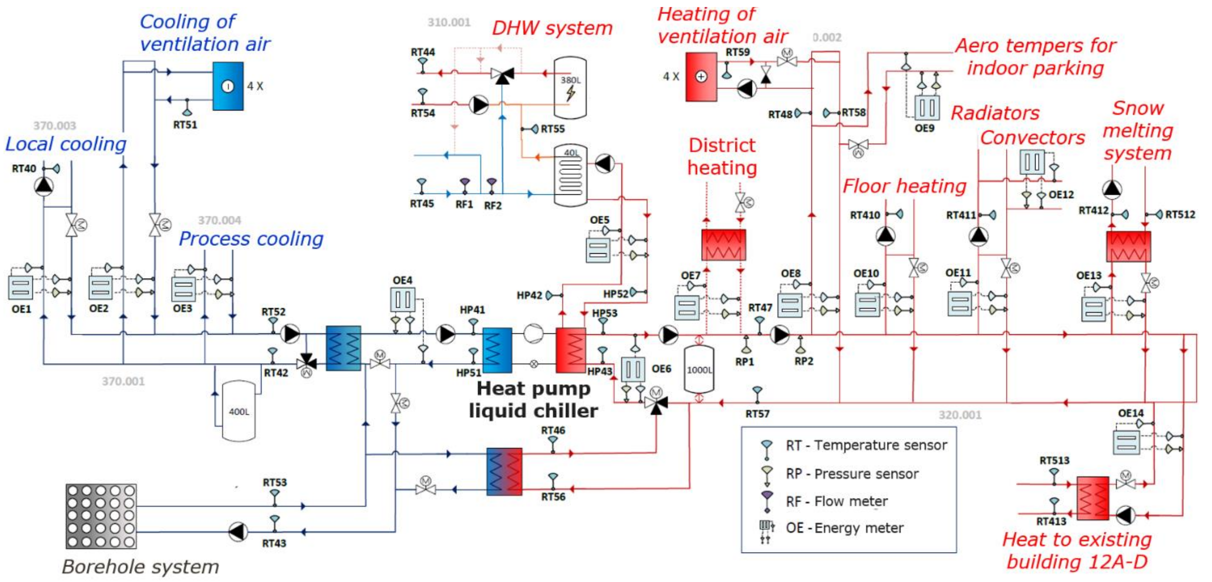
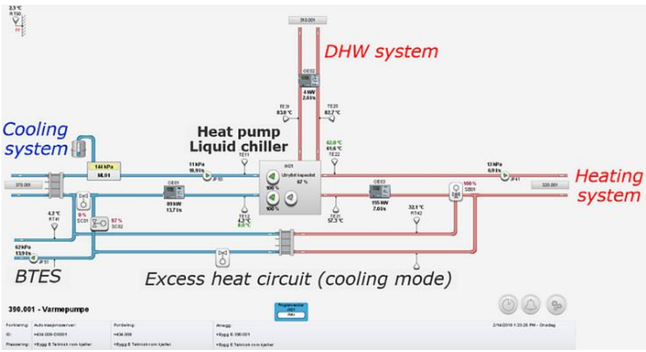


Figure 181: Principle system sketch of the thermal energy system in Otto Nielsens vei 12 E incl. instrumentation (energy meters, flow meters, temperature/pressure sensors) (Alfstad, 2018).

Figure 182 shows the monitoring system.



The monitoring comprises the heat pump and liquid chiller unit including thermal energy meters for the evaporator, condenser and desuperheaters, electric energy meter for the compressors as well as temperature sensors for all the supply and return pipelines. There is no separate thermal energy meter for the BTES.

Figure 182: Monitoring system for the heat pump and liquid chiller unit including thermal and electric energy meters (OE) as well as temperature sensors (Stene, 2019).

5.4.3 Monitoring Results

5.4.3.1 First Year of Operation (2017-18)

Figure 183 shows the measured heating and cooling supply for the thermal energy system for Otto Nielsens vei 12 E and 12 A-D during the first year of operation. The measurements were carried out and analysed by a Master student at NTNU (Alfstad, 2018).

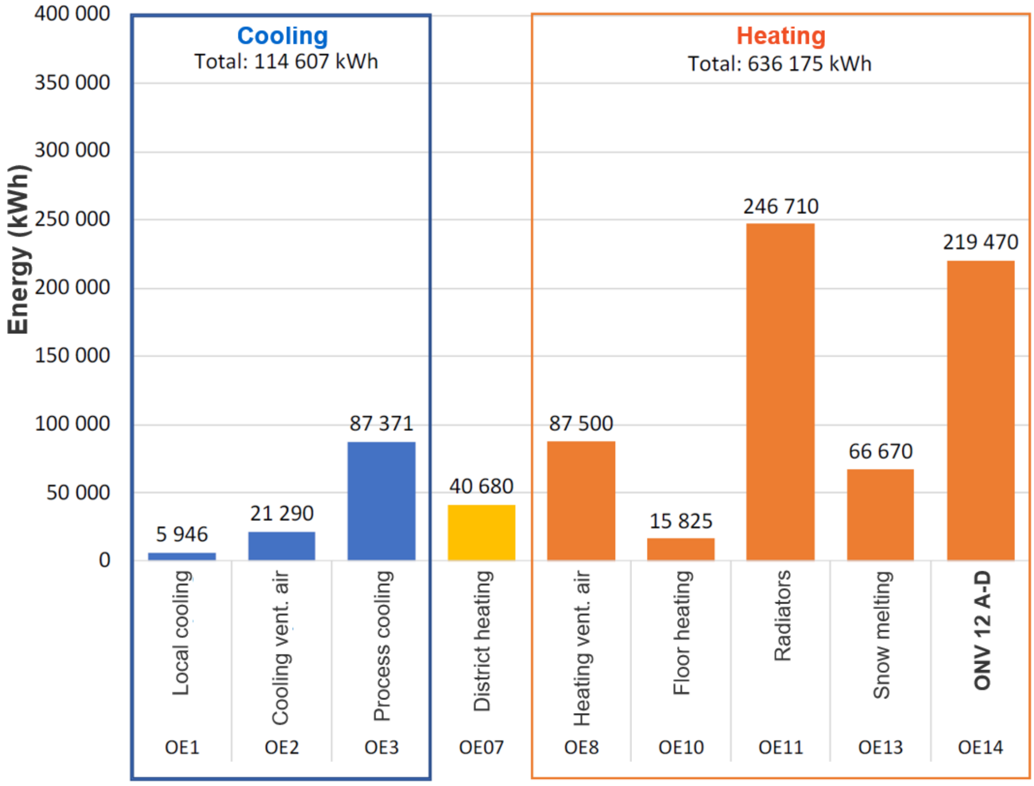


Figure 183: Measured heating/cooling supply during the first year of operation, 2017-18 (Alfstad, 2018).

The total cooling supply (approx. 115,000 kWh/year) corresponding to an average cooling demand of approx. 15 kW, was much lower than the calculated value of 50 kW since the Nordic Semiconductor test equipment and server stations were not completely installed in 2017. When excluding the first two month with commissioning (start-up period), the measured total annual heating demand (approx. 300,000 kWh) for Otto Nielsens vei 12 E was about 50% higher than the calculated value (approx. 200,000 kWh). During the first year of operation about 220,000 kWh was transferred from the heat pump and liquid chiller system in 12 E to the existing building 12 A-D (Alfstad, 2018). The heat pump was operated in "overall heating mode" the entire year since with maximum heat supply to the existing buildings, since this was the most profitable operational strategy.

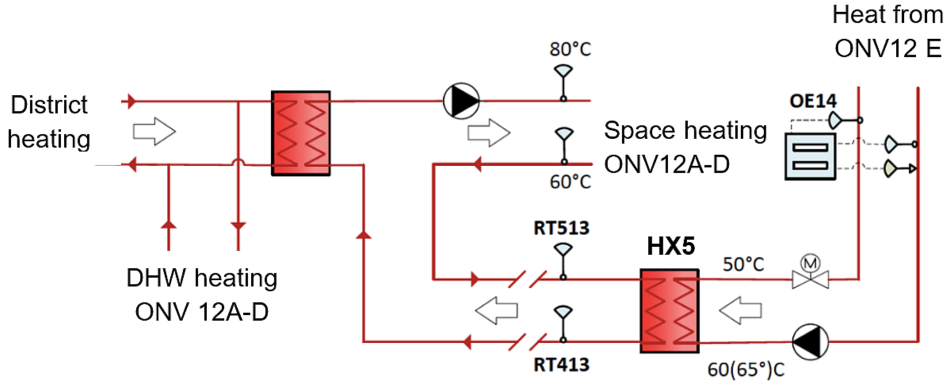


Figure 184: Principle sketch of the heat exchangers for transfer of heat from Otto Nielsens vei 12 E (ONV12 E) and from district heating system to Otto Nielsens vei 12 A-D (ONV12A-D) (Alfstad, 2018).

Due to problems with one of the reciprocating compressors, the heat pump was shut down and district heating covered the entire heating demand during that period (40,000 kWh). Figure 185 shows the measured supply/return brine temperatures for the BTES and the corresponding evaporator capacity for the heat pump and liquid chiller unit (Alfstad, 2018).

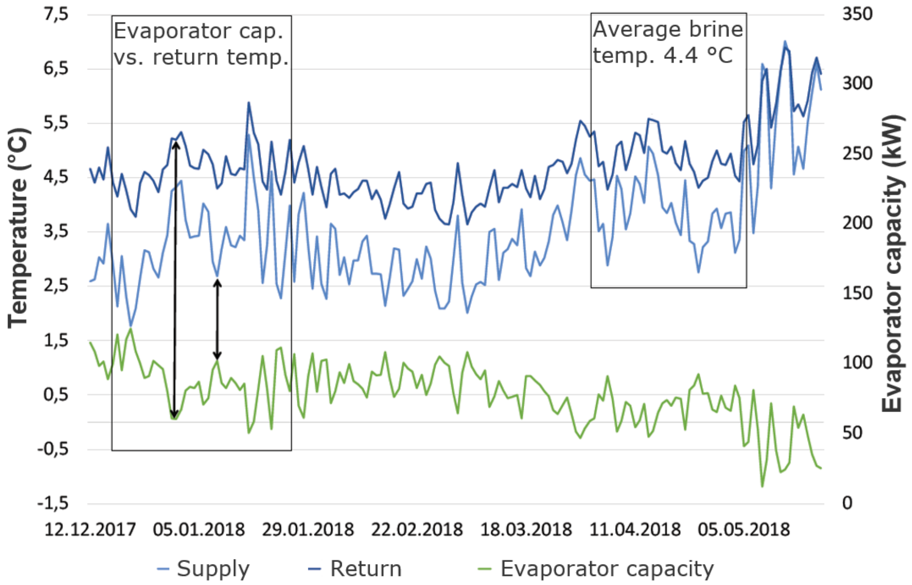


Figure 185: Measured supply/return brine temperatures for the BTES and the corresponding evaporator capacity (kW) for the heat pump and liquid chiller unit (Alfstad, 2018).

The measurements show that despite the more or less continuous heat extraction from the BTES during the first year of operation the average temperature level was virtually unchanged. This is due to good heat inflow from the surrounding bedrock volume including heat transferred by ground water inflow. It is important that the temperature level in the BTES is monitored continuously in order to prevent freezing of the ground water in the boreholes which may damage the PE ground heat exchangers (GHE). The measured average, weighted COPs for the heat pump and liquid chiller unit during a 6 months period (November 2017 – May 2018) are shown in Table 42. $SCOP_2$ including the input energy for the pump in the BTES/cooling circuit (Alfstad, 2018).

Table 42: Measured SCOP's for the heat pump and liquid chiller unit for November 2017 to May 2018 and the second measurement period May 2018-May 2019. $SCOP_1$ – pump energy for BTES not included, $SCOP_2$ – pump energy included (Alfstad, 2018).

Demands	**Period Nov. 2017 – May 2018**		**Period May 2018 – May 2019**
	$SCOP_1$	$SCOP_2$	$SCOP_1$
Heating only	2.6	2.3	2.6
Heating and cooling	4.1	3.5	4.3

The measured $SCOP_1$ in heating mode (2.6) is close to the design value from the manufacturer (2.7). The reason for the relatively low SCOP is the high average temperature lift for the heat pump in order to supply heat to the existing buildings in Otto Nielsens vei 12 A-D. Since the main purpose of the heat pump and liquid chiller unit is to supply as much heat as possible to the existing buildings in 12 A-D, the temperature level for the outdoor temperature compensation curve has been changed to 80 °C, 62 °C and 50 °C set-point temperature at -20 °C, 0 °C and +10 °C ambient temperature, respectively. This is as much as 20 °C higher than the set-point temperature for the heat distribution system in Otto Nielsens vei 12 E. Figure 186 shows the measured duration curve for the outlet water temperature from the condenser and the inlet brine temperature for the evaporator (Alfstad, 2018). The supply temperature exceeded 60 °C most of the time and the maximum supply temperature was as high as 75 °C. Although the heat pump can handle very high outlet water temperatures, a high temperature lift will reduce the SCOP as well as the lifetime of the compressors.

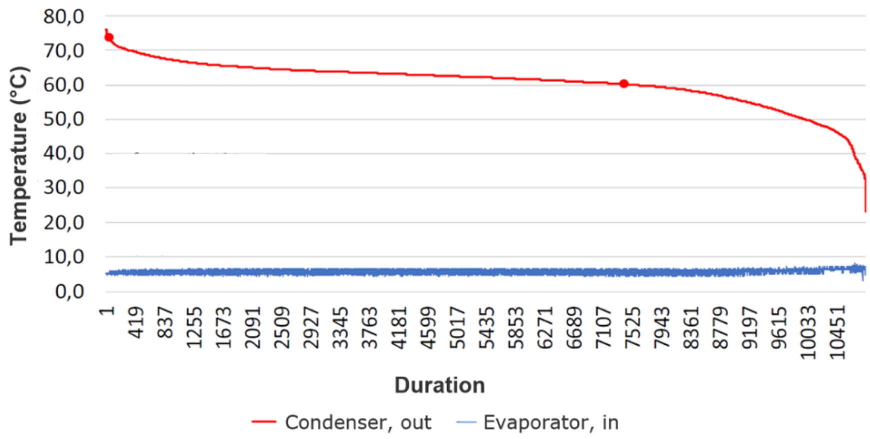


Figure 186: Measured duration curve for the outlet water temperature for the condenser and the inlet brine temperature for the evaporator (Alfstad, 2018).

5.4.3.2 Second Year of Operation (2018-19)

From October 2018 to October 2019 the measured total heat supply was approx. 600,000 kWh, incl. 235,000 kWh to 12 E and 365,000 kWh to the existing buildings. Although the measurements have not been adjusted to a "normal year" they show that the heat supply to 12 E has been considerably reduced (-20%), most likely due to completed "drying-up" of the building and more optimum operation of the ventilation and thermal energy systems. Fall/ Winter 2018 Nordic Semiconductor installed a new server centre which increased the average cooling power demand.

This explains the significant increase in the annual cooling demand from about 115,000 kWh to 380,000 kWh. The average cooling power demand was about 44 kW, which is close to the design value of 50 kW (Koteng Eiendom, 2019). Due to the considerable increase in the annual cooling demand, the heat supply to the existing buildings in 12 A-D increased from 220,000 kWh to 380,000 kWh (+65%). Table 42 also shows the measured SCOP's for the heat pump and liquid chiller system. The annual pump energy for the BTES system is not included (Koteng Eiendom, 2019).

The measured $SCOP_1$s for the last operating year (Koteng Eiendom, 2019) are virtually identical to the $SCOP_1$s for the first operating year (Alfstad, 2018), *i.e. the heat pump and liquid chiller unit has more or less been operating with the same average temperature lift and part load conditions as the first year of operation*.

5.4.4 Results and Discussion – Improvement of the Existing System

<u>Reduce temperature level for heat rejection to existing buildings in 12 A-D</u>

- Current system – The outlet water temperature from the condenser is above 60 °C most of the time, and the highest measured temperature is 75 °C. The average temperature level in the BTES is relatively constant (Alfstad, 2018). A high temperature lift for the heat pump results in a relatively low SCOP as well as larger risk of operation problems and reduced lifetime for the compressors. So far, there has been 2 compressor failures. The reasons for the failures are not known, but the high temperature lift for the compressors with subsequent high discharge temperature and large pressure ratio may be one of the reasons.
  - Improvement – Reduce the set-point temperature in the heat distribution system and measure the heat given off to the existing buildings 12 A-D to see if it is possible to operate the heat pump at a lower temperature level and still cover the same annual heating demand. Consider replacing the brazed plate heat exchanger (VV5, Figure 184) with a new heat exchanger with a larger surface in order to reduce the LMTD and with that the supply temperature from the condenser (cost/benefit optimization).
  - Benefit – Increased SCOP for the heat pump and liquid chiller unit (i.e. higher annual energy saving) as well as longer lifetime and reduced risk for operation failure for the compressors (cost/benefit optimization).

Redesign of the DHW System – include reheating of circulating DHW

- Current system – Heat from the heat pump desuperheater is used to heat domestic hot water, DHW (consumption DHW). Due to the relatively high supply water temperature from the condenser and consequently high discharge gas temperature from the compressor, the temperature level in the desuperheating accumulator tank (600 litres) is sufficient to heat DWH to at least 70 °C (set-point), Figure 187. However, electric heaters in another accumulator (400 litres) heat the DHW in the circulation system. Measurements have shown that as much as 60% of the annual DHW heating demand is for heating of DHW in the circulation system (Alfstad, 2018).
  - Improvement – Redesign the DHW pipeline system in order to cover the DHW re-heating demand in the circulation system with heat from the desuperheater, Figure 187.
  - Benefit – Approx. 100% energy coverage for the heat pump system for DHW heating.

Continuous monitoring of the BTES

- Current system – Since it is profitable for the building owner Koteng Eiendom AS to supply heat to both the new building 12 E and the existing buildings (12 A-D), the heat pump has mainly been operated in "overall heating mode". The heat sources for the heat pump are the BTES as well as excess heat from the cooling systems in 12 E.
  - Improvement – The temperature level in the BTES should be monitored continuously. If the temperature level for the brine drops below the recommended minimum level (approx. -2 °C), less heat should be supplied to the existing buildings in order to limit the heat extraction from the BTES.
  - Benefit – Long-term thermal energy balance in the BTES in order to maintain good operating conditions for the heat pump and prevent freezing of the ground water in the boreholes which may damage the PE ground heat exchangers (GHE).

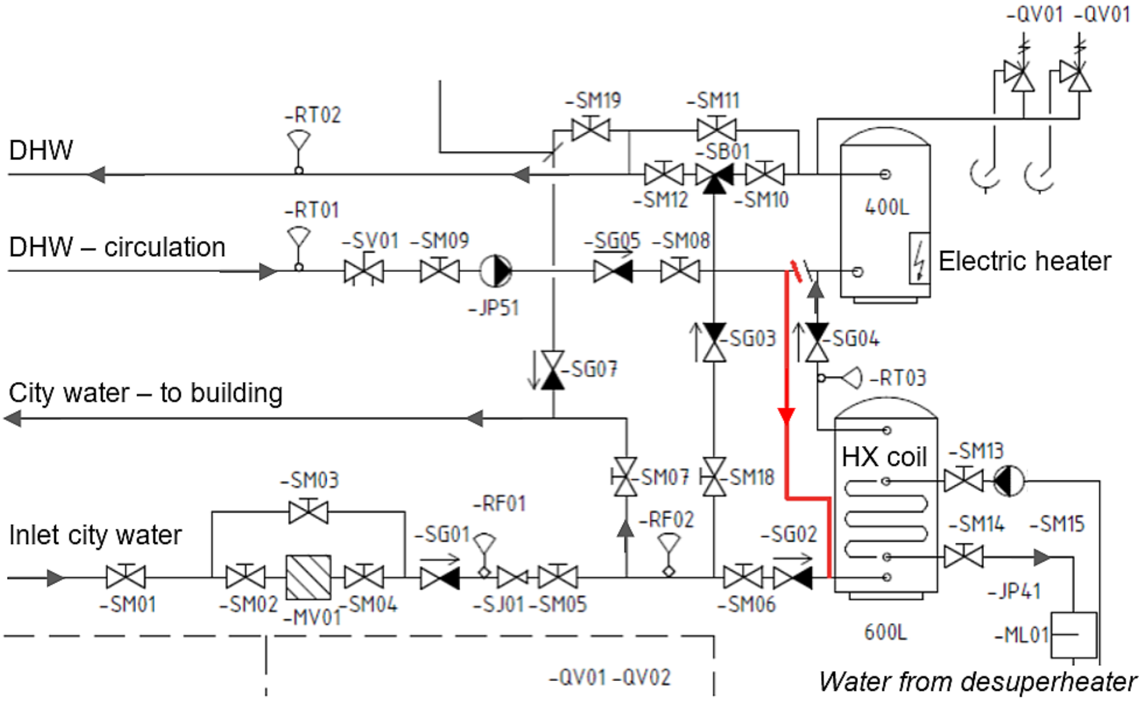


Figure 187: Redesign of the DHW system – the red line shows the recommended new pipeline from the DHW circulation system to the desuperheater accumulator tank (Alfstad, 2018).

5.5 Conclusions monitoring results for groups of buildings

In Annex 49 also different groups of building have been investigated in monitoring. Thereby, residential and non-residential buildings applications are contained. In general a positive conclusion can be drawn from groups of building connected by grids.
In the Herzo Base project a very high seasonal performance of the two central heat pumps is achieve, which is on the one hand due to good part load performance, on the other hand due to the good ground source temperature with 5 °C at minimum. The DHW booster heat pumps reach an SPF of 4, but it has to be considered that it is a cascase system, so overall efficiency of an SPF_{DHW} of 2.5 is in a moderate range. The overall system performance is with 3.4 also in a moderate range, which, however, is also distorted by user behaviour, so optimisation potentials could be identified and a better performance should be possible in the future.
In the Aspern project a larger amount of flat are supplied by a sophisticated combination f different heat pumps, solar heat generators and different heat sources, which are connected by a high and low temperature grid. However, despite the system complexity positive conclusions could be drawn by integrating different types of heat sources. While air source systems showed advantages during summer, also for high temperature production, good source temperatures were provided by ground-couples systems in the winter. Furthermore, synergies among the source led to a good availability and redundancy. However, also importance of loss reduction in thermal grid is stressed and thorough design and adequate application of solar components is adviced. Moreover, systems with several source have also an inherent complexity which should not be reinforced by complex controls strategy.
In the office building Otto-Nielsens Vei heat is supplied from a new building extension 12 E to the older building 12 A-D, which has a particular tenant Nordic Semiconductor with both space heating and process cooling. The system is operated with a regenerated borehole heat exchanger field. The overall SCOP for space heating and cooling is with 4.3 in a good range, but the space heating only operation is with 2.6 moderate. This limited SCOP in space heating mode is caused by the high supply temperatures in the existing buildings and corresponds to the manufacturer data sheet. An optimisation potential would thus be a temperature reduction in the space heating mode, which could lift the overall SCOP to high values would most likely also improve the lifetime of the heat pump components.
Summarising positive energy district offer a favourable perspective for heat pump deployment in the future and would be an interesting field for further research.

6 Conclusions of monitoring of heat pumps in nZEB

Building uses:
Monitorings of heat pumps in nZEB in Annex 49 comprise a variety of different building uses. A focus is thereby on larger buildings as larger multi-family buildings, mixed office and residential use as well as several examples of non-residential uses with two schools, a kindergarten, a hotel and supermarket. Furthermore, groups of buildings with heat export from one building to another or a connection by the thermal grid are monitored.

Heat sources:
Due to the larger buildings, only one standard air-source heat pump application is covered by the monitoring projects. Most projects use a ground-source in form of conventional borehole heat exchanger fields or even BTES, which are also regenerated. However, among these ground sources are also new or more seldom systems like agrothermal fields and energy piles. One system uses the combination of an ice storage and a solar absorber below the PV installation and one systems uses groundwater. One multi-source system also incorporates garage air besides the ground and ground-water. Thus, in general, the source temperature offer good operation conditions for the monitored heat pumps. All source allowed a stable operation and seasonal performance factor are in most project in the higher range.

Monitoring vs. design values
In several projects the monitoring values agree to the design values, in particular in the residential and the office buildings. However, for rather new applications of non-residential uses with some particular boundary conditions in the project, larger deviations between the planning and measured values exist, which partly have also an impact on the system performance and show optimisation potential.

nZEB balance
Regarding the monitoring results on the nearly Zero Energy Balance, smaller applications like single family buildings and groups of single family building can meet the balance with moderate PV-areas, i.e. the roof area is sufficient to even achieve a plus energy balance. In larger residential multi-family buildings, only the roof is not sufficient to reach a plus balance, and the façade is additionally needed. With additional office or commercial use, the effective surface may be too small to reach a plus balance, and even a reduced nZEB balance boundary regarding the building technology may be challenging.

Performance values
Many of the monitored systems, in particular the residential and office applications, reach good system performance with high seasonal performance factors of the heat pump SPF_{HP} which are in the range from 4-5 and even higher. Non-residential uses, which may be newer applications for heat pump use tend to show lower seasonal performance values, with the exception of the Willibald Gluck secondary school with a seasonal performance in the range of 5. However, for the systems with lower performance factors, also optimisation potentials were identified, so better system performance is to be expected in the future.

Refrigerants
Regarding refrigerant, most of the applied heat pumps still use conventional synthetic refrigerants, so no experience could be gather with low GWP or natural refrigerants, with the exceptions of the CO_2-heat pump in Justvik Skole and the supermarket refrigeration at KIWI Dalgard.

As conclusion of the manifold and long-term monitoring projects contributed to Annex 49, heat pumps are confirmed as high performance building technology especially for the application in future nZEB which increase the heat pump performance by high performance building envelope and thus opens up large market shares for heat pumps.

Moreover, also regarding on-site production the heat pump enables smart controls and demand response, which can reduce future grid interaction. Due to multifunctional heat pump use, the all electric building concept is establishing as one archetype to fulfil future ambitious building target. Heat pumps are thus an important - if not the important component - to reach high performance building required to tackle ambitious climate protection targets and achieving net negative emission beyond 2050.

Following general conclusion and recommendations can be given from the heat pump monitoring in order to further increase the performance and sustainability:

- Variable speed drive (VSD) is the recommended capacity control for heat pump compressors. In addition to reducing wear and tear, this also leads to much higher SCOP and considerably improved controllability at low heating demands.
- Heat pumps and liquid chillers should preferably use natural working fluids, i.e. propane (R290), CO_2 (R744) and ammonia (R717). Unfortunately, there is no "ideal refrigerant" for all purposes, and the choice must be made as a trade-off between the advantages and drawbacks of the different refrigerants. Propane is a flammable fluid (class A3), ammonia is a toxic and slightly flammable fluid (class B2L) while CO_2 is non-flammable and non-toxic. The main challenge with regard to the use of CO_2 as working fluid is to achieve high SCOP and energy coverage factor for heat pumps for combined space heating, DHW heating and cooling. However, considering the phase-out schedule of HFCs, natural refrigerants are considered to be long-term, environmentally benign and energy efficient options for future heat pump systems in different capacity ranges and application areas.
- Available surplus heat at different temperature levels should always be utilized, either directly through heat recovery or as a heat source for heat pump systems. It is important to identify the thermal demands with associated temperature requirements, for space heating and cooling, heating of ventilation air, heating of DHW and process cooling. This should be considered in the design phase and taken into account before sizing heating and cooling systems and selecting suitable technology. The surplus heat can either be used within the same building or in neighbouring buildings. A good match between the source of surplus heat and the heat load is important. If there is a poor match, thermal energy storage can be an option by utilization of BTES (ground) or accumulation tanks with water or phase-changing materials (PCM). Duration curves represent a good tool for designing heating and cooling systems and to visualize the potential of surplus heat sources that can be utilized.
- Heat recovery from surplus heat sources may cover relatively large parts of the heating demand in a building. The application and utilization are depending on the temperature level. Low-temperature surplus heat can be used as a heat source for heat pump systems directly by increasing the fluid temperature before the evaporator or indirectly by means of thermal energy storage in a BTES or other energy storage system.

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8 Abbreviations

Abbreviation	Meaning	Remark
A-HP	Air heat pump	
AHU	Air handling unit	
AS	Air source	
ASBP	Austrian Sustainable Building Platform	
Aux	Auxiiary	
BAU	Business as usual	
BC	Boundary condition	
BGF	Gross floor area	Bruttogeschossfläche
BIM	Building information modelling	
BIPV	Building integrated Photovoltaic	
BMK	Austrian Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology	Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie
BMS	Building Management systems	
BPIE	Buildings Performance Institute Europe	
BREEAM	Building Research Establishment Environmental Assessment Method	UK sustainable building label
BRI	gross volume	Brutto Rauminhalt
BS	Buffer storage	
BSB	electric energy demand (non-residential sector)	Betriebsstrombedarf
BTES	Borehole Thermal Energy Storage	
BTO	Building technology office	Office of DOE
CEN	Committee Europeen des Normalisation	EU Standardisation Organisation
CDF	cumulative distribution function	
CHP	Combined Heat and Power	
CND	Condenser	
COP	Coefficient Of Performance	
CV	Coefficient of Variation	
DC	Direct Current	
DGNB	German Sustainable Building Council	Deutsches Gütesiegel für nachhaltiges Bauen
DHW	Domestic hot water	
DIN	German Institute for Standardisation	Deutsches Institut für Normung
DOE	US Department of Energy	
DR	Demand response	
DSH	Desuperheater	
DSM	Demand Side Management	
DWD	Deutscher Wetterdienst	
EC	European Commission	
ECBCS	Energy conservation in Buildings and community systems	IEA TCP, now called EBC
EEB	Final energy demand	
EEB	final energy demand	Endenergiebedarf
EL	electric	
EnEV	German Energy saving directive	EnergieEinsparVerordnung
EPBD	Energy Performance of Buildings	EU Directive
ErP	Energy related Products	EU Directive also call Ecodesign Directive
EU	European Union	
EVP	Evaporator	
GFA	gross floor area	

Abbreviation	Meaning	Remark
GS	Ground source	
GWP	Global Warming Potential	
GW	Ground water	
HC	heat control	
HD	Heat demand	
HDD	Heat degree days	
HM	Heat meter	
HP	Heat pump	
HPWH	heat pump water heater	
HPP	Heat Pump Programme	
HPT	Heat Pumping Technologies	IEA TCP
HTEB	Maximum allowed final energy demand	
HVAC	Heating, Ventilation and Air-conditioning	
HWB	Space heating demand	Heizwärmebedarf
IBO	Building Biology and Ecology	Baubiologie und -ökologie
IEA	International Energy Agency	
IGS	Institut für Gebäude und Solartechnik	
IHP	Integrated Heat Pump	
IISBE	International Initiative for a Sustainable Built Environment	
IPEEC	International Partnership for Energy Efficiency Cooperation	
ISO	International Standardisation Organisation	
IWT	Institut für Wärmetechnik	
JRC	Joint Research Centre	
KB	Space cooling demand	Kühlenergiebedarf
KfW	Kreditanstalt für Wiederaufbau	German bank for funding high performance buildings
KNN	artificial neural network	
KPI	key performance indicator	
LCA	Life cycle assessment	
LCF	load cover factor	
LED	light emitting diode	
LEED	Leadership in Energy and Environmental Design	US sustainable building label
LEB	low energy building	
LEH	Low energy house	
MFB	Multi-family building	
MFH	Multi-family house	
MHP	modulating heat pump	
MPC	Model predictive control	
MS	(EU) member state	
msr	measured	
MuKEn	Model ordinance of the cantons in Energy	
MVHR	mechanical ventilation heat recovery	
MV	mixing valve	
NFA	net floor area	
NIST	National Institute of Standards and Technology	
NREL	National Renewable Energy Laboratory	
NS	Norge Standard	
NTH	Neue Heimat Tirol	
nZE	nearly Zero Energy	
nZEB	nearly Zero Energy Building	
NZEB	Net Zero Energy Building	
NZERTF	Net Zero Energy Residential Testing Facility	

Abbreviation	Meaning	Remark
ÖGNB	Österreichische Gesellschaft für Nachhaltiges Bauen	Austrian Society for Sustainable Building
ÖGNI	Austrian Society for Sustainable Real Estate Management	Österreichische Gesellschaft für Nachhaltige Immobilienwirtschaft
OHP	on- off controlled heat pump	
OIB	Austrian Institute of Construction Engineering	Österreichisches Institut für Bautechnik
ÖÖI	Austrian Institute of Ecology	Österreichischen Ökologie-Instituts
ORNL	Oak Ridge National Laboratory	
OVN	Otto Nielsens vei	Monitoring Building in NO
PE	Primary energy	
PEB	Primary energy demand	
PER	Primary Energy Renewable	
PH	Passive house	
PHPP	Passive House Planning Package	Passivhaus-Projektierungs-Paket
PV	Photovoltaic	
PV	Photovoltaic	
PV/T	photovoltaic/thermal	
RE	Renewable energy	
REHVA	Federeatio of European HVAC associations	
RES	Renewable Enrgy Sources	EU Directive
RK	Reference climate	
RMSE	Random Mean Square Error	
RTD	resistance temperature detectors	
SBA	Sustainable Building Alliance	
SC	Space cooling	
SCF	supply cover factor	
SCHV	Small duct high velocity	
SCOP	Seasonal Coefficient of Performance	
SFH	Single family house	
SFP	specific fan power	
SGNI	Swiss Society for Sustainable Real Estate Management	Schweizerisches Gütesiegel für nachhaltige Immobilienwirtschaft
SH	Space heating	
SHC	Solar heating and cooling	IEA TCP
SIA	Swiss society of engineers and architects	
sim	Simulated	
SK	Site climate	
SNK	sink	
SOS	special ordered set	
SPF	Seasonal performance factor	
SRC	source	
SS	Swedish standard	
ST	Solar thermal	
TA	treated area	Konditionierte Fläche
TABS	Thermally activated building system	
THN	Technische Hochschule Nürnberg	
UIBK	Universität Innsbruck Baukonstruktion	
VRFB	Vanadium Redox Flow Battery	
VSD	Variable speed drive	
VSD	Variable Speed Drive	
WBGC	World green building council	
WGG	Willibald Gluck Gymnasium	School of monitoring project DE
WWW	domestic hot water demand	Warmwasserwärmebedarf
PRBC	Predictive rule-based controls	

Abbreviation	Meaning	Remark
PUR	polyurethane	
PV	Photovoltaic	
PVC	PV control	
PV/T	photovoltaic/thermal	
WGG	Willibald Gluck Gymnasium	
WLG	Heat conduction group	Wärmeleitgruppe

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