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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 49

Design and Integration of heat pumps for nearly Zero Energy Buildings

Final Report

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Preface

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

The IEA

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

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

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

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

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

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The Heat Pump Centre

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

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby 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

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Project outline and main results

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

The work presented here is a contribution to the Annex 49 in the Heat Pumping Technologies (HPT) Technical Collaboration Programme (TCP) of the International Energy Agency (IEA)

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Executive Summary

Political Background

In many countries worldwide, buildings contribute significantly to the primary energy consumption and the CO_2-emissions. In the EU, for instance, about 40% of the primary energy and 36% of the CO_2-emissions are due to building operation and buildings are the single largest consumers. Thus, energy efficiency in buildings is a major strategy to reach ambitious CO_2-reduction to fulfil climate protection targets. Current building energy demands in the new built sector are in the range of low energy buildings of a space heating demand around 50 kWh/(m^2yr). As next step Net or nearly Zero Energy Buildings (NZEB/nZEB) are envisaged as future building standards, which have an energy demand of almost (nearly) zero by including on-site renewable energy production. By these concepts building loads have to be reduced and building system performance increased to an extend that on-site production can meet the net zero balance. Thereby, the new built sector can become climate neutral or even turn to a net energy producer in the case of a plus energy balance. In order to reach these ambitious targets, building and system performance as well as on-site renewable production have to be integrated in optimised overall concepts.

Outline of IEA HPT Annex 49

Thus, high performance building technology for nZEB application is of high interest for the implementation of the nZE requirements in the new built sector. IEA HPT Annex 49 entitled “Design and integration of heat pumps for nZEB” is carried out in the Technology Collaboration Programme (TCP) on Heat Pumping Technologies (HPT) of the International Energy Agency (IEA) and deals with heat pumps as core component of the HVAC system for nearly or Net Zero energy buildings. Heat pumps are considered as ideal building technology for nZEB due to their unique features:

- Heat pumps are highly efficient generators at low temperatures differences to the conditioned space which is enabled by the high performance building envelope and low loads of nZEB
- In nZEB space heating loads are decreasing and different building loads have an equal impact on the overall energy performance. DHW can make up more than half of the total heat demand and cooling in Europe or an additional dehumidification in the USA and Asia get more prevalent. Heat pumps can serve multiple building services with high performance.
- System integration of multiple functions with the heat pump can unlock further performance increase, since a simultaneous production of different buildings services can enable internal heat recovery, e.g. for space cooling (or dehumidification) and DHW. Simultaneous operation yields higher performance due to multiple use of the electricity.
- Use of the same components for multiple building services can justify investment in high quality components (e.g. capacity-controlled components with inverter)
- 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

Based on these features the combination of the heat pump and PV systems already established as archetype system technology for nZEB. On this background Annex 49 has been structured into the following Tasks

- Task 1: State of the art of heat pumps in nZEB in the participating 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

Table 1 gives an overview on the participating institutions in Annex 49 and the national contributions. A strong focus of the Annex 49 contributions of the participating countries was on monitoring with no less than 15 projects in different types of nZEB with heat pump. Thereby, the focus was set on larger residential and non-residential buildings, which put higher challenges to achieve ambitious performance targets for the nZE or plus energy balance.

Table 1: Overview of contributions of the participating countries to Annex 49

Country/Institution	Contribution to IEA HPT Annex 49
Austria Unit EE building, Univ. of Innsbruck, IWT TU Graz, AIT, Vienna	• Monitoring & simulation of two nZEB passive houses for optimization • Development of a prototype of a façade integrated heat pump • Evaluation of larger nZEB buildings
Belgium Free Univ. Brussels	• Evaluation of heat pump in office nZEB with sewer heat recovery
Germany TH Nürnberg, IGS, TEB GmbH	• System integration, design and field monitoring of different nZEB • Development of control strategies for smart grid integration
Norway SINTEF, NTNU, Cowi AS	• Monitoring of nZE demonstration buildings in Norway • Evaluation and control of energy flexibility in nZEB
Sweden RISE	• Monitoring/Comparison of heat pump systems in two equal test houses, Evaluation of heat pump solutions for nZEB in Sweden
Switzerland IET HSR	• Integration and design options of solar and heat pump systems • Field monitoring of nZEBs with residential and office use • Investigation of design of speed-controlled heat pumps
UK Glen Dimplex	• Evaluation of design and control of nZEB model houses
USA ORNL, CEEE & City@UMD, Univ. of Maryland, NIST	• Field monitoring of integrated (IHP) heat pump variants • Technology testing/comfort evaluation in NZEB test facility (NZERTF) • Prototype development of a personal cooling device for NZEB offices

Furthermore, prototypes were developed and lab- and field-testing was performed. Moreover, some of the monitoring projects were accompanied with in-depth investigations by simulations. On the one hand, the objectives were to identify system optimisation potentials and verify the nZE balance. On the other hand integration options for the heat pump, in particular with storages to accommodate different required building services like space heating or cooling and smart controls to increase the self-consumption and grid-support were investigated.

Task 1: State-of-the-art of nZEB

In the EU, the time schedule for the introduction of the nZEB requirements is depicted in Figure 9 and stipulates the introduction of nZEB for all new buildings by January 1, 2021 according to the recast of the EU-Directive on the Energy Performance of Buildings (EPBD recast, 2018). The first step, the introduction for all new public buildings has already taken place by January 1, 2019. In other countries worldwide, e.g. in the USA and Canada as well as in Asian countries like Japan or China, the introduction is intended in the time frame between 2020 and 2030.

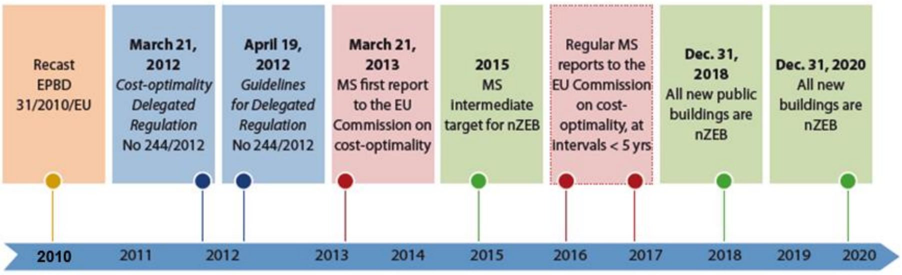


Figure 1: Time schedule for the implementation of nZEB in the EU member states (source: Atanasiu et al. 2013)

The state-of-the-art of nZEB in the different participating countries of the Annex 49 has been analysed. The intention of the EPBD recast (2010/2018) is to set higher objectives for building energy performance in new buildings in order to decrease energy use in buildings to nearly zero and thereby also promote renewable production at the building site or nearby. However, in the EPBD, only a vague outline of an nZEB as "a building with high energy performance" whose remaining energy demand shall be covered "to a large extent by renewable source on-site or nearby". The detailed definition are left to EU-member states (MS).

Despite different harmonisation initiatives, e.g. the collaboration of the Federation of European Heating, Ventilation and Air Conditioning Associations REHVA and the European standardisation organisation CEN to elaborate a common nZEB definition (Kurnitski et al., 2013) and a set of accompanying standards including the overarching standard EN ISO 52000-1 (ISO, 2017), resulting nZEB definitions in the EU MS vary in criteria, metrics and limits. In the USA, however, a similar definition to REVHA has been published in 2015 (DOE, 2015), so there is still a perspective of an internationally more harmonised definition to be introduced. An overview of the different definitions is compiled in BPIE (2015), JRC (2016) and IPEEC (2018). Moreover, despite the common CEN standards, which are currently elaborated also as ISO-standards, the different national definitions of nZEB are related to national rating procedures, which use national calculation methods to prove compliance with the nZEB requirement according to the national implementation. As a consequence, even with a common definition, the implementation in the individual countries would vary due to different national boundary conditions, climate data and calculation methods. Thus, it is hard to assess and compare the ambition level across the EU-MS. The ambition level denotes, how ambitious the national requirements are to derive a high energy performance of the nZEB implementation.

According to EU requirements the minimum ambition level for a national nZEB implementation shall be the cost-optimal level, i.e. the best energy performance at minimum cost. The EU has published guidelines (EC, 2012) how to perform the cost-optimality evaluation and obliged the EU MS to report in 5-year intervals on cost-optimal levels, see also time schedule in Figure 9. Moreover, in 2016 the EU has published recommendations for four European climate zones as orientation of the ambition level to be achieved by the national nZEB implementations for single family houses and office buildings (EC, 2016).

The ambition level of different countries can be shown either relative to each other (by normalizing the boundary conditions such as climate, internal gains, etc.) or with respect to an ambitious energy standard such as the widespread passive house. The comparison of ambition levels would be useful information for policy makers to set requirements for high ambition levels in the new built sector, as intended by the EPBD recast.

Therefore, in the Task 1 of Annex 49, a methodology to compare the ambition levels of different nZEB implementations has been elaborated. The method is based on simulations of the national implementation of the nZEB building at common boundary conditions. Thereby, a relative ranking regarding the ambition level is possible. The method has been tested for a single family building and the countries Austria, Germany and Switzerland, which covers central European climate with pronounced heating demand. The evaluation confirms that also the ambition level of the implementations strongly vary across the countries and do not fulfil EU recommendations in all countries.

Details on the background and state of the art of nZEB as well as the developed methodology to compare ambition levels of the EU nZEB implementation in participating countries of Annex 49 is found in the Report Annex 49 part 1 on the state-of-the-art of heat pumps in nZEB.

Conclusion State of the art of nZEB

nZEB implementation in the EU has started with public new buildings in 2019 and is concluded with all new buildings by January 1, 2021 according the EPBD recast (2018). Other countries worldwide like the USA and Canada as well as Japan and China will follow in the time frame of 2020-2030. Current nZEB implementation, however, vary in terms of criteria, metrics and limits, and thus, the ambition level of the individual implementation are hard to compare.

A methodology elaborated in Annex 49 indicates that some countries set higher requirements to building performance, while other virtually stay on the same lower ambition level as before nZEB implementation. It also indicates that some countries are less ambitious than required by the EU recommendations. Therefore, a common methodology to assess ambition levels should be established and approved/recognized to entirely implement the EPBD.

The all electric building concept, as a combination of heat pump and PV, is an archetype for an nZEB implementation and already found often in realised nZEB. Thus, the introduction of nZEB for all new buildings could be a market driver for heat pumps due to the high performance requirements for the building technology.

Monitoring of nZEB with heat pumps

A focus of the work and national contributions in IEA HPT Annex 49 was the monitoring of in total more than 15 monitoring projects in nZEB with integrated and multifunctional heat pumps in residential, office and other non-residential use as well as in groups of connected buildings. The focus of the monitoring projects was on larger buildings, since the nZE balance is relatively easy to meet for smaller residential buildings, where building loads are limited with high performance building envelope and the outer building surface is large enough for on-site energy production. In larger residential and non-residential buildings, though, the ratio between building load and on-site energy production capability is shifted and achievement of ambitious nZEB or even plus energy targets is much more challenging than in smaller residential buildings. Actually, many projects set higher ambition 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.
Thus, optimised building technology in combination with high performance buildings envelopes and optimised on-site energy production are a prerequisite to meet ambitious energy target for the future sustainable built environment. The detailed and long-term monitoring over a period of several years give valuable evaluation of real-world performance of nZEB with heat pumps and show typical optimisation potentials. On-site PV self-consumption is another aspect which is evaluated regarding load management with the heat pump and storage technology. Key performance indicators used for the evaluation of the on-site production and consumption of PV electricity are the load cover factor (LCF), which relates the on-site PV self-consumption to the total building energy demand and the supply cover factor (SCF), which relates the on-site PV self-consumption to the total PV-yield. Details on all monitoring projects in Annex 49 are found in the Report Annex 49 part 2 on Field monitoring.

Monitoring in residential nZEB

The focus on residential buildings were single family and multi-family buildings with high ambition level of a plus energy balance. Figure 2 depicts the monitoring projects of the residential buildings in Annex 49. The U-values are in the range of high performance building envelopes with values for the outer building surface components of 0.09–0.3 W/(m^{2}K) and for the windows of 0.8–1.1 W/(m^{2}K). Due to the high ambition level the space heating demand is with 11-30 kWh/(m^{2}yr) in the range of ultra-low energy houses, while some buildings are explicitly designed as passive houses. All investigated buildings are equipped with a ground-coupled heat pump, except for one groundwater heat pump and one building equipped with solar-ice heat pump system, i.e. a solar absorber and ice-storage as heat source for the heat pump.

Figure 2: Monitoring projects of residential buildings in IEA HPT Annex 49

Results confirm that the single family can meet a plus energy balance, while not all multi-family building met a plus balance. A plus balance is harder to achieve in larger multi-family buildings with limited options for on-site production. Even if the façade is additionally used for energy production, the achievement of the positive energy balance can be challenging despite a good performance of the heat pump. Seasonal performance factors (SPF) are in the range of an SPF of 3-5, while for the lower SPFs, optimisation potentials could be identified. Evaluated PV-self-consumption in terms of the load cover factors (LCF)/supply cover factors (SCF) are in the range of 20-30%/30-50% for single family houses and in the range of 20-40%/50-70% for the multi-family houses. However, design of the PV systems and installed thermal and electric storage capacity differ among the buildings.

Conclusion of monitoring in residential nZEB

In conclusion of the monitoring experience in residential nZEB the following can be summarised:

- In smaller residential houses, a plus energy balance is reachable with a PV installation on the roof only. In general the building envelope offers enough space to reach a surplus energy in the annual balance, even in northern climates.
- In larger multi-family buildings of 3-5 storey of even higher, the achievement of an ambitious balance is more challenging, and normally the roof does not offer enough space, but the façade has to be additionally used for on-site energy generation. Thus, a high performance building envelope and an optimised system performance are a prerequisite to achieve ambitious nZE balance criteria.
- This also implies higher cost for a plus energy balance due to PV façade integration, but may also contribute to higher PV self-consumption due to shifted production of the façade.
- On-site PV self-consumption tends to be higher in multi-family buildings with differing occupancy and load structures of the inhabitants.

Monitoring in nZE buildings with office use and groups of buildings

Besides the residential applications also groups of residential/office buildings and buildings with mixed residential/office use were monitored. This comprises two buildings with retail/ offices on the ground level and flats in the upper storeys. A high-rise office building also contains retail on the ground floor. Moreover, two groups of residential buildings, one group with 8 single family houses and one group with 6 multi-family houses, and a group of five office buildings, where a new building supplies heat to the four older buildings, have been monitored. Figure 3 shows the monitored buildings with office use and the groups of buildings.

Figure 3: Monitoring projects with office use and groups of buildings in IEA HPT Annex 49

All buildings are equipped with ground source heat pumps, expect for the group of 6 residential buildings, which uses a combination of the ground, ground water, exhaust air and solar heat. However, for the building with cooling demand, also regeneration heat or waste heat is used as heat source. Installed capacities vary from 30 kW in the residential buildings to MW range in the high rise office building, reference areas range from 1,000–50,000 m^2. The space heating demand is in the range of 10–35 kWh/(m^2yr), so independent of the use, high performance building envelopes are installed. In particular for the groups of buildings and the mixed residential and office use, also the integration of a cooling function is a focus in the system concepts in order to increase the heat pump performance by simultaneous heating and cooling, waste heat recovery and ground regeneration.

The monitored group of residential buildings and mixed residential and office use show high SPF values in the range of 5 and higher, which facilitates meeting the balance. For the single family house application, actually, a plus energy balance is reached. However, for the buildings with office use, ambitious balance target are still challenging, despite the good heat pump performance values, which are also due the integration of different building services with the heat pump, e.g. combined space cooling and DHW operation. For high rise office building, only information on the commissioning phase were available. The focus in the project was an integrated planning process for complex nZEB. The larger group of the multi-family and office buildings, only first year or commissioning data were available. The combination of the different heat sources showed a good availability and robustness, and the best available heat sources could be used depending on the season, i.e. the ground in winter operation and exhaust air and solar in summer operation. The group of office building yielded an overall SPF of 4.3 in the first year of operation, but investigation also indicated further optimisation potentials. Evaluated LCF and SCF are in the range of 25-60%/30-40% and tend to be higher with mixed use or in groups of buildings similar to multi-family houses.

Conclusion of nZEB with mixed use and groups of nZEB buildings

nZEB groups of buildings show positive monitoring experiences and reach high SPF, in the case of the 8 residential building houses an SPF of the central heat pumps above 5 and good load management options were found, see chap. 0. Also the combination of office use and residential use can have synergies by the different load structures, enhancing the heat pump performance. However, system complexity may also rise, but the connection of buildings hold the potential to recover waste heat by combined heating and cooling operation with the heat pump.

Regeneration of the ground source is applied in all projects, either by freecooling or by waste heat recovery. Result found in the monitoring are promising, and further investigations of the benefits by thermal and electric integration in groups of buildings should be performed in the future.

Monitoring in nZEB with other non-residential use

Also some projects with non-residential use other than retail/offices have been contributed to the Annex 49, namely two schools, a kindergarten, a large hotel and a supermarket. Besides the nZE balance these applications are not standard applications for heat pumps, yet. Thus, experience with the heat pump application could be gathered for these applications. However, some of the projects use also combinations with other heating systems and heat generators, e.g. fractions of space heating and DHW are covered by district heating and solar thermal collectors in the hotel application. Moreover, also quite different heat sources are used in the projects, e.g. energy piles and an agro-thermal ground collector in the school building and waste heat from the supermarket refrigeration for heating and ground regeneration. The reference areas range from 833-14'400 m^2. Installed heat pump capacities range from 19-200 kW and the space heating demand is in the efficient range of 19.2-32.1 kWh/(m^2yr).

Figure 4: Monitoring projects of non-residential buildings in IEA HPT Annex 49

Performance values range from moderate to good performance, and SPF values of the heat pumps are in the range of SPF = 3-5 for the different applications. Another peculiarity is that the planning values are surpassed in most of the projects, i.e. the measured energy demand is partly double of the design values. However, even though the large secondary school reaches seasonal performance values of 4.7-5.2 over a four year monitoring, the intended plus energy balance could not be reached, but the energy demand was reduced from year to year. Other performance values were affected by differences to planning values. The primary school was equipped with a tailored CO_2-heat pump and adapted emissions system including radiators and floor heating, but DHW use was much lower than expected. Moreover, the CO_2-heat pump had a malfunction of the high pressure sensor. Thereby, only a moderate SPF of 3 was evaluated, but optimisation potential were already implemented.

Conclusion of nZEB with other non-residential use

In the non-residential application other than offices, larger deviation to planning values were observed in the monitoring. Thereby, the projected plus energy balance of the secondary school was not reached despite a good SPF of the heat pump in the range of 5, and also the other projects deviated from the expected performance values. In the other projects the heat pumps had moderate SPF in the range of 3, which was partly due to malfunctions detected in the first year of operation, but partly also due to the deviations of the load from the planning values. However, all projects with moderate performance also showed optimisation potentials, so better performance is expected in the future. Also in the non-residential application the integration of space cooling by the heat pump is of particular interest to recover waste heat and increase the performance by simultaneous operation or regeneration of ground sources.

Prototype developments for nZEB

In Annex 49, also new prototypes of heat pumps or chillers for nZEB application have been developed as highly integrated and compact units. Developed prototypes had also an emphasis on cooling, either as integrated or as main operation mode of the unit. Also new and existing prototypes have been further investigated by lab- and/or field testing. Details on the prototypes depicted in Figure 5 are contained in the Report Annex 49 part 4 on prototypes.

Figure 5: Prototypes and test sites in IEA HPT Annex 49

At **IWT of TU Graz**, a **façade integrated cooling device** with 2 kW cooling capacity has been developed by simulations, prototyping and monitoring. The prototype heat pump is covered by façade-integrated PV-modules, which are sufficient to cover the cooling demand of the adjacent room due to good load match. In space heating mode the unit can cover about 40-60% of the heating demand for Graz climate. Different operation modes like grid-independent and grid-coupled operation with and without battery storage as well as different cooling options by fan coils or thermally activated concrete ceiling have been investigated.

At the **HSR Rapperswil**, an **unglazed absorber** has been tested **for night time cooling application**. The component is already market available for space heating and DHW application, and the system shall be extended by an integrated freecooling function. Cooling capacities, though, are strongly depending on the weather conditions. At clear sky and moderate nighttime temperatures between 23-13 °C, cooling capacities of 175-250 W/m^2 have been measured, while for cloudy sky values are in the range of 75-100 W/m^2 were evaluated.

At the **CEEE of the University of Maryland**, a **roving comforter (RoCo) unit**, which is a personal-sized heat pump that cools indoor air to guarantee occupants comfort has been developed as several prototypes and is now in the market introduction. Energy analysis in office buildings for 9 climates revealed that RoCo can provide between 9-49% energy savings. Phase change material development was another focus of the project, both regarding good latent heat capacity and thermal conductivity. Field testing showed that RoCo can provide 10 W effective cooling, reducing body temperature by 1 K and heart rate by 9 BPM. Most people expressed a better thermal sensation with RoCo.

At the **ORNL** a long-term development of the **Integrated Heat Pump (IHP)** for space heating/cooling, DHW and dehumidification has been carried out. A ground-source and three air-source variants have been designed, lab-tested and simulated and subsequently field tested. Field tests results for the different prototypes variant are summarised with implications to market state and introduction. While the ground-source variant is already on the market for several years, for the gas-driven air-source variant, a value engineering is carried out in order to improve cost-competitiveness.

At **NIST** campus the **Net Zero Energy Residential Testing Facility** (NZERTF) has been designed and operated for several years. The test house with tunable loads is a testing platform for nZE technologies. As contribution to the Annex 49 two air-source heat pumps, a conventional ducted system and a small duct high velocity system have been extensively tested in space heating and cooling mode. Future testing will incorporate also the ground-source IHP.

Conclusions prototype developments

- All prototype developments in Annex 49 were dedicated to highly integrated units, both regarding integrated functionalities to cover all building services with one unit and regarding compact design, e.g. an integrated recooling storage or a compact façade integrated unit
- Prototype developments and testing had a focus on integrated space cooling operation, since with rising temperatures, the need for sustainable space cooling options increases
- Besides developments, also component and system testing of prototypes in the lab and in field testing has been contributed to Annex 49.

Accompanying investigations to heat pump application in nZEB

Besides the monitoring more detailed investigations on the integration, design or control of the heat pump for nZEB have been carried out partly linked to the monitoring. But also investigations apart from the monitoring projects have been contributed, e.g. the storage of heat in the building structure or a simulation study on the design of speed-controlled heat pumps. Details on the accompanying simulations are contained in the Report Annex 49 part 3 on simulation.

Figure 6: Monitoring projects for accompanying detailed analysis of integration, design and control

A focus of these accompanying investigations was set on smart integration of the heat pump with other building components, in particular thermal/electric storages for demand response.

- For the building **Berghalde**, a single family house with large PV installation, both self-consumption and grid support have been investigated by smart control as well as thermal and electric storage design. Electric storage can notably increase the self-consumption, but is currently not economically feasible. Moreover, control strategies and thermal storage up to 2,500 l have the potential to increase self-consumption. Design diagrams have been derived based on the investigations.
- For the group of 8 single family terraced houses in the **HerzoBase project**, rule-based control has been applied for load management by a central battery as well as central and decentralized thermal storages. Simulations confirm that grid load peaks could be reduced up to 24% in the winter month. While direct use of PV electricity could be increased up to 21%, grid feed-in could be reduced by 10% and battery charging by 11%.
- In **NTNU in Norway**, the load management has been assessed from the grid perspective. By the control of the heat pump the CO_2-balance of electricity use can be improved, but this may counteract with electricity pricing.
- At **UIBK**, two multi-family passive houses have been modelled in detail and validated with monitoring data of four years of measurements. The validated models have been used to perform detailed investigation on desuperheater use and system configurations and optimization potentials of the nZE balance. Results confirm that with extended PV-area instead of solar thermal (ST), an nZE balance can be reached. A desuperheater use at low heating demands does not promise high performance increase due to reduced running time.

Further investigations for heat pumps in nZEB have been carried out independent of monitoring

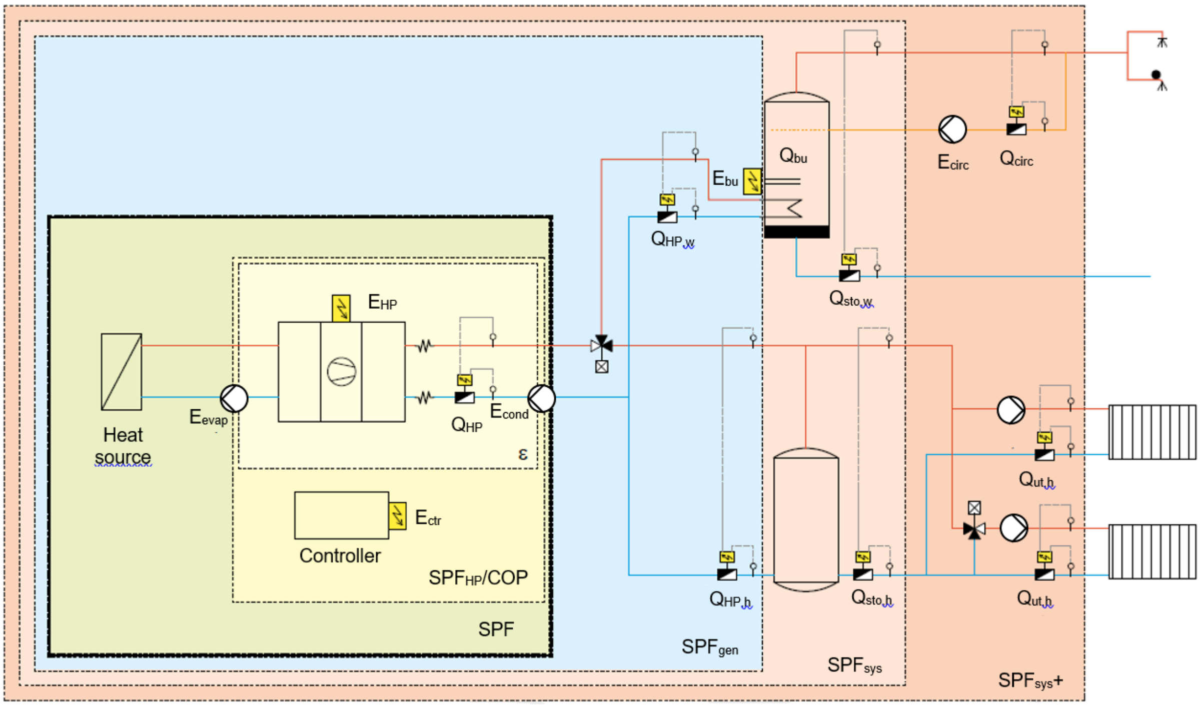
- At the **TU Graz**, the storage of solar heat produced by ST or solar PV in the building structure has been investigated. It was found that thermally-activated building system can offer a favourable option to reach high solar fraction both for PV and ST yield.
- At **HSR Rapperswil**, the design of capacity-controlled heat pumps for the application in nZEB has been investigated. It was found that a rather scarce design yield more part load operation at high COP values. Together with the NTNU, smart control has been tested. Results are ambiguous, since cost can be reduced, but energy use increases.

Conclusion of accompanying investigations by simulations

- Some of the monitoring projects were also used by for accompanying simulations
- Calibrated simulations proved to be a valuable means to identify optimisation potentials regarding the system configuration and integration as well as the design of components
- Load management options by the heat pump and thermal and electric storages confirmed the potential of the heat pump to significantly increase the on-site PV-self-consumption and grid support
- The building thermal mass can also by be beneficially used for load management and increase solar thermal of solar PV fractions
- Capacity-controlled heat pumps should be designed scarcely in order to maximize part-load operation at high COP values

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})

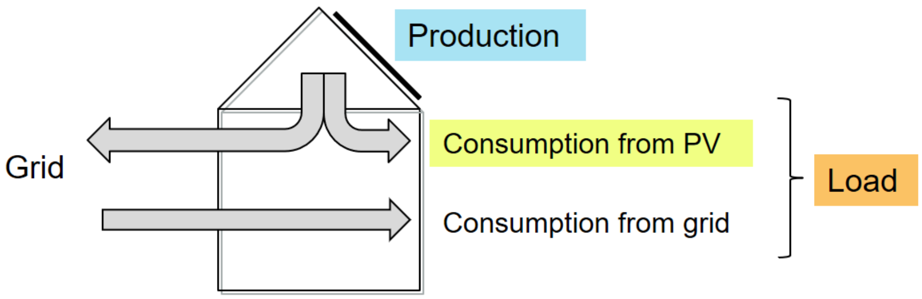
$$SPF_{sys} = \frac{Q_{sto}}{E_{HP} + E_{src} + E_{sink} + E_{ctr} + E_{defrost} + E_{carter} + E_{bu} + E_{bu,aux}}$$

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 7: 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 additional carter 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 dehumification.



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

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

Figure 8: Definition of load cover factor and supply cover factor (source: FhG-ISE)

Figure 8 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 IEA HPT Annex 49 project and national contributions

The IEA HPT Annex 49 entitled "Design and integration of heat pumps for nZEB" in the Technical Collaboration Programme (TCP) of Heat Pumping Technologies (HPT) of the International Energy Agency (IEA) is carried out cost- and task-shared with the eight participating countries AT, BE, CH, DE, NO, SE, UK and the USA. The project management (Operation Agent) is accomplished by the Institute of Energy Technologies (IET) of the University of Applied Sciences Rapperswil (HSR) in charge of the Swiss Federal Office of Energy (SFOE).
The main objectives of IEA HPT Annex 49 are

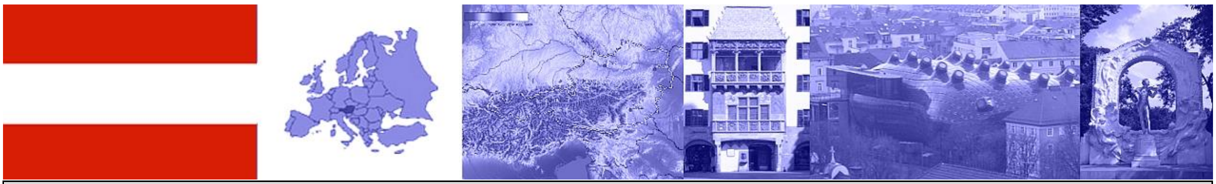
- Heat pump integration, component design and control
  - Integrated operation of the heat pump for different building services
  - Integration of heat pump with thermal/electric storage and PV
  - Heat pump control for increased on-site electricity self-consumption and reduced grid interaction
  - Standardised system solutions
- Assessment of heat pump operation in built nZEB by field testing
  - Field test of marketable heat pump systems in larger nZEB
  - System modelling and optimisation
  - Identification of optimisation potentials, hints for further system developments
  - Design recommendations and Best Practice Systems
- Prototype developments
  - Development of integrated heat pumps for nZEB application
  - Lab- and field testing of integrated heat pumps for nZEB

Table 2 gives an overview on the national contributions of the countries in Annex 49. Details of the involved persons and contributions of the participating countries is shown as an overview in the following chapters 1.1 - 1.8.

Table 2: Overview of contributions of the participating countries to Annex 49

Country/Institution	Contribution to IEA HPT Annex 49
Austria Unit EE building Univ. of Innsbruck, IWT TU Graz, AIT, Vienna	• Monitoring & simulation of two nZEB passive houses for optimization • Development of a prototype of a façade integrated heat pump • Evaluation of larger nZEB buildings
Belgium Free Univ. Brussels	• Evaluation of heat pump in office nZEB with sewer heat recovery
Germany TH Nürnberg, siz+, TEB GmbH	• System integration, design and field monitoring of different nZEB buildings • Development of control strategies for increased PV self-consumption and reduced grid interaction
Norway SINTEF, NTNU, Cowi AS	• Monitoring of nZE demonstration buildings in Norway • Evaluation and control of energy flexibility in nZEB
Sweden RISE	• Monitoring and comparison of heat pump systems in two equal test houses • Evaluation of heat pump solutions for nZEB in Sweden
Switzerland IET HSR	• Integration and design options of solar and heat pump systems • Field monitoring of nZEBs with residential and office use • Investigation of design of speed-controlled heat pumps
UK Glen Dimplex	• Evaluation of design and control of nZEB model houses
USA ORNL, NIST, CEEE, City@UMD Univ. of Maryland	• Field monitoring of integrated (IHP) heat pump variants • Technology testing and comfort evaluation in NZEB test facility (NZERTF) • Prototype development of a personal cooling device for NZEB offices

1.1 Austria



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National contribution financially supported by	
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Project overview

Based on the detailed state of the art analysis of the nZEB implementation in residential and office buildings, the UIBK has contributed to the development of the methodology to compare ambition levels of nZEB across countries. Moreover, two multi-family houses as certified Passive House Plus have been monitored over a four-year period and investigated by simulations to optimise the system configuration and the nZEB balance. Therefore, a model of the two-compressor heat pump the storage and the building has been validated by monitoring results and different optimisation potentials have been derived by simulation.

At the IWT of the TU Graz, a prototype of a façade-integrated heat pump has been developed, simulated and monitored in two test cells on the University campus in the project COOLSKIN. The development goal was to create an autonomous cooling system driven by PV modules in the façade for the supply of the adjacent office room. The heating was also evaluated. In a further simulation study based on the solSPONGEhigh project, the solar fraction with A/W-heat pump and solar thermal collectors or PV modules in combination with thermally activated building systems has been investigated for different control strategies. Results confirm, that with rather simple control strategies the solar fraction can be significantly increased.

At the Austrian Institute of Technology AIT in Vienna, two monitoring projects of nZEB have been contributed. One monitoring has taken place in a group of buildings at the Smart city P&D neighbourhood Aspern and in the other project refers to a large office building which serves as the new headquarter of the Austrian "Post am Rochus". Besides the evaluation of the nZEB implementation, the focus of the first project was the integration of multiple sources for the 7 heat pumps in the neighbourhood connected by thermal grids. The focus of the second project was the evaluation of the integral planning/commissioning process for a complex office nZEB.

Summarising Austria contributed the following projects to the Annex 49 Tasks:

Task 1: Analysis of the Austrian nZEB implementation OIB in detail for residential and office buildings and simulation of Austrian nZEB for the comparison of ambition level

Task 2: Modelling and simulation of system integration, design and control of the two multi-family buildings

Task 3: Long-term monitoring of a four-year period of two multi-family passive buildings
Monitoring of a residential group of buildings with multi-heat sources and nZEB offices
Development and monitoring of a façade integrated heat pump prototype

Task 4 Simulation of control strategies for solar fraction with TABS

1.2 Brussels region of Belgium

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Project overview

At the Aero Thermo Mechanics lab of the Free University of Brussels (Université Libre de Bruxelles) the use of waste water in the sewer is investigated as the heat source and heat sink for heat pumps in order to supply heating and cooling to buildings. The project partner Vivaqua intends to retrofit the sewer with heat exchangers during work which has to be performed on the sewer.

Measurements of the volume flow rate and of the temperature level in the sewer have been performed in collaboration with the project partners.

In order to evaluate the performance of the sewer heat recovery for the waste water as a heat source and sink for heat pumps a field monitoring project for a group of five nZEB office buildings in Uccle near Brussels is performed. The sewer shall be applied for both heating and cooling operation of the office buildings. The sewer is combined with a second system, so the sewer heat source will only cover a part of the total source energy demand.

A second monitoring project is in discussion, which is linked to university buildings in Brussels. The sewer runs under the street in front of the building and shall be retrofitted with a heat recovery as heat source for the supply of the buildings.

Due to delays in the monitoring projects no measurement data could be evaluated in the time frame of the Annex 49.

Furthermore the developments of an autonomous modular building MØDÜLL 2.0 was presented.

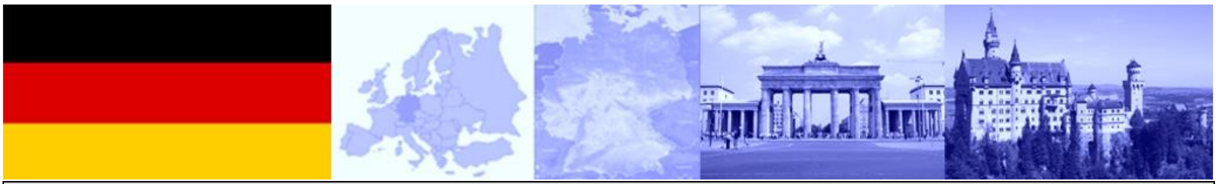
Summarising Brussels region of Belgium contribution to the Annex Task is:

Task 1: State of the art of nZEB implementation in Brussels region of Belgium

Task 2: Integration of heat pumps in the autonomous modular building MØDÜLL 2.0

Task 3: Measurements of volume flow and temperature of heat recovery from the sewer
Monitoring of sewer heat recovery for the heating and cooling of a group of five nZEB office buildings (no measurements in the time frame of Annex 49)

1.3 Germany



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National contribution financially supported by	
	Bundesministerium für Wirtschaft und Technologie, http://www.bmwi.de

Project overview

The national projects of Germany are dedicated to the integration, control and field monitoring of heat pumps in nZEB. Based on the state of the art analysis of the nZEB implementation in Germany, the EnCN building and the TEB GmbH have contributed to the development of the methodology to compare the ambition level.

In Task 3 different long-term monitoring projects have been carried out. A group of eight single family terrace houses are investigated by simulations and in field monitoring in the project HerzoBase by EnCN building. The group of houses is connected by a thermal grid to two central heat pumps. The system includes also an electric battery and thermal buffer storages. The DHW is produced in decentralized storages with booster heat pumps. The plus energy balance is reached by the 98 kW_p PV system installed on the roof of the houses. Besides the verification of the plus energy balance also storage integration and control are investigated.

At the IGS of TU Braunschweig (now: Steinbeis-Innovationszentrum Energie+ (SIZ energie+)), long-term monitorings over 4-8 years have been accomplished for three different nZEB, a single family building, a 5-story multi-family building and a secondary school, which have all been designed to reach a plus energy balance. While the single family house and the school use ground-coupled heat sources (borehole heat exchanger, energy piles and a horizontal agrothermal field, respectively), the multi-family building uses absorbers installed under the PV installation on the roof and an ice storage.

Based on the monitoring projects, the integration of both electric and thermal storage with the heat pump has been investigated by simulation in Task 2. In Task 4, smart controls to optimise on-site PV use with the combination of heat pump and storage have been developed.

Summarising the following contributions have been made to the Annex 49 Tasks:

Task 1: Analysis of the German implementation of nZEB for residential and office buildings and simulation of German nZEB implementation for comparison of ambition level

Task 2: Simulation of the thermal and electric storage integration with the heat pump and PV

Task 3: Monitoring of a group of 8 single family buildings
Long-term monitoring of 3 different types of nZEB (single/multi-family/school)

Task 4: Development of smart heat pump control as rule-based and model-predictive control to increase PV self-consumption and decrease grid interaction

1.4 Norway

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National contribution financially supported by	
ENOVA ZEN	Enova SF, http://www.enova.no ZEN – Norwegian Research Center on Zero Emission Neighborhoods in Smart Cities (FME ZEN), https://fmezen.no/

Project overview

In Norway, there is no official definition of an nZEB currently. However, while most of the countries include a primary energy limit in the requirement for nZEB rating, the research centres on Zero Emission Buildings (ZEB) and Neighbourhoods (ZEN) focus on limiting CO_{2eq}-emissions. These centres also focus on the emissions over the entire building lifecycle.

In the state-of-the-art analysis, an overview of Zero Emission Building criteria and the state of high-performance buildings and heat pumping technologies is provided.

In Task 2 and Task 4 (on heat pump integration, design and control), the energy flexibility potential of Norwegian residential buildings has been investigated. Different (predictive) rule-based control strategies have been examined by simulation, among them a price-based and CO_2-intensity based control. The objective is also to reduce the grid interaction, typically in terms of peak load in the electricity grid and PV self-consumption. The simulations were based on the ZEB Living Lab located at the Gløshaugen campus of NTNU in Trondheim. The ZEB Living Lab is a single family plus-energy wooden building equipped with a ground-source heat pump and a solar thermal system with 4 m^2 collector area as well as a 12 kW_p solar PV system. Also, the impact of the modelling complexity on the accuracy of simulation results have been investigated for different control strategies.

In Task 3, Norway performed monitoring of office buildings, a large hotel, a primary school, a kindergarten and a supermarket, which were designed as high-performance buildings according to the Nordic passive house standard and one of them certified according to BREEAM Nor. Each of the buildings is equipped with a ground-source heat pump with borehole thermal energy storage regeneration in the case of cooling applications, except for the hotel, which is equipped with an air-to-water heat pump. The kindergarten uses a horizontal ground collector as heat source.

Summarising Norway contributed the following projects to the Annex 49:

Task 1: State of the art of heat pumps and high performance buildings in Norway
Task 2: Integration of storage and heat pump for grid supportive operation
Task 3: Monitoring of different larger nZEB with office and other non-residential uses
Task 4 Investigation of predictive rule-based control strategies for grid supportive operation by simulation for a single family nZEB

1.5 Sweden

National team leader	
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Project overview

In Task 1 Sweden has provided the current state of the art of nZEB implementation in Sweden. At RISE in Borås and Valberg, there are two so-called twin houses, which refer to identical houses at the same weather conditions. However, one house is inhabited by a real family, while the other house is equipped with tunable loads. In one house, an on-off controlled ground-source heat pump is installed, while the other house is equipped with an inverter controlled ground-source heat pump.

In Task 3, monitoring results of the two houses were evaluated, including the integration of the heat pump and the heating buffer storage with the floor heating system in the second house. Furthermore, a free cooling operation for the summer by a borehole heat exchanger connected to the ventilation air system has been evaluated.

In Task 4 different heating systems for nZEB in Sweden have been investigated. While formerly ground-source heat pumps were a viable solution, currently, exhaust air heat pumps are a favourable heat pump system for residential nZEB application in Sweden

Summarising, the following contributions to the Annex 49 Tasks were made by Sweden:

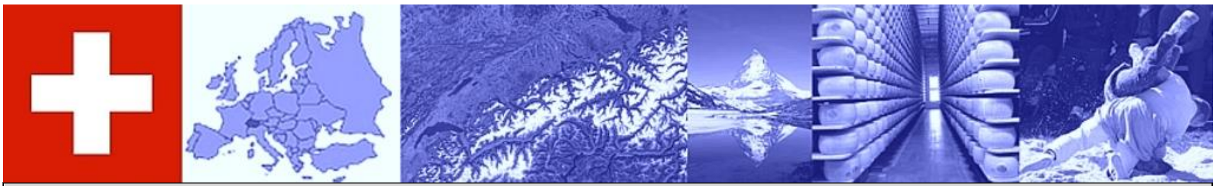
Task 1: Swedish implementation of nZEB

Task 2: Evaluation of buffer storage and floor heating integration, evaluation of free-cooling operation of the ventilation air by borehole heat exchanger

Task 3: Monitoring of heat pumps in single family twin houses in Borås and Valberg
Monitoring of free cooling operation

Task 4 Comparative investigation of heating systems for nZEB in Sweden

1.6 Switzerland



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National contribution financially supported by	
Schweizerische Eidgenossenschaft Confédération suisse Confederazione Svizzera Confederaziun svizra Swiss Federal Office of Energy SFOE	Swiss Federal Office of Energy SFOE, Research Programme refrigeration and heat pumping technologies, Head: Dr. Carina Alles, Stephan Renz https://www.bfe.admin.ch/

Project overview

In Task 1 the HSR Rapperswil provided the state of nZEB implementation in Switzerland. Even though Switzerland is not bound to EU-Directives, the EPBD is also implemented in Switzerland by the building regulation MuKEn 2014 in the Swiss cantons. Simulations of the Swiss implementation were made for the development of the methodology to compare ambition level across European countries.

In Task 2 a feasibility study has been accomplished for heat pump and source integration for three groups of buildings with office, lab and hotel uses as well as a home for elderly people in Rapperswil-Jona. The objective was an NZEB balance for the three groups of buildings.

In Task 3, two nZEB buildings with mixed office and multi-family use designed to fulfil the MINERGIE-A® of 2014 have been monitored. One was the first MINERGIE-A certified building in canton Zurich with office use and the second building is situated in the city centre near the station with a façade integrated PV-system. Furthermore, two multi-family houses designed for a plus energy balance have been monitored. The one building in Wetzikon has 10 flats and a façade integrated PV system, the other is a four family building in Horgen, which is equipped with a low-temperature lift heat pump and a PV system on the roof. All buildings use a ground-source heat pump as a core component of the building technology, which are regenerated.

As prototype development in Task 3, tests of an unglazed solar absorber for freecooling application has been performed on the test rig in Rapperswil. Due to a selective coating, the absorber is wetted for nighttime cooling in order to increase the longwave heat rejection by radiation to the night sky, which is notably colder than the ambient at clear sky conditions.

In Task 4 a simulation study for the design and control of speed-controlled heat pumps has been performed. In collaboration with the NTNU a price based control has been tested for the Swiss market conditions.

Summarising the following contributions to the Annex Task have been made by Switzerland:

Task 1: Analysis of the Swiss nZEB implementation
Development of methodology to compare ambition levels in nZEB across countries

Task 2: Feasibility study for the integration of heating and cooling with heat pumps for nZEB group of building for a neighbourhood in Rapperswil-Jona

Task 3: Monitoring of two nZEB buildings with mixed office and residential use designed to meet MINERGIE-A®-label requirements (version 2014)
Monitoring of two multi-family buildings designed for a plus energy balance
Measurement of solar absorber for the integration of nighttime free-cooling for heat pumps with solar source system

Task 4 Investigation of the design and control of speed-controlled heat pumps by simulation

1.7 United Kingdom

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Project overview

The UK has followed a nearly Zero implementation based on CO_2-emissions instead of primary energy, so the EPBD should be implemented as nearly zero carbon emission building. However, due to the Brexit political development the implementation of the EU-Directives is no longer binding for the UK.

Glen Dimplex has developed a standard system solution for a residential nZEB in the UK in collaboration with a building company, which should have been monitored in Task 3. However, due to Brexit developments the priorities changed and no monitoring was performed in the time frame of the Annex 49.

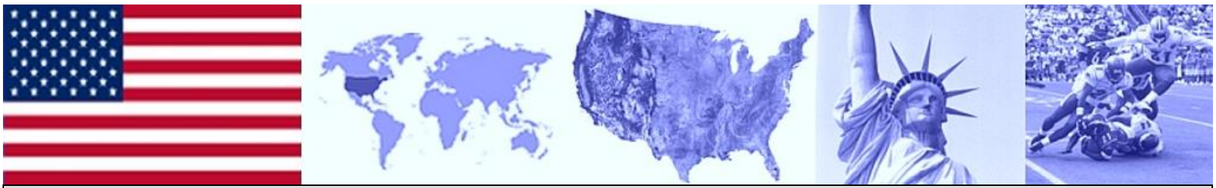
Summarising, the UK contribution to the Annex 49:

Task 1: Outline of UK boundary conditions for the nZEB implementation

Task 2: Concept of standard system solution for an residential nZEB in the UK in collaboration with a building company

Task 3: Monitoring of standard system solution for residential nZEB (no monitoring data in the time frame of the Annex 49)

1.8 United States of America



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Project overview

In Task 1 the USA provided a state of the art analysis of NZEB in the US. The introduction of nZEB is intended for the time frame between 2020 and 2030. A definition similar to REHVA has been introduced in 2015. Moreover, the DOE started a website with design guidelines and best practice examples and a nZEB ready label for home builders.

The Annex 49 contributions of the US are in Task 3. With the Net Zero Energy Residential Testing Facility, a Net Zero Energy Home on the NIST Campus with tunable loads, an ideal test bed for Net Zero building technology is operated. In Annex 49, a variable speed, small duct high air velocity air source heat pump system, which is easier to install than a conventional ducted air source heat pump, has been measured in detail in parallel to a conventional ducted air-source heat pump in the NZERTF both in heating and cooling mode.

In the frame of the integrated heat pump (IHP) development at ORNL four variants of highly integrated heat pumps with the functionalities of space heating, DHW, space cooling, ventilation and dehumidification have been developed, one ground-source variant and three air-source variants. The ground-source variant is already on the market, while the air-source prototypes have been field tested. Two of the air-source variants are electrically driven, and one variant is gas-engine driven and intended for classical gas supplied regions. Field test results and cost calculation of the units have been provided in a summary of the development. For the gas-engine-driven unit, a value engineering is planned in order to reduce cost and improve competitiveness.

At the CEEE of the Univ. of Maryland, a prototype of a personal cooling device, the Roving Comforter (RoCo) has been developed in multiple steps. The system provides cool air with an intelligent nozzle directly to the user to guarantee thermal comfort. Different climate zones in the US have been evaluated to derive energy savings. The unit can be operate for 8 hours due to an onboard phase-change material (PCM) that stores the waste heat of the cooling.

Summarising the US contributions to the following Annex Tasks have been made:

Task 1: Analysis of the state-of-the-art of NZEB in the USA

Task 3: Field monitoring of IHP variants and summary of development at ORNL
Testing of small duct and convention air source heat pump at NZERTF
RoCo development of personal cooling device with integrated PCM storage

2 State-of-the-art IEA HPT Annex 49

In the following the state-of-the-art of nZEB is shortly summarised. Details on the political background, the implementation of nZEB in the individual participating countries of the IEA HPT Annex 49 as well as a methodology for the comparison of the ambition level of the different nZEB implementation elaborated in Annex 49 and the heat pump application in nZEB are contained in the Report Annex 49 part 1 on the state-of the-art.

2.1 Political Background

In many countries worldwide, Net or nearly Zero Energy Buildings (NZEB/nZEB) are envisaged as future building standards. In the EU, the time schedule for the introduction of the nZEB requirements is depicted in Figure 9 and stipulates the introduction of nZEB for all new buildings by January 1, 2021 according to the recast of the EU-Directive on the Energy Performance of Buildings (EPBD recast, 2018). The first step, the introduction for all new public buildings has already taken place by January 1, 2019. In other countries worldwide, e.g. in the USA and Canada or Asian countries like Japan or China, the introduction is intended between 2020 and 2030.

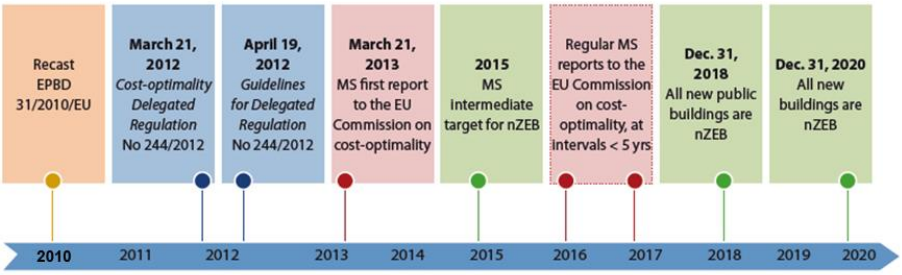


Figure 9: Time schedule for the implementation of nZEB in the EU member states (source: Atanasiu et al. 2013)

In the EPBD, though, only an outline of what is understood by an nZEB is given, and the elaboration of the detailed definition and requirements of nZEB has been mandated to the EU Member States (MS). In the present EPBD version of 2018, MS are also obliged to develop retrofit strategies for the building stock to be transformed to high energy performance.

2.2 State-of-the-art and methodology for comparison of nZEB

In Task 1 the state-of-the-art of nZEB in the different participating countries of the Annex 49 has been analysed. The intention of the EPBD recast is to set higher objectives for building energy performance in order to decrease energy use in buildings to almost (nearly) zero and thereby promote renewable production on the building site and nearby. However, in the EPBD, only a vague outline of an nZEB as "a building with high energy performance" whose remaining energy demand shall be covered "to a large extent by renewable source on-site or nearby". The detailed definition and requirements are left to EU-member states (MS). Despite different harmonisation initiatives, e.g. the collaboration of the Federation of European Heating, Ventilation and Air Conditioning Associations REHVA and the European standardisation organisation CEN to elaborate a common nZEB definition (Kurnitski et al., 2013) and a set of accompanying standards including the overarching standard EN ISO 52000-1 (2017), resulting nZEB definitions in the EU MS vary in criteria, metrics and limits. In the USA a similar definition as the REVHA definition has been introduced in 2015 (DOE, 2015), so there is still a perspective that in a next revision step, an internationally more harmonised definition will be introduced. An overview of the different definitions is compiled in BPIE (2015), JRC (2016) and IPEEC (2018). In the USA the Department of Energy (DOE) Energy efficiency and renewable Energy Office (EERE) has introduced a Zero Energy ready home initiative, defining strategies and requirements to achieve low to net Zero Energy consumption of new build homes (DOE, 2017). Different other initiative are directed to energy efficient retrofitting of existing homes and to commercial buildings.

Moreover, despite the common CEN standards, which are currently elaborated also as ISO-standards, the different national definitions of nZEB are related to national rating procedures which use national calculation methods in order to prove compliance with the nZEB requirement according to the national implementation. As a consequence, even with a common definition, the implementation in the individual countries may vary due to different national boundary conditions, national climate data and calculation methods.
Thus, by the different definitions and calculation methods, it is hard to assess and compare the ambition level across the EU-MS. The ambition level denotes, how ambitious the national requirements are to derive a high building energy performance. This can be shown either relative to each other (by normalizing the boundary conditions such as the climate and internal gains, etc.) or with respect to a certain ambitious energy standard, i.e. like the widespread passive house standard. The comparison of ambition levels would be useful information for policy makers to set requirements for high ambition levels in the new built sector, as intended by the EPBD recast. Therefore, in the Task 1 of Annex 49, a methodology to compare the ambition levels of different nZEB definitions has been elaborated. The methodology is developed and tested for the three D-A-CH countries Germany, Austria and Switzerland based on Reference framework (Dott et al., 2013), which refers to a single family building depicted in Figure 10 left. Some modifications have been made in order to turn the building into an nZEB.

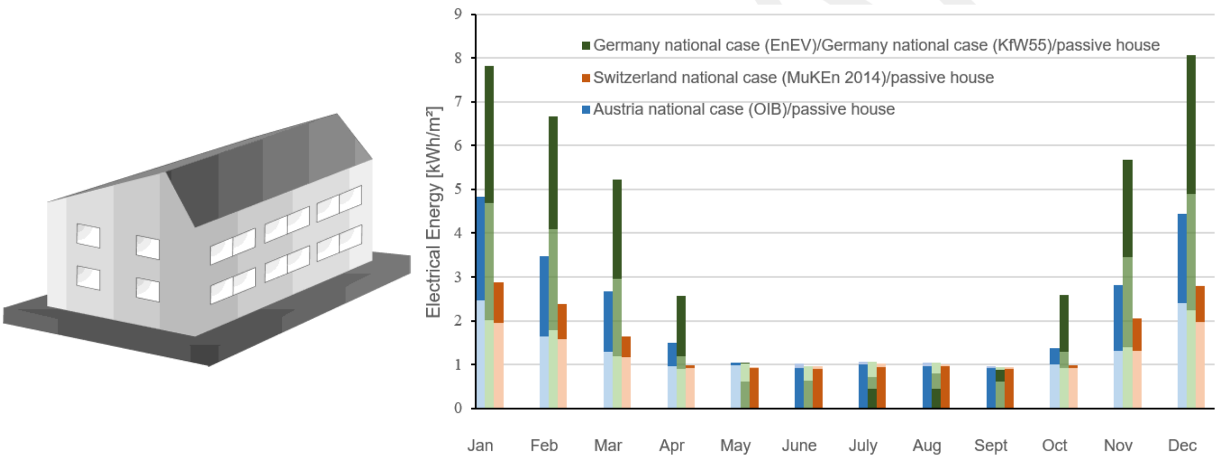


Figure 10: Single family building as used in other projects (left, Dott et al., 2013) and comparison of the electrical energy for the nZEB requirements in the D-A-CH countries (right)

Since a heat pump is applied as heat generator for space heating and DHW operation, the building corresponds to an all-electric building, which is understood within the Annex 49 as a building, which is equipped with a heat pump and solar PV and only uses electricity as delivered energy. As first step, based on the common reference building, the building is transferred to the local conditions and modified to exactly fulfil the national nZEB requirements. As second step the building is transferred back to common boundary conditions and then compared. Different comparisons have been carried out. For the same climate zone, the building can be compared at the common site which was set to Strasbourg based on the Reference framework. For the countries with the same climate zone, a comparison at the same site is possible, but for buildings e.g. for cooling dominated climate zone in southern Europe, this may bring problems. Thus, also a comparison based on the local site climate has been performed with the reference of the high performance building according to the widespread passive house standard. In Figure 10 right a comparison with a passive house in local climate is depicted. Results are shown as bars of the electrical energy of the different buildings on a monthly basis. The electrical energy required by the nZEB is shown as dark bar, while the electrical of the passive house as light bar. For Germany (green bars) two nZEB definitions, the EnEV 2016 (dark green) and the KfW55 (lighter green) are compared to the passive house (lightest green). The methodology (Wemhoener et al. 2019) enables a relative comparison. The figure shows that the ambition level in Switzerland is closest to the local passive house and is thus set higher than in Germany and Austria, where the difference to a local passive house is higher.

In this depiction, however, requirements for on-site renewable production are not included, yet, which would even amplify the difference, since Switzerland has also a requirement for PV-installation in nZEB, while Germany and Austria do not have a prescription regarding on-site renewable production in their nZEB implementation.
According to EU requirements the minimum ambition level for a national nZEB implementation shall be the cost-optimal level, i.e. the best energy performance at minimum cost. The EU has published guidelines (EC, 2012) how to perform the cost-optimality evaluation and obliged the EU MS to report in 5-year intervals on cost-optimal levels, see also time schedule in Figure 9. Moreover, in 2016 the EU has published recommendations for four European climate zones as orientation of the ambition level to be achieved by the national nZEB implementations. Values have been published for residential and office buildings (EC, 2016). Furthermore, two additional benchmarks have been defined within Annex 49. The worst level is limited by building physics to avoid moisture on internal wall surfaces and to guarantee thermal comfort, which requires minimum thermal insulation level. As best nZEB variant, a building, which reaches an annual zero energy balance is calculated, but only the self-consumed on-site PV electricity is balanced, thereby leaving a net energy consumption. Based on the different benchmark values of cost-optimality, building physics and nZEB with only self-consumption balance, a diagram has been developed in the colour code of building energy performance certificates, where the ambition level of the nZEB implementation in the individual countries can be depicted. The minimum requirement in Figure 11 (in yellow) is thereby a range of ±10% around the cost-optimal level, since the optimum can be quite flat. If energy performance requirements are higher than the cost optimal level the building ambition level shifts in the green area with the limit of the self-consumption rated nZEB, if it is worse, it shifts in direction of the orange boundary of building physics and thermal comfort limits. Figure 11 depicts the energy-cost diagram for the ambition level for Austria (left) and Switzerland (right).

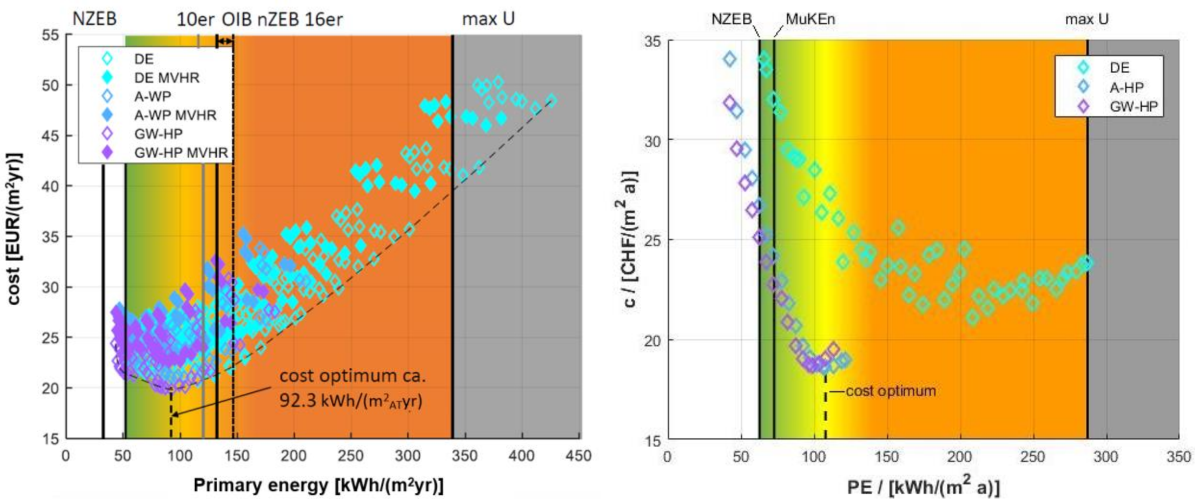


Figure 11: Comparison of the Austrian (left) and the Swiss implementation (right) of nZEB in an energy-cost diagram based on cost-optimality calculations (legend: OIB–Austrian building regulation, 10er/16er–different nZEB rating methods according to OIB, NZEB–Net Zero Energy Buildings, MuKEn–Swiss building regulation, DE–direct electric heating, MVHR–mechanical ventilation heat recovery, A-WP–Air-to-water heat pump, G-WP–Brine-to-water heat pump, max U – maximal allowed U-value by building physics/thermal comfort)

In correspondence to Figure 10 right it can be seen, that the Austrian implementation is less ambitious with a position in the yellow-orange range than the Swiss implementation in the green area, i.e. Austria is on the fringe of EU requirements, while Switzerland is more ambitious than required by the minimum cost optimal requirement.

2.3 Heat pump application in nZEB

Heat pumps are considered as ideal building technology for nZEB due to their unique features:

- Heat pumps are highly efficient generators at low temperature differences to the conditioned space which is enabled by the high performance envelope and low loads of nZEB

- In nZEB space heating loads are decreasing and different building loads have an equal impact on the overall energy performance. DHW can make up more than half of the total heat demand and cooling in Europe or an additional dehumidification in the US and Asia get more prevalent. Heat pumps can serve multiple building services with one generator, which is ideal for new built high performance buildings like nZEB
- System integration of multiple functions with the heat pump can unlock further performance increase, since a simultaneous production of different building services can enable internal heat recovery, e.g. for space cooling (or dehumidification) and DHW. Simultaneous operation yields higher performance due to multiple use of the electricity
- 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

The combination of heat pumps and PV already established as an archetype building system in residential buildings. Thereby, also more ambitious targets like a plus energy balance can be reached depending on the design of the system components. However, due to the above mentioned particular features of heat pumps, further integration of the building technologies with storage and renewable energy productions can enhance system operation and be beneficial both for building owners as for the public power grid. Moreover, combining different building functions with the heat pump as generator can further increase the heat pump performance. Larger buildings are still more challenging regarding an nZEB balance, so system performance get even more important. Also with non-residential use, cooling demand can be more important, while DHW requirement may decrease or increase depending on the use. Moreover, larger buildings are more individual than more standardised residential applications. Thus, the Annex 49 work has a focus on larger buildings with residential, but also office and other non-residential use. Other topics for heat pumps, which are also covered by the Annex 49 contributions, are new refrigerants for heat pumps, smart control and demand response options, highly integrated compact heat pump units for multi-functional use and low temperature lift and capacity control for heat pumps.

2.4 Conclusion State of the art

By Jan 1, 2021, all new buildings in the EU member state have to comply with nZEB requirement according to the EPBD recast. However, what is understood by an nZEB varies among the member states both in criteria, metrics and limits and nZEB rating procedure are not harmonised despite different European and international initiatives. In the USA and Canada as well as in Asian Countries Japan and China an NZEB implementation is intended in the time frame from 2020-2030. In 2015, the DOE presented an nZEB definition which is similar to the REHVA definition, and NZE ready homes are already promoted by the DOE.

The methodology elaborated in Annex 49 enables a relative rating and indicates, that some countries make a step to higher building performance, while other virtually stay on the same lower ambition level as before the nZEB implementation. It also indicates that some countries are less ambitious than required by the EU recommendations for nZEB ambition levels (EC, 2016). A diagram to visualise the ambition level of nZEB in the respective country based on the cost-optimality guideline (EC, 2012) has been developed in the colour-coding of the energy performance certificates. The cost-optimal building as minimum requirement for the nZEB implementation serves as reference to mark the yellow range, while more ambitious nZEB implementation are in the green and less ambitious in the orange part of the diagram.

It is thus proposed that the methodology should be further developed and tested also for other application cases like multi-family buildings and offices. Thereby, a common methodology to assess ambition levels should be established and approved/recognized in order to approach countries and entirely implement EPBD requirements in order to support fulfilment of climate protection targets in the new built environment. At the same time a harmonisation of the nZEB implementation could be promoted, which would also facilitate the development of standardised high performant heat pump and building technology solutions for nZEB application.

3 Monitoring of nZEB

A focus of the work and national contributions in IEA HPT Annex 49 was the monitoring of nZEB projects with heat pump for different types of use from residential to office and other non-residential use to groups of connected buildings.
The focus of the monitoring projects was on larger residential and non-residential buildings, since the nZE balance is relatively easy to meet for smaller residential buildings, where building loads are limited by a high performance building envelope and the outer building surface is large enough for on-site energy production. In larger residential and non-residential buildings, though, the ratio between the building load and on-site energy production capability is shifted and achievement of ambitious nZEB or plus energy targets is much more challenging than in smaller residential buildings.
Thus, optimised building technology in combination with high performance buildings envelopes and optimised on-site energy production are a prerequisite to meet ambitious energy targets for the future sustainable built environment. The detailed and long-term monitoring projects over a period of several years give valuable evaluation of real-world performance of nZEB with heat pumps and show typical problems and optimisation potentials.
In order to characterise the temporal aspects of load match between on-site renewable production and consumption, the key performance indicators of the load cover factor (LCF), which relates the on-site PV consumption to the total building energy consumption, and the supply cover factor (SCF), which relates the on-site PV consumption to the total PV production, see also definition in the before chap. 2, on system boundaries and characteristic numbers in the beginning of the report. For the SPF values, the boundary heat pump is used unless not otherwise mentioned.
Detail on the monitoring is found in Report Annex 49 part 2 on monitoring.

3.1 Monitoring in residential nZEB

In Annex 49 different residential applications have been monitored. Most single family houses have been designed to a plus energy balance, i.e. a surplus in the year shall be reached. Also some of the larger residential multi-family applications were designed to achieve a plus energy balance, but showed a more heterogeneous picture regarding the achievement of ambitious energy balance targets. Achievement of the balance is also dependent on the local boundary conditions and may remain challenging for larger buildings depending on the ambition level.

3.1.1 Single family plus energy house Berghalde in Leonberg-Warmbronn, DE

The 260 m^2 single family house Berghalde in Leonberg-Warmbronn near Stuttgart, Germany, was commissioned in 2010 as one of the first residential plus energy buildings within the "Effizienzhaus Plus" (efficiency house plus) Initiative in Germany. The building envelope has U-values of 0.15/0.15/0.18 W/(m^2K) for outer walls/roof/basement and 0.8 W/(m^2K) for the windows. The building is equipped with a 10 kW_{th} heat pump with three 100 m ground probes as heat source. The roof is entirely covered with a 15.3 kW_p PV system in south orientation. The house is naturally ventilated by the window, but also has a mechanical ventilation system with 85% heat recovery. As storages a 825 l water storage and a 20 kWh electric battery are integrated in order to perform additional investigations for load management. Moreover, the building has a charging station for an electric vehicle. A 80 m ground-to-air heat exchanger preheats the air in winter and precools the air in summer by the ground. Figure 12 left shows the building concept.
The building has been continuously monitored for over 6 years. In each year a plus energy balance could be clearly confirmed, although there are differences in the surplus over the 6 year evaluation period depicted in Figure 12 right. The heat pump also performed well with overall seasonal performance factors in the range of 5. The Load Cover Factor (LCF) was in the range of 33% and the Supply Cover Factor (SCF) varies in the range of 32-49%, see definitions in chapter on the characteristic number. Starting in 2013, investigations of the load management have been performed, see chap. 5.1.

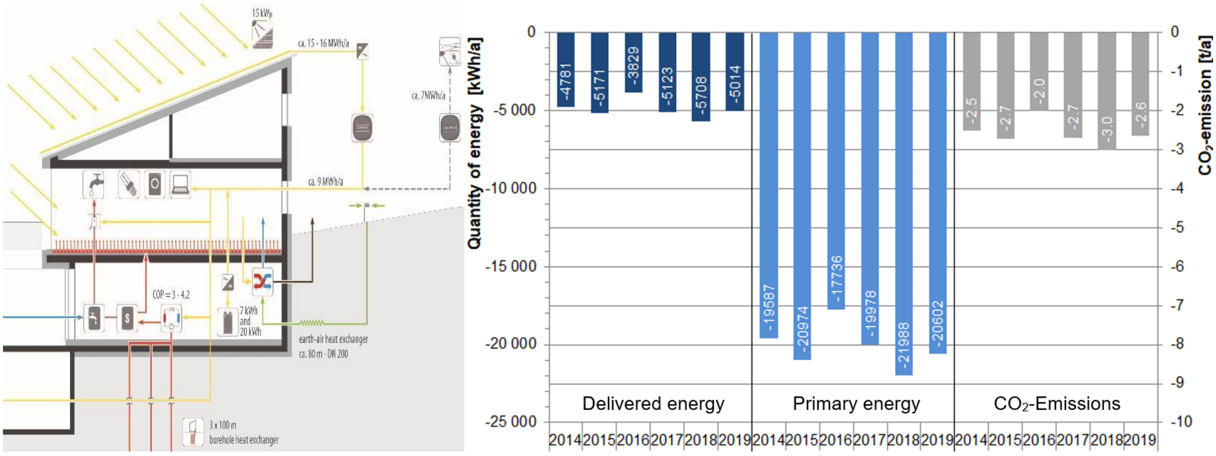


Figure 12: Building technology concept (left) and energy and CO_2-balance for the monitoring period of 2014 – 2019 of the single family plus energy building Berghalde in Leonberg-Warmbronn, DE

3.1.2 Multi-family passive houses in Vögelebichl/Innsbruck, AT

The two multi-family houses in Innsbruck Vögelebichl with 10 and 16 flats on a total energy reference area 2150 m^2 of the social housing company NHT are the first in the world to fulfil the Passivhaus Plus Standard (Feist, 2015). Furthermore, the buildings were designed to achieve the annual net-zero energy balance based on the on-site renewable energy generation. The building system is equipped with a double-stage groundwater heat pump with 44 kW (W0/W35) heating capacity, 80 m^2 of solar thermal collectors, PV panels of 24.5 kW$_p$ and a 6 m^3 buffer storage. Ventilation with 81% heat recovery is implemented to always ensure hygienic air renewal, while minimizing energy consumption. The HP unit is additionally equipped a desuperheater for simultaneous DHW production.
Figure 13 left shows the system technology concept. The building was monitored since 2016. Monitored space heating and DHW energy are in the same range. Figure 13 right shows the thermal and electric balance. The on-site PV production was not high enough to meet the balance of the building technology, so the nZE balance was not reached, yet. One reason identified was the unexpectedly high auxiliary energy consumption. However, based on the monitoring data, a validated simulation model has been derived for the main building technology components. Optimisations of the system configuration and operation confirms that the nZE balance for the boundary system technology can be reached, see chap. 5.3.

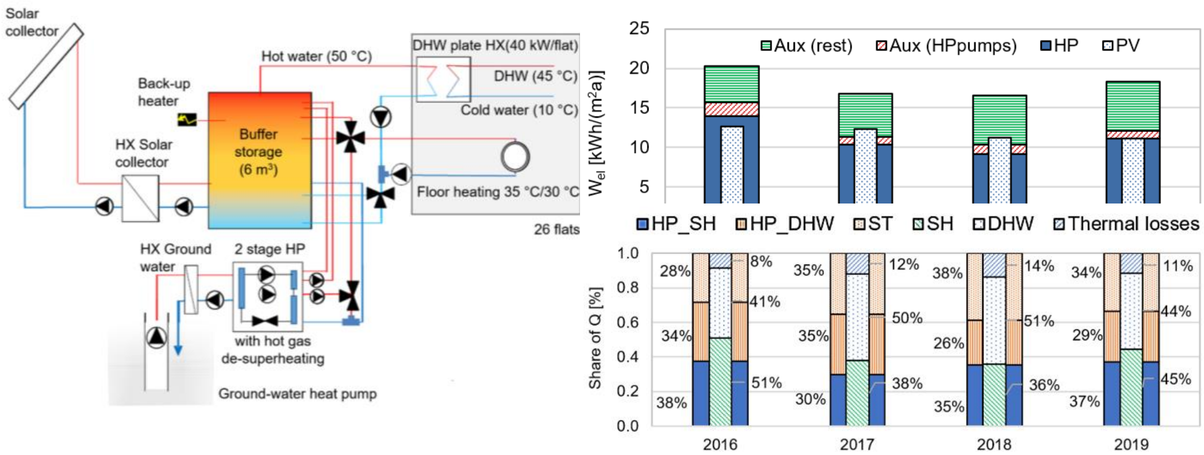


Figure 13: Building technology concept (left) and energy and electricity balance for the monitoring period of 2016 – 2019 of the multi-family passive house Vögelebichl in Innsbruck, AT

For the overall balance with household appliance, though, the PV roof installation is not sufficient and the façade has to be additionally used for PV electricity production. Seasonal performance is in the range of 5 for space heating and below 3 for DHW. The generator performance including the solar thermal fractions reaches values of 4.9.

The overall seasonal performance including all system components is 4.2. The evaluated annual LCF was in the range of 19-24% and the SCF 66-68%.

3.1.3 Multi-family house Riedberg, Frankfurt/Main, DE

The five-storey multi-family building Riedberg with 17 apartments in Frankfurt am Main, Germany, was commissioned in August 2015. The building is equipped with a 50 kW_{th} brine-to-water heat pump that uses 85 m^2 of solar absorber in combination with an ice storage as heat source. In order to reach a plus energy balance a 84 kW_p PV system is installed on the roof and 15 kW_p in the façade.

Moreover, a mechanical ventilation system with 84% heat recovery is installed. For load management a 60 kWh LiFePo electric battery is included, and a 1000 l water storage serves as buffer storage. Figure 14 left shows a sketch of the system concept. Figure 14 right depicts the balance of the monitoring period of 2016 to 2019. In the four years of operation, the plus energy balance has not been reached due to an increased consumption of heating energy as well as increased distribution losses compared to the planning. The heat pump only achieved SPF values of 1.7–2.6 due to excessively high return temperatures and problems with the heat transfer at the solar absorbers. System optimization included the integration of an additional buffer tank as a hydraulic diverter and adjusting the setpoint for switching between the solar absorbers and ice storage and support of the heat supply by electric instantaneous water heaters. With implementation of the optimisation potentials the plus energy balance should be reachable. Over the monitoring period, the average LCF is in the range of 42%, and the average SCF of 53% have been evaluated.

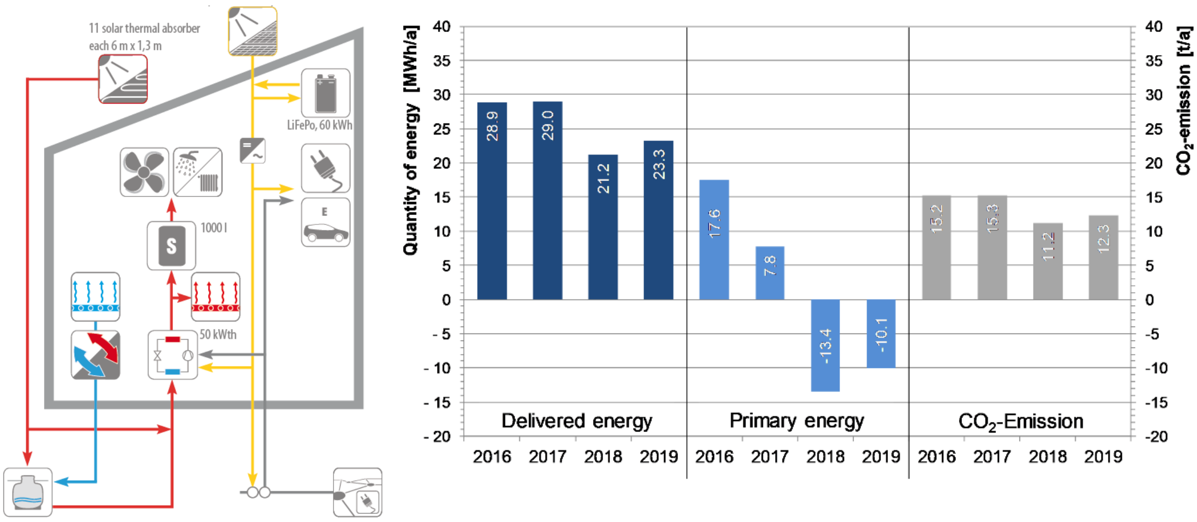


Figure 14: Building technology concept (left) and energy and CO_2-emission balance (right) for the monitoring period of 2016 – 2019 of the multi-family house Riedberg, DE

Due to the problems with the operation in the first years the detailed monitoring of the system proved to be very useful to detect faults and improve the system performance. As conclusion that can be drawn from this experience, in particular if new system integration options and technologies like the solar absorber installation below the PV system and an ice storage as heat source in this case, a monitoring is essential to derive "as planned" operation of the system and identify system operation errors and potentials to improve the system operation.

3.1.4 Multi-family house Sonnenpark Plus Wetzikon, CH

The five-storey multi-family house in Wetzikon, Switzerland accommodates 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, a 44.5 kW_p PV system was integrated on the roof and a 36.1 kW_p PV system in the south-east and south-west façade.

The building has been commissioned in spring 2018 and the evaluation of the monitoring was performed for the year 2019. The building is certified to the Swiss MINERGIE-P® label, i.e. the building envelope features passive house U-values of 0.1/0.12/0.18 W/(m^{2}K) for outer wall/roof/basement and for the triple glazed windows 0.8 W/(m^{2}K). The calculated space heating demand was 17 kWh/(m^{2}yr). The core of the building technology is a two-stage ground-coupled heat pump of max. 22.9 (11.9) kW$_{th}$ heating capacity / COP 4.6 (4.9) at B0/W35 and two stages (one stage), respectively, which is supplied by two 230 m boreholes, which are also used for freecooling in summer operation. In the annual balance for 2019, a plus energy balance with a surplus of 40% related to the total PV-yield was reached. However, the occupancy in 2019 was relatively low, which has affected the DHW and the electricity consumption. With a standard use the plus energy balance would still be challenging. The heat pump SPF could not be evaluated due to a sensor failure, but is estimated based on the ground and the supply temperature to a range of 4. An LCF of 64% and an SCF of 54% including all electric consumers and the e-mobility was evaluated.

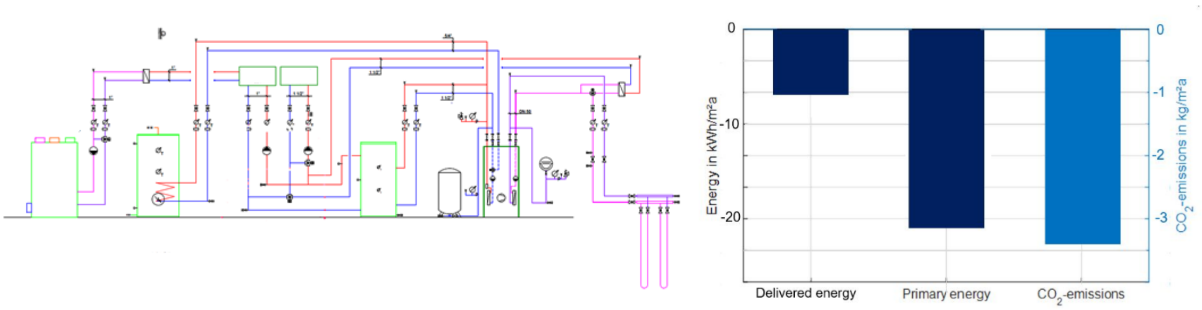


Figure 15: Building technology concept (left) and energy and CO_2-emission balance (right) for the monitoring period of 2019 of the multi-family house Sonnenpark Plus in Wetzikon, CH

3.1.5 Multi-family house Allmendholz Horgen, CH

The two storey multi-family house Allmendholz in Horgen, ZH, has been built in 2017 and comprises four flats on a total energy reference area of 500 m^2. The flats are inhabited by totally 8 persons. The building envelope approaches a high energy quality of U-values of 0.18/0.13/ 0.12 W/(m^{2}K) for the outer walls, the roof and the ground and 1 W/(m^{2}K) for the triple-glazed windows. The calculated space heating demand is 30 kWh/(m^{2}yr). The building is equipped with a capacity-controlled ground-source heat pump of 20 kW (B0/W35), which extracts the ground heat of two double U-tube borehole heat exchangers of 225 m each. Figure 16 left shows the hydronic sketch of the system configuration. In order to reach a nZE balance, the building is equipped with a 13.3 kW$_p$ PV system on the flat roof in south east orientation. In the flats, individual wood stoves are additionally installed, which create a cosy atmosphere at cold days.

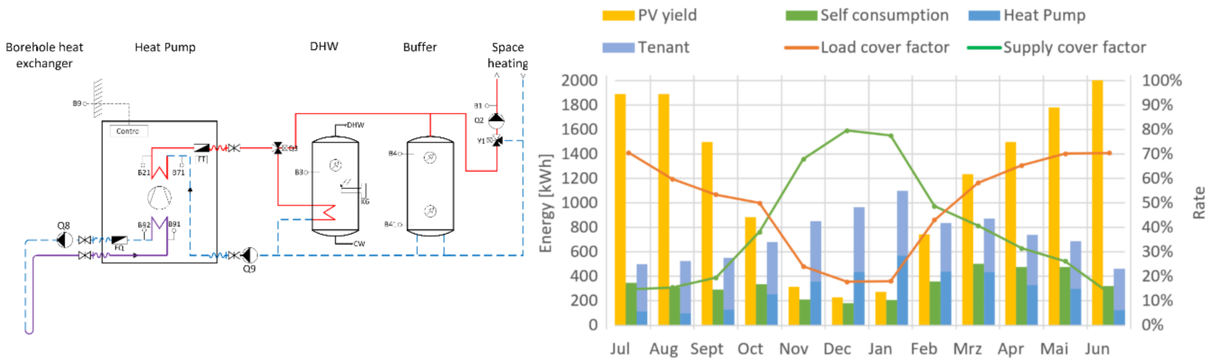


Figure 16: Building technology concept (left) and monthly energy consumption and yield as well as the monthly self-consumption and LCF/SCF (right) of the multi-family house Allmendholz in Horgen, CH

The monitoring was evaluated from July 2018 to June 2019 and yield a good SPF of 5, which can be decomposed to an SPF in space heating mode of SPF_h = 6.3 and in DHW mode of SPF_{DHW} = 3.5. The high SPF in space heating mode can be explained by an oversized ground source which leads to high source temperature of minimum 9 °C and a particular heat pump unit, which is optimised for low temperature lifts, and thereby leads to high performance factor at low temperature lifts, even though the heat pumps is oversized, since the maximum heat load was evaluated to 13 kW in the monitoring period. Moreover, the heat pump is supported by the decentralised wood stove in the flats, which are applied on the coldest day, which also contributes to lower temperature lifts for the heat pump. Figure 16 right shows the total energy consumption as energy for the heat pump and the additional use including also the household electricity for appliance and plug loads.
The building reaches a plus energy balance with a yearly surplus of 50% of the PV generation compared to the annual consumption. However, the electricity consumption of the inhabitants is a total electricity of 1000 kWh/person relatively low compared to the standard use. Furthermore, the total PV yield, the on-site self-consumption and the LCF and SCF are shown. The annual LCF and SCF yield 27%/46%.

3.1.6 Conclusion of monitoring in residential buildings

In conclusion of the monitoring experience in residential nZEB the following can be summarised:

- In single-family and smaller multi-family house, a plus energy balance is reachable with a PV installation on the roof only. In general the building envelope offers enough space to reach surplus energy in the annual balance, even in northern climates.
- In multi-family buildings higher than 3-4 storeys, the achievement of an ambitious balance is challenging, and normally the roof does not offer enough space, but the façade has to be additionally used for energy generation in order to reach ambitious balance targets. Thus, a high performance building envelope and an optimised system performance are a prerequisite to achieve ambitious nZE balance criteria.
- This also implies higher cost for a plus energy balance due to PV façade integration, but may also contribute to higher PV self-consumption due to shifted production of the façade system
- Evaluated LCF/SCF are in the range of 20-30%/30-50% for single family houses and in the range of 20-40%/50-70% for the multi-family houses, so tend to be higher in multi-family houses due to higher load difference among the different flats. However, design of the PV system and installed thermal and electric storage capacity differ also among the buildings.

3.2 Monitoring in office nZEB

In the Annex 49 two buildings with mixed office and residential multi-family use have been monitored. Both buildings were planned to reach an nZE balance for the boundary building technology. As in the multi-family buildings, it turned out that meeting the balance can be even more challenging, since with the office use, also cooling demand and appliances are more predominant. Thus, an efficient system operation is important to reach the balance, where freecooling should be given priority for the space cooling operation and waste heat from active cooling should be used as far as possible to increase the performance.

3.2.1 Office building with mixed use in Uster, CH

The building was the first MINERGIE-A®-certified building with office use in canton Zurich. The building comprises 20 office workplaces on 367 m^2 on the ground-floor and 7 flats on 839 m^2. The building envelope with a calculated space heating demand of 33.1 kWh/(m^{2}yr) features U-values of 0.13–0.18 W/(m^{2}K) and 1 W/(m^{2}K) for the triple-glazed windows. The building technology consists of a 33.1 (30.5) kW_{th} heat pump at B0/W35 (W50) with a heat source of 11 ground probes each 80 m deep, which are also used for freecooling in summer. The freecooling was sufficient to guarantee thermal comfort both in the office and the residential part of the building. For meeting the balance a 24.5 kW_p PV-system is installed on the south-east and south-west oriented roof.

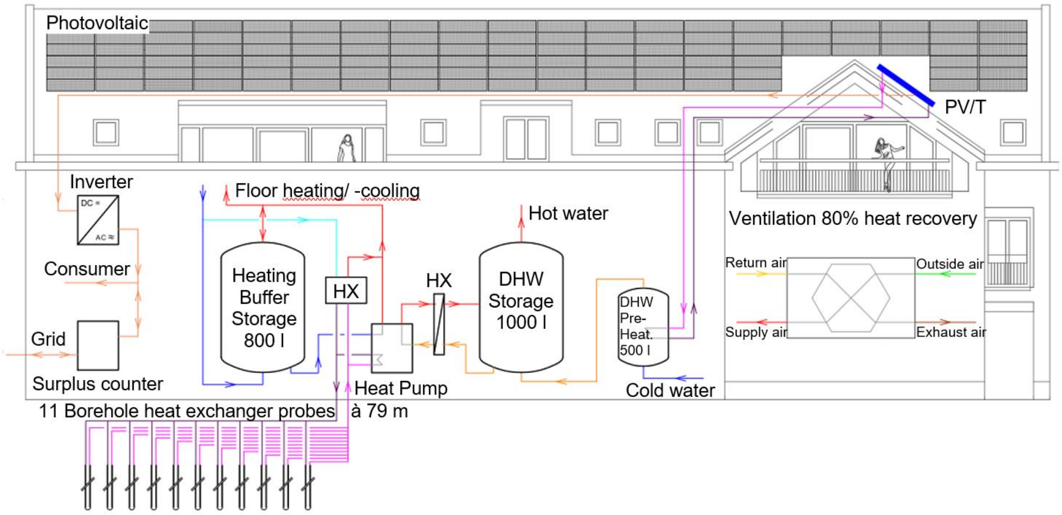


Figure 17: Building technology concept of the office building with mixed use in Uster

Figure 17 left shows the system concept. The balance of the building technology of the 2-year monitoring period could be met in both years. In the second year, a reduction of the electricity for the accompanying direct electric pipe heating for DHW tapping comfort by 60% was implemented by control optimisation. Thereby, the total surplus could be increased from -6 kWh/(m^{2}yr) to -15 kWh/(m^{2}yr). The LCF/SCF have been evaluated in the range of 35%/40%, respectively.

3.2.2 Office Building with mixed use in city centre of Pfäffikon, SZ, CH

The building Black&White is situated in the city centre and has a commercial/retail use on 616 m^2 on ground floor, an office use of 617 m^2 on the first and second floor and a multi-family use of 1527 m^2 in the upper floors and the attic. The building envelope reaches U-values of 0.16/0.12 W/(m^{2}K) for outer wall/roof and 0.92 W/(m^{2}K) for the windows. The core of the building technology is a ground-source heat pump of 70 kW$_{th}$ for space heating, space cooling and DHW operation. As heat source a field of 15 ground probes with each 150 m is installed. For the space cooling ground-coupled freecooling is given priority, and for the additional active peak load cooling the waste heat is recovered for space heating, DHW or for regeneration of the ground. Therefore, each a 2150 l cold storage, heating buffer storage and DHW storage is integrated, and an additional 925 l storage for DHW preheating from space cooling waste heat. For meeting the nZE-balance a 26 kW$_p$ PV system is installed on the roof and a 48 kW$_p$ PV system is integrated in the east, south and west façade.

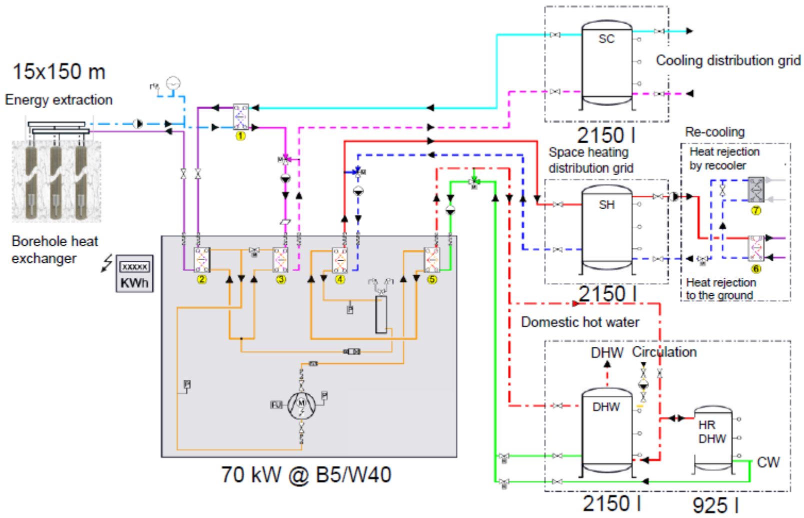


Figure 18: Building technology concept of the building Black & White with mixed commercial and residential use

As monitoring period, the year 2017 has been evaluated. The heat pump is with an overall performance of 5.2 including the freecooling in a good range of the overall SPF. However, the façade integrated PV system yield was very low, so only an average of all façade integrated PV areas of 500 kWh/kW$_p$ was measured, whereby the roof delivered the PV yield of 928 kWh/kW$_p$ as can be expected. The south façade yield is only 490 kWh/kW$_p$, while a specific yield in the range of 650 kWh/kW$_p$ could be expected. The specific yield of the west and east façade is with 290 kWh/kW$_p$ and 137 kWh/kW$_p$ respectively, far below the expectation. For both facades, a yield in the range of 500 kWh/kW$_p$ could be expected. Based on the measurement data, however, it could not be identified, what reasons are responsible for the low PV yield in the façades. Therefore, the balance was not reached in the monitoring period, but simulations show, that with the designed PV yield, the balance could be reached. The LCF/SCF was 25%/30%, which are, however, is also affected by the lower PV yield. Higher LCF/SCF could be expected, since the PV yield in the façade is more evenly spread over the year, which enhances the self-consumption.

3.2.3 High rise office Building, Vienna, AT

The third building with office use is the new headquarter of the Austrian Post "Post am Rochus". The high-rise building has a commercial/retail use on the ground floor and office use in the upper floors on a total gross area of 49,300 m^2. The building is partly refurbished with U-values of the outer walls of 0.09–0.15 W/(m^{2}K) and 1.0 W/(m^{2}K) for the triple-glazed windows. There are no monitoring data of the building, but the focus of the project was the integral planning process of a complex nZEB, also including software support by modelling and simulation for the controller design and commissioning. Summarizing, there is a positive feedback of the software supported integral planning process, but there is still a long way to go to fully implement it with all stakeholders.

3.2.4 Conclusion of monitoring in buildings with office use

For both buildings with mixed residential/office use the boundary for the nZEB balance was the building technology, thus the ambition level was not as high as the plus energy balance in the residential buildings, since only a zero energy balance regarding the building technology energy consumption is to be compensated by the on-site renewable production. With little office use as in the building in Uster, the balance for the building technology can be reached with PV on the roof only. However, with larger office and/or commercial use fraction in the Black & White building, even achievement of the balance in terms of the building technology is only possible by using also the façade. Simulations confirm that the balance can be reached with designed PV yield in the façade, but in the monitoring, it was missed due to the under-performance of the façade-integrated PV despite the high performance building envelope and a good overall performance of the heat pump system. Thereby, already a large fraction of the façade have been used for electricity generation. So, a more ambitious balance may be challenging to reach even with the façade.

For the larger office building, no monitoring data were available in the time frame of the Annex 49. However, the integral planning process of a complex nZEB has been analysed and is a promising process which comprises also simulation and software-aided controller design and commissioning. Nevertheless, as a conclusion of the practical experience, the full implementation of integral planning processes will still need time.

3.3 Monitoring in nZEB with other non-residential use

Also some projects with non-residential use other than offices have been contributed to the Annex 49, namely two schools, a kindergarten, a large hotel and a supermarket. Besides the nZEB balance these applications are also not standard applications for heat pumps, i.e. there are not so many examples of heat pump use in these building applications. Thus, experience with heat pump application could be gathered, too.

3.3.1 Willibald-Gluck secondary school in Neumarkt in der Oberpfalz, DE

The Willibald-Gluck secondary school for 1,400 pupils in Neumarkt in der Oberpfalz comprises on totally 14,400 m^2 the four storey main school building and a gym and was designed to achieve a plus energy balance. The building envelope features U-values of 0.14-0.17 W/(m^{2}K) and triple-glazed windows with 0.9 W/(m^{2}K). Figure 19 left shows the system concept. A 85.6 kW$_{th}$ ground-source heat pump connected to 96 energy piles of a depth of 8-12 m and a 4,400 m^2 agrothermal field. Furthermore, server waste heat is integrated as heat source.

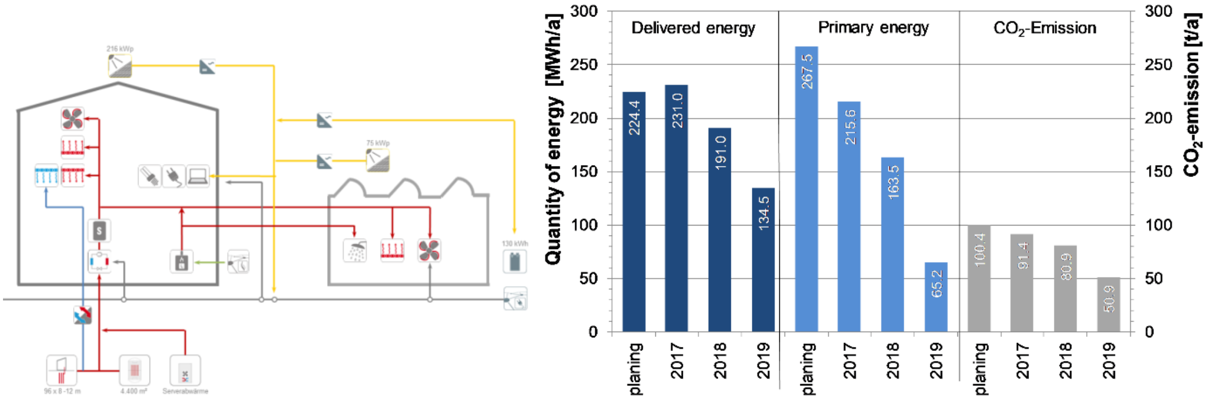


Figure 19 Building technology concept (left) and energy/CO$_2$-balance (right) for monitoring 2017-2019

The ground-source system is also used for freecooling in summer and is thereby regenerated. The heat pump design is to cover 70% of the load, while the remaining 30% peak load is covered by a gas condensing boiler.

For the plus energy balance a 291 kW$_p$ PV system is installed on the roof of the school building and of the gym and a 130 kWh Redox flow electric battery is used for electricity surplus storage. Moreover, a ventilation with maximum air exchange of 4.4 h^{-1} and a heat recovery of 85% is installed.

Figure 19 right shows the energy and emission balance. Despite a good SPF of the heat pump in the range of 4.7-5.2 over three-year monitoring period, the plus energy balance could not be reached. Even though the delivered energy and thus also the primary energy are decreasing over the years, which confirms optimised operation after the first year of commissioning, the on-site produced PV electricity did not yield a surplus, even though the primary energy and CO_2-emission decreased year by year. Also the annual self-consumption reached good values. The LCF/SCF were to an average of 59%/47% over the monitoring years.

3.3.2 Justvik primary school in Kristiansand, NO

Justvik Skole has been commissioned in 2017 and is certified according to the Norwegian passive houses standard NS 3701. The building technology consist of a ground-source heat pump unit which uses CO_2 (R744) as working fluid. Figure 20 left shows the systems for DHW heating and heat distribution which have been designed to provide the best operating conditions for the CO_2 heat pump in order to maximize the performance, i.e. to reach a high temperature spread and low return temperatures to the heat pump. The unique design of the system received the Norwegian heat pump award in 2018.

Figure 20 right shows the measured monthly heating demands for February to September 2018, approx. 72,000 kWh. Space heating (floor, radiators) and ventilation air heating accounted for 57% and 18% of the total heat demand, respectively, and the rest is used for the DHW heating and the DHW circulation system. Since the measuring period was only 8 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 a Norwegian passive house.

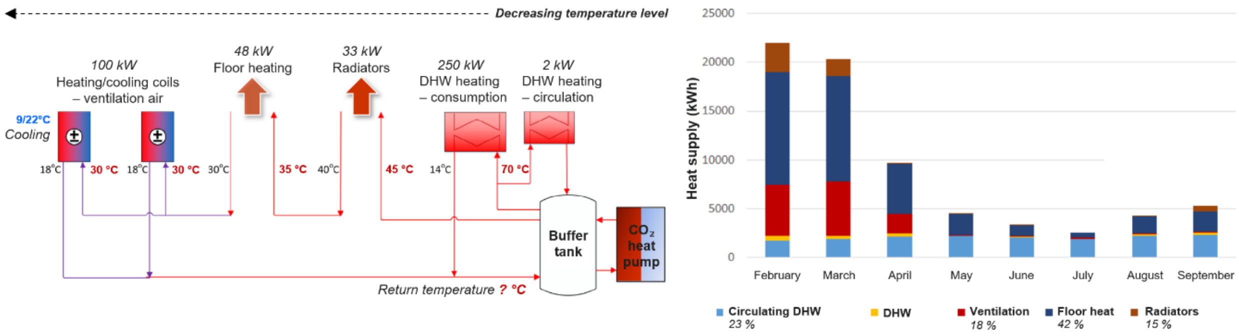


Figure 20 Heating emission system design for optimised CO_2-heat pump operation (left) and monitoring data of Feb-Sept. 2019

This is probably due to “drying out” of the building, higher room temperature, longer operating time and lower heat recovery of the ventilation system, higher U-values for the building envelope and non-optimised operation of the thermal energy system. The DHW demand was very low, which might be due to a measurement error, caused by a large number of small tappings, but also shows that not many pupils take a shower after sport.
Therefore, the SPF of the heat pump was with 3.05 rather moderate. Moreover, a sensor failure was discovered, so the setpoint for the CO_2-heat pump was by 9 K higher than 70 °C. After replacement of the sensor, COP increased by 10-15% and the heating capacity of the heat pump by 20%. Thus, for the next operation period with better heat pump performance and higher DHW tappings, the performance should notably increase.

3.3.3 KIWI Dalgård supermarket in Trondheim, NO

The supermarket KIWI Dalgård 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 1,250 m^2, is built according to the Norwegian passive house standard NS3701 (2012) and utilizes heat recovery from the refrigeration system.
It was planned to produce during operation more energy than it uses due to the application of PV roof-mounted panels and a ground-source heat pump. Surplus heat is delivered to 60 apartments in three neighbouring buildings. Figure 21 left shows a sketch of the system concepts and the energy flows.
The total net annual energy demand at KIWI Dalgård was estimated to be approx. 125 MWh/yr. During the measurement period 01.01.–30.11.2018 the measured energy use was 284,723 kWh, i.e. more than twice as high. The CO_2 refrigeration system is the largest single consumer of energy, using approx. 100 MWh, close to the estimated total energy demand for a full year. If free-standing display cabinets are included, the refrigeration system alone amounts to approx. 140 MWh. The space heating demand of the supermarket could be mainly covered by the recovered heat from the refrigeration plant. The recovered heat was approx. 90,000 kWh and contributed 92% to cover the space heating demand which used the ventilation air for heat emission into the supermarket. The heat pump covers the remaining 8%.

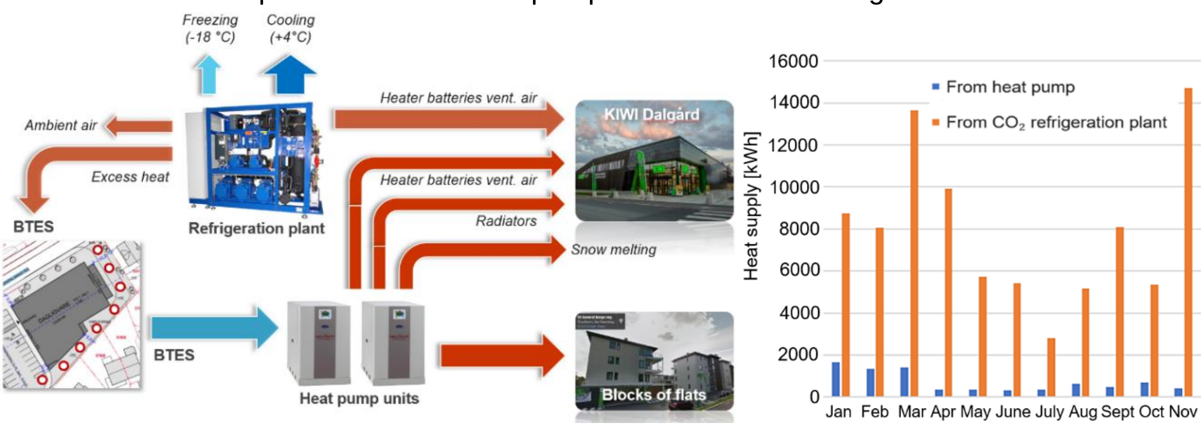


Figure 21: Building technology concept (left) and energy (right) for monitoring 2018 for KIWI Dalgård

In addition, 70,000 kWh from the CO_2-refrigeration plant was rejected to the Borehole Thermal Energy Storage (BTES) during the summer months, which is, however, much lower than the design value. Extracted heat from the BTES by the heat pump was 60,000 kWh and the minimum brine temperature was -1 °C, which indicates that there is a good thermal energy balance in the system. The heat pump supplied 160,000 kWh to the neighbouring apartment buildings. As the design value was 350,000 kWh/yr, this is a considerable deviation, but the design value was probably highly overestimated. The measured SPF_{HP} for the two heat pump units were with 3.0 and 2.9 moderate. The two heat pump units were originally controlled on/off, which led to frequent starts and stops of 4-5 times 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, so higher SPF are expected for the future.

3.3.4 Conclusion of nZEB with other non-residential use

In the non-residential application other than offices, which are not standard applications for heat pumps, larger deviation to planning values were observed in the monitoring. Thereby, the projected plus energy balance in the Willibald Gluck secondary school was not reached despite a good SPF in the range of 5. The other heat pumps had moderate SPF in the range of 3, but also showed optimisation potentials, so better performance is expected in the future. Also for these non-residential applications heat recovery from the cooling operation/systems in supermarkets and regeneration of the ground with waste heat during summer are integrated in the system configurations and increases the overall performance.

3.4 Monitoring in nZE groups of buildings

In Annex 49, not only single buildings, but also smaller groups of buildings have been monitored. This comprises two projects with residential buildings, one group with 8 single family houses and 6 multi-family houses. Moreover, a group of five office buildings where the new building E supplies heat to the four older buildings A-D has been monitored.

3.4.1 Herzo-Base – group of 8 terraced single-family house in Herzogenaurach, DE

In the Herzo Base project, Herzogenaurach, Germany, 8 terraced single family houses of a total area of 1,200 m^2 are connected by a heating grid to two central speed-controlled ground source heat pumps of 17 kW_{th} each with 7 boreholes of 100 m each. The buildings are designed to plus energy with U-values in the range of 0.13–0.18 $W/(m^2K)$ for outer walls, roof and basement and 0.8 $W/(m^2yr)$ for the triple glazed windows.

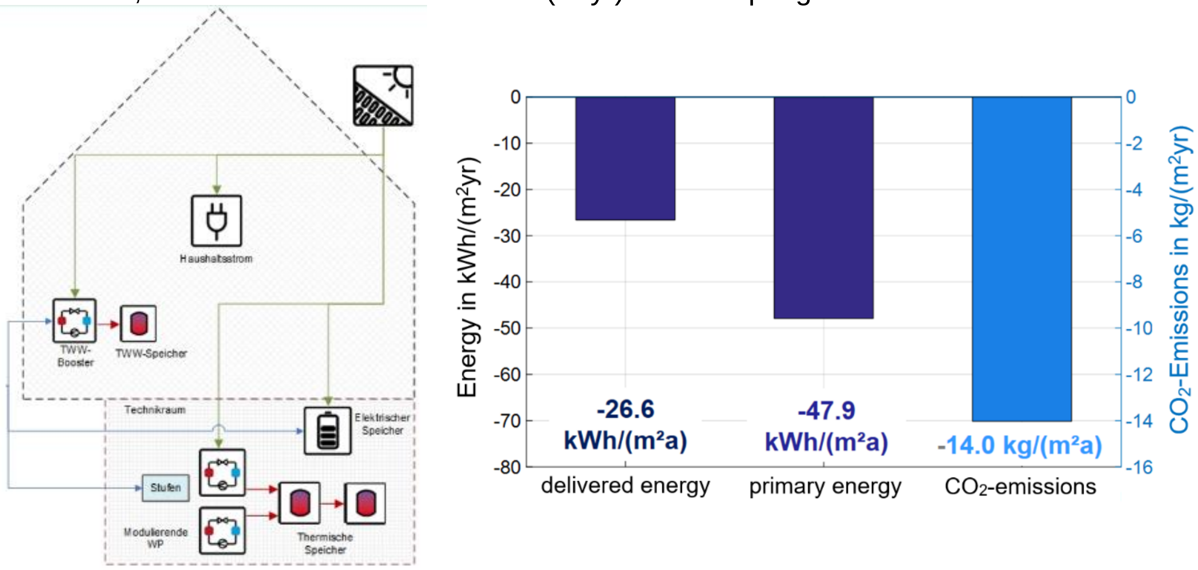


Figure 22: Building technology concept (left) and energy and CO_2-balance (right) for the monitoring period of 4/2018-3/2019 (right) of the group of 8 terraced houses

The calculated space heating demand of 9.6 kWh/(m²yr), which is also supported by the mechanical ventilation with heat recovery of 86%. To reach a plus balance an 88 kW_p solar PV-system is integrated on the roofs. The DHW is produced decentrally in the houses using the heating system return as heat source for 2 kW DHW booster heat pumps installed in the 200 l DHW storages. As also an optimised self-consumption by storage and advanced control was investigated in the project, a thermal storage cascade of 2,800 l and an electric battery storage of 40 kWh are integrated at the two central heat pumps. Further information on the load management investigations is found in chap. 5.2.
Figure 22 left shows the system concept including the model predictive control, and Figure 22 right confirms that the plus energy balance was reached with a surplus of 26.6 kWh/(m²yr) PV electricity. The two central heat pumps reached a high SPF of 5.6 and the decentralised booster heat pumps a SPF of 4. The total yield of the PV-system is 87 MWh/yr, which is a good yield, typical for optimally oriented PV systems. The self-consumption was evaluated to an LCF/SCF of 61%/32% and reaches good values.
The overall performance factor related to used energy is 3.4, which is basically due to user impact and suboptimal local controller setting, so despite the good performance of the central heat pumps, different optimisation potentials were identified.

3.4.2 Group of residential buildings Aspern D12, Vienna, AT

The 6-storey wooden six multi-family buildings with retail use on 900 m² in the ground floor comprises 213 flat on totally 19,080 m² conditioned area. The building were commissioned in March 2016 and are built in "Seestadt Aspern" in the North of Vienna, which is used as testbed for energy management and smart building/grid/ ICT and smart users. With 15.6 kWh/(m²yr) the space heating demand is in the passive house range. The buildings are supplied by 7 heat pumps, which use different heat sources and are connected by a low- and high-temperature thermal grid. The system with different heat sources has been designed for load management, and each one 2000 l storage per building is used for short-term storage, while the shallow ground source is seasonally regenerated. DHW is supplied by fresh-water stations at 60 °C to the flats. The multi-source system guarantees a high redundancy and availability, while 80% of the energy is taken from the ground-coupled heat sources ground and groundwater. Exhaust air from underground parking is mainly used in summer to produce high temperatures. Solar and PV/T collectors inject heat into the thermal grids and recharge the ground sources. The system is also connected to the local district heating grid, which guarantees the thermal comfort during winter, but generally, no back-up is needed. For achieving high solar fraction and avoiding stagnation of the solar collectors, solar heat basically always charge/feed the ground 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. Further conclusion drawn from the project are that regarding hydraulics tight dampers and valves are needed for pressure management. However, complex control strategies tend to overburden the facility management and service personnel. From the practical experience, one large technical room instead of six rooms would have saved money, but enough space is to be planned and provided.

3.4.3 Group of office buildings– Otto Nielsens vei 12 A-E, Trondheim, NO

The new office buildings at Otto-Nielsens vei (ONV) 12 E in Trondheim, Norway was completed in June 2017 as an extension of 9,100 m² of four other buildings, ONV 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, a Norwegian company that is world-leading in advanced electronics and has large server installations as well as testing facilities that require process cooling. Therefore, waste heat from the cooling operation shall be used to heat the existing office buildings ONV 12 A-D.

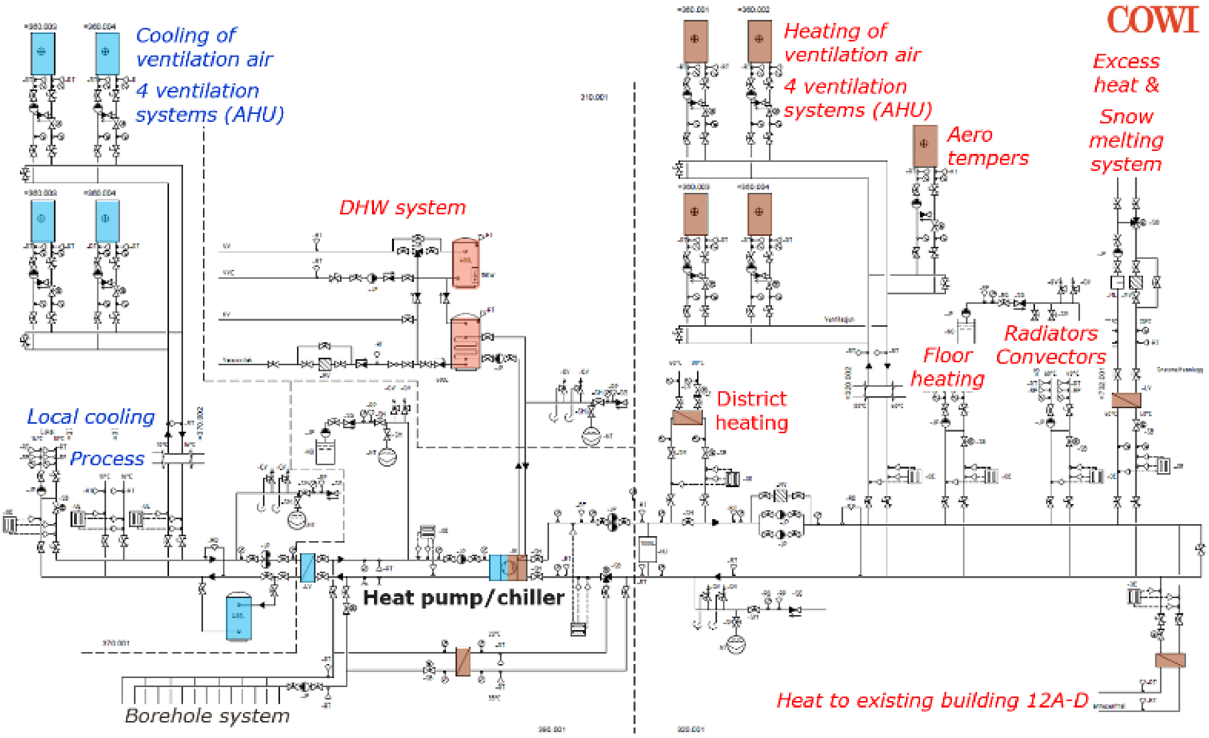


Figure 23   Building technology concept of Otto-Nielsens vei 12 E and 12 A-D

Figure 23 shows the as-built heating and cooling system of ONV 12 E, which is equipped with a ground-coupled high temperature (75 °C) heat pump with good part load COP and a heating capacity of 200 kW sufficient to cover the heat demand of 160 kW of ONV 12 E.
The heat source consists of the Borehole Thermal Energy Storage (BTES) of 25 ground probes of 260 m each in 7 m mutual distance, i.e. a total length of 6500 m. The waste heat from cooling operation is used for heat export to ONV 12 A-D.
At no heating demand, the BTES is regenerated to a maximum temperature of 25 °C, and then, the waste heat is transferred to the snow melting system or the ambient air. Figure 24 left shows the monitoring data of the first operating period 2017/18 and Figure 24 right the concept of the heat pump. The cooling demand was with 15 kW much lower than the 50 kW design values, since not all testing facilities were operated.

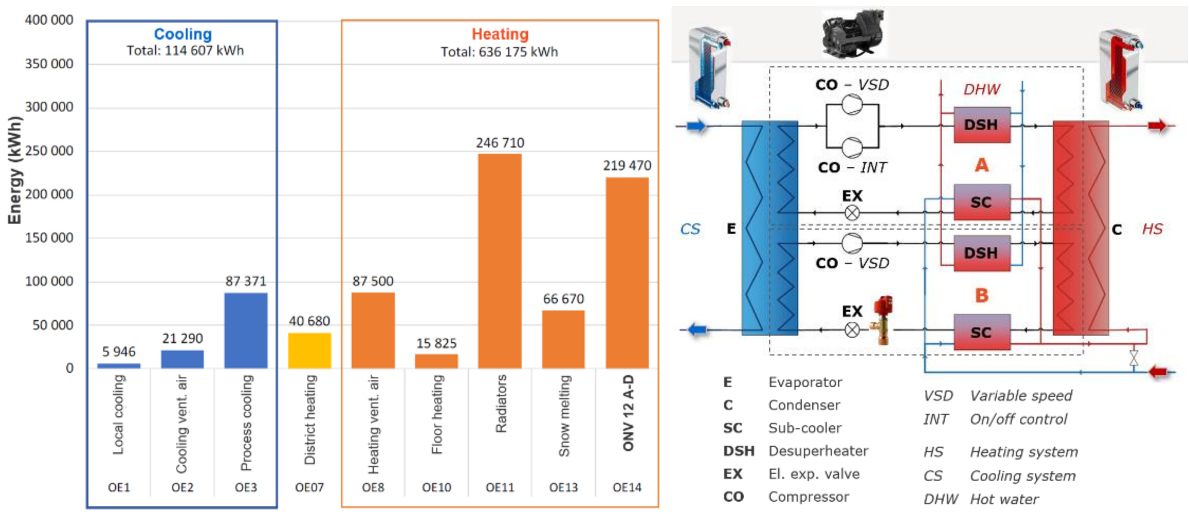


Figure 24 Energy measurements (left) for the first year operation 2017/18 (left) and layout of the heat pump (right)

The space heating demand of ONV 12 E was 50% higher due to the first operation year. SPF was 2.6, corresponding to data sheet value of 2.7 and is due to the high temperature of 60-75 °C for the heating system in ONV 12 A-D. In the second monitoring period 2018/19, cooling demand increased by 44 kW to nearly the design value.

Space heating in ONV 12 E decreased by 20%, and due to full installation server/testing, heat export to ONV 12 A-D increased by 65%. The heating SPF_h stayed at 2.6 in the same range due to same temperature and part load levels. Overall SPF including the cooling reaches values up to 4.3. Optimisation potentials are seen in lowering the temperature levels in ONV 12 A-D to achieve higher SPF, an inclusion of the DHW recirculation water in the system and a continuous monitoring of the BTES.

3.4.4 Conclusion of nZEB groups of buildings

nZEB groups of building show positive experiences and in the case of Herzo-Base high SPF of the central heat pumps above 5 and good load management options, see chap. 5.2. In the project in Aspern, a multi-source system was installed, leading to high redundancy and respectively good availability. Moreover, best available heat source for the respective season can be used. Last but not least, waste heat of industrial processes can be used for heating purposes as shown in the connected office buildings at Otto-Nielsens vei. SPF is still moderate with an overall SPF of 4.3, but holds optimisation potentials due to currently high supply temperatures in the existing building. However, also the system complexity may rise by the connection of the buildings. Nevertheless, the connection of buildings holds the potential to recover waste heat by combined heating and cooling operation with the heat pump or chillers. Regeneration of the ground source is applied in all projects, either by freecooling or by waste heat recovery. Thus, further investigations of benefits of thermal and electric integration of groups of buildings should be performed in the future.

4 Prototype developments for nZEB

In Annex 49, also new prototypes of heat pumps or chillers for nZEB application have been developed. The developments have in common that highly integrated and compact prototypes have been focused on. Moreover, prototype developments had also an emphasis on cooling operation, either as integrated operation mode or as main operation mode of the unit. Besides the development, also new and existing prototypes have been further investigated by lab- and/or field testing.
Details on the prototypes are contained in the [Report Annex 49 part 4 on prototypes.]

4.1 Façade integrated prototype for PV driven space cooling and heating

At the IWT of TU Graz a façade integrated heat pump, which is covered by façade-integrated PV panels in order to produce the electricity to drive the heat pump has been developed in the frame of the project COOLSKIN. The prototype has been investigated by simulations as well as by field monitoring of the prototype unit in two test cells on the University campus. Figure 25 left shows a cut-away sketch of the unit and Figure 25 right shows each a photo of the prototype and the test cells for the field monitoring with two different PV panel covers for the unit. The prototype unit has different options that were tested: the cooling distribution and emission can be accomplished by a water-driven system, e.g. a cooling ceiling or thermally-activated buildings systems (TABS) or air-driven by the integrated fan-coil unit (green).

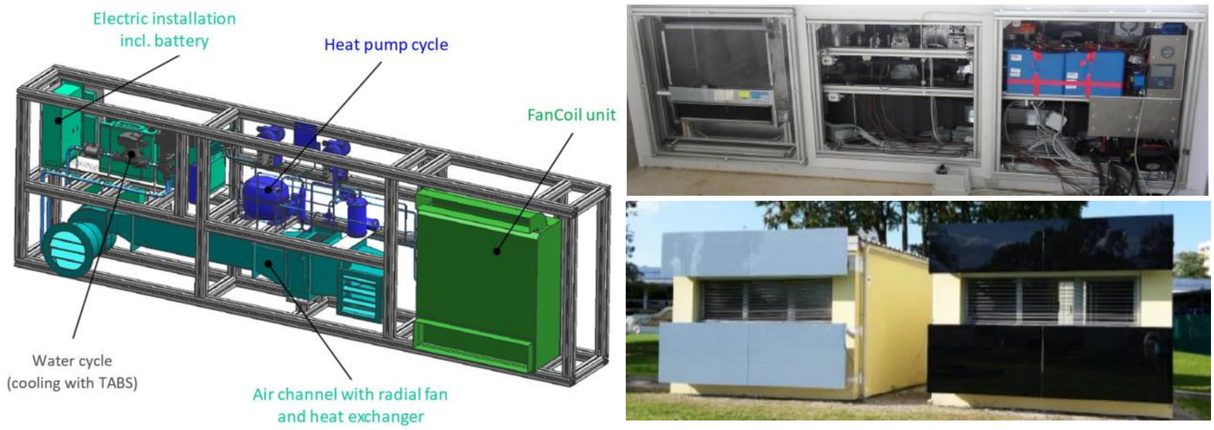


Figure 25 Cut-away of the prototype (left) and photo of the prototype (top right) and test cells for the field monitoring (bottom right)

The core component is the heat pump refrigeration cycle (blue). Also an electric battery is integrated to enable an autarkic operation (blue green). The air ducts with fan and heat exchanger are depicted in turquoise. Simulations approved that for Graz conditions the adjacent office room can be kept in the comfort range with the façade-integrated cooling unit. In space heating operation about 40%-60% of the total demand can be covered with the maximum PV area. In the field monitoring, the prototype was operated successfully both for space cooling and heating mode. The room temperature in the cooled test cells was 3-6 K lower than the reference, and also in grid independent operation, the room temperature could be kept below 27 °C for most of the operation time.

4.2 Prototype solar absorber for free-cooling operation

Due to rising outdoor temperatures, augmenting number of devices and increasing thermal comfort requirements the cooling needs are increasing. Globally, cooling is expected to be the second-largest source of global electricity demand growth after the industry sector, and the strongest driver for buildings by 2050 (IEA, 2018). Freecooling methods can cover space cooling demands with high efficiencies of typically 10 – 30 by using ambient heat sinks.
A novel approach is to use activated parts of the building envelope, e.g. solar components like uncovered solar collectors or PV/T components to reject the heat to the ambiance by nighttime radiation to the sky and by convection to the ambient air.

With additional wetting of the surface, radiation is enhanced by the high long-wave emissivity of the water and an additional evaporative cooling effect is used.
At the accredited solar test rig at the HSR Rapperswil, measurements of the cooling capacity of a prototype an unglazed solar absorber has been tested. The standard solar absorber component, which has a selective surface coating with a low IR-emissivity in the range of 0.15, has been amended with wetting installations of a water film, which runs down the absorber from a top mounted reservoir. A second wetting installation are nozzles mounted on the absorber edges for spraying water on the absorber. Figure 26 show the absorber prototype on the test rig.

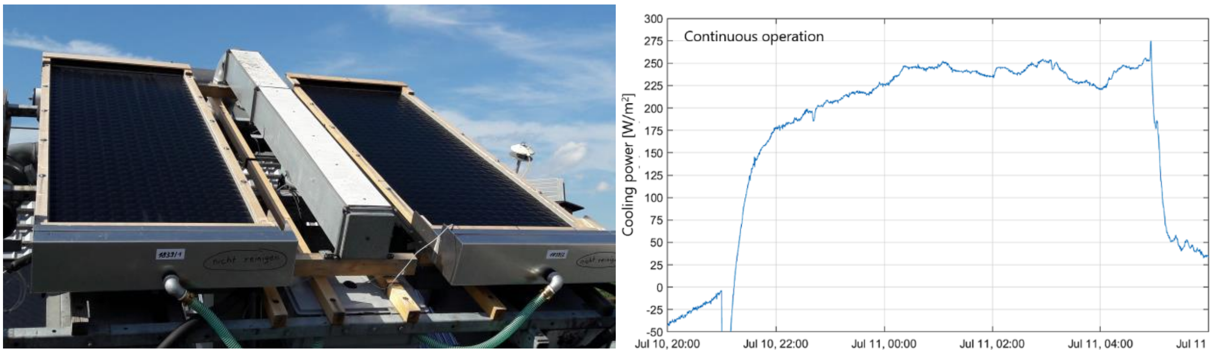


Figure 26: Test rig with solar absorber prototypes (left) and measured cooling capacity for night with clear sky (right).

Cooling capacities depend on the ambient conditions, which is typical for freecooling methods. In nights with outdoor temperature decreasing from 25 °C at 8 pm to 15 °C at 6 am and clear sky conditions, cooling capacities of 200 – 250 W/m^2_{abs} have been measured, which is depicted in Figure 26 right. Capacities decrease at similar ambient conditions (23 °C – 13 °C) and cloudy sky to 100 – 175 W/m^2_{abs}. Wind further increases the cooling capacities due to enhanced heat and mass transfer. At adverse ambient conditions of warm nights, the absorber can also be used in recooling mode of active cooling by a chiller. At a temperature difference to the ambiance of 15 K, cooling capacities increase to 300 – 450 $W/m^2_{abs.}$ (21 °C – 15 °C), with wind of 3 m/s up to 550 $W/m^2_{abs.}$ (22 °C – 15 °C). (Wemhoener and Buesser, 2021). On-site treated grey- or wastewater as described in chapter 3.5 would be a sustainable water source for the operation of the evaporative freecooling.

4.3 Personal cooling unit for nZEB offices - Roving comforter (RoCo)

RoCo (Roving Comforter), a development of the CEEE of the University of Maryland, College Park, is a personal-sized heat pump that cools indoor air to maintain occupants' thermal comfort. The latest version of RoCo has a stylish appearance, is 30 inch tall, and weighs ~40 lb. The top of RoCo is an intelligent air nozzle that automatically locks onto its user and directs the airflow to the desired parts of the body. RoCo can operate for up to 8 hours due to the onboard state-of-the-art phase-change material (PCM) that stores the waste heat. The novel PCM regeneration process requires only a "one-click" switch and ensures the thermal battery can be recharged in less than 40% of its operating time.
Initial experimental work shows that RoCo's cooling capacity around 150 W successfully provides thermal comfort without rejecting waste heat or requiring wires and ducts during operation. This cooling capacity sets RoCo apart from other conditioning devices (e.g., fans, ice coolers) currently on the market. Therefore, RoCo was designed with the vision of opening the market for new technology in the space conditioning and thermal comfort field. The primary feature of this personal cooling/heating device is the next-generation miniature HP system with built-in PCM storage.
Benefiting from linear mini-compressor and next-generation air-to-refrigerant heat exchangers, the system delivers cooling and heating at minimum power consumption without releasing waste heat. With the help of RoCo, building operators and homeowners can extend HVAC setpoints and achieve considerable energy savings without compromising occupants' thermal comfort. RoCo reaches an overall COP of 3.54 (project goal of vapor compression cycle COP is ≥ 3.0) with a measured evaporator capacity of 150 W.

Figure 27: Progression of RoCo prototypes (left) and latest version of RoCo (right).

The overall cycle COP with the total power consumption from cooling and PCM recharging is 1.6. An assessment was performed on RoCo energy saving potentials for office buildings in the US. For seven cities representing various climates, RoCo can provide up to 49% energy savings in a mild climate, such as San Francisco, and 9% in a hot climate, such as Phoenix.

4.4 Integrated heat pump (IHP) development and field-testing at ORNL

The DOE Building Technologies Office long-term goal is to maximize the energy efficiency of the US building stock by 2030. Maximizing building energy efficiency is an essential facilitating step to enable market uptake of nZEBs. To achieve this vision, the energy used by the energy service equipment (e.g., equipment that provides space heating (SH), space cooling (SC), DHW heating) must be significantly reduced by 50% or more compared with today's best common practice.

One promising approach to achieve this is to produce one piece of equipment that provides multiple services. The Oak Ridge National Laboratory (ORNL) developed a general concept design for such an appliance, called the *Integrated Heat Pump* (*IHP)*. There are two primary versions of the IHP: geothermal (or GS-IHP) and air-source (AS-IHP). ORNL activities have focused on developing four different embodiments of the IHP in collaboration with manufacturing partners. The first focused on an electric GS-IHP and is now a commercially available product. The other three are AS-IHPs (two electric-driven and one natural gas engine-driven), which were also developed collaboratively with manufacturing partners. All three AS-IHP developments have reached the prototype packaged system stage and have completed field evaluation. Field test results have been contributed to Annex 49. The gas-driven unit for single family homes is undergoing a value engineering to reduce cost and increase competitiveness.

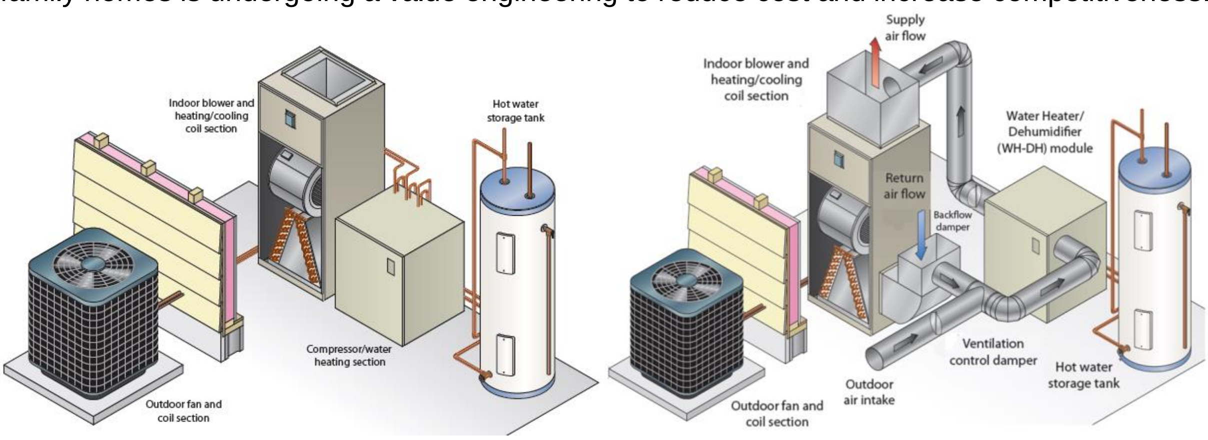


Figure 28: Conceptual installation of AS-IHP system concept 1 (left) and system concept 2 (right)

4.5 Air-to-air Heat Pump System Tests at NZERTF at NIST

The Net Zero Energy Residential Testing Facility (NZERTF), a residential-style net-zero home on the NIST main campus depicted in Figure 29 offers a unique test bed for residential HVAC technologies. Several HVAC systems can be installed in parallel so that the systems can be operated at nearly the same weather and load conditions. The net-zero house includes a detached two-car garage. It is a two-story, three- to four-bedroom house with three full bathrooms and is separated from the garage by a breezeway. The first floor includes a utility closet for the clothes washer and dryer and a future multisplit HP indoor unit, a kitchen and dining area, a family room, an office (optional bedroom), a full bathroom, and a foyer open to the second floor. The second floor comprises a master bedroom with an adjoining bathroom, two additional bedrooms, a second bathroom, and a hallway. The house includes a full 135 m^2 (1,435 ft^2) basement. The detached garage contains the data acquisition/control equipment associated with the facility. The front of the house faces true south and accommodates two solar systems: A 10.2 kW_p photovoltaic system located on the main roof and four 2.2 m^2 (24 ft^2) solar thermal collectors on the roof of the front porch (Fanney et al., 2015).

Figure 29: NZERTF: left front at ground level (left) and right front elevated view (right).

With this in mind, a small duct high-velocity (SDHV) HP was installed in parallel with a conventionally ducted air-source HP to enquire, if an SDHV HP system whose ductwork is much easier to install than a conventional duct system provide comparable energy-use efficiency. The two systems were installed side by side in the house with one system operating for a week and the other system operating for a week in an alternating fashion for a whole cooling and heating season. The main parameters were measured on both systems, namely, electrical energy use and cooling/heating thermal energy. Human comfort performance of the two systems is described in a complementary publication in detail in Kim et al. (2019).

5 Accompanying investigations to heat pumps in nZEB

Besides the monitoring projects more detailed investigations for heat pump application in nZEB have been carried out which are partly linked to the monitoring. For instance for the single family houses Berghalde and Herzo-Base, load management options by heat pumps control and storage integration have been evaluated and for the multi-family houses in Vögelebichl, a system model has been derived from the monitoring data and system variants have been evaluated. But also investigations apart from the monitoring projects have been contributed, e.g. the storage of heat in the building structure or the design of speed-controlled heat pumps. Details on the simulations are contained in the Report Annex 49 part 3 on simulation.

5.1 Load management in nZEB

Based on the building Berghalde, see chap. 3.1.1, investigations of load management with the heat pump in combination with thermal and electric storages have been performed in order to increase self-consumption of on-site electricity. The simulation results show that by using the different components (battery, buffer storage, etc.) the SCF can be increased from 27% (base) to over 45% and the LCF from 34% (base) to over 50%. Furthermore, the proportion of electricity from grid supplies can be reduced by up to 30%, when the variants are integrated and implemented. Design recommendations have been derived for the size of thermal and electric storage integration.

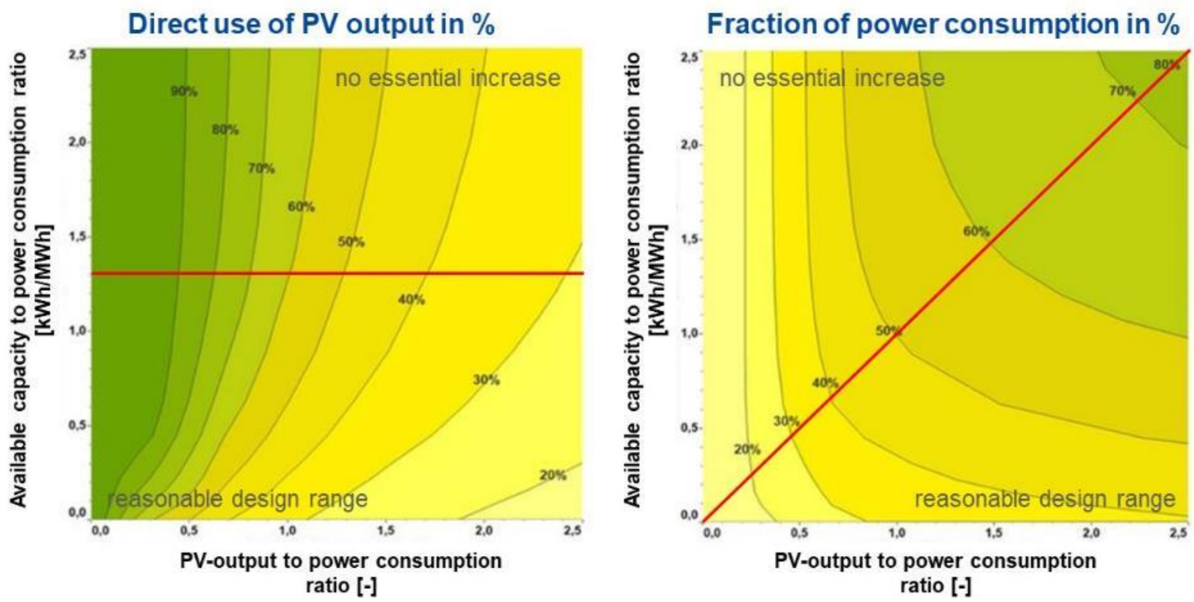
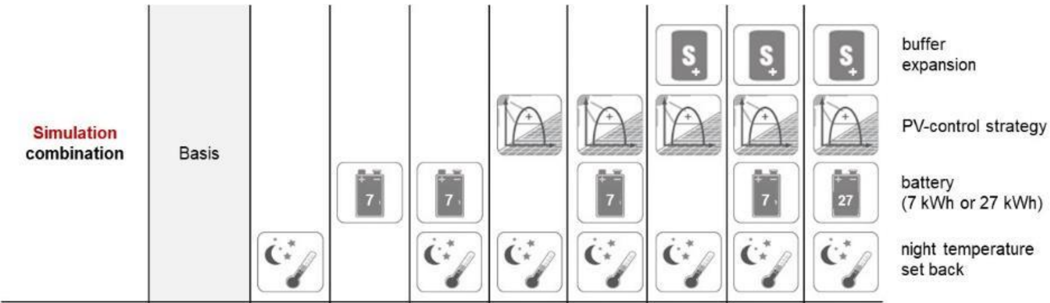


Figure 30: PV supply- (left) and load cover factor (right) of electric storage in single-family houses

Figure 30 shows electric battery storage design for a single family house. It can be seen, that above a ratio battery storage capacity to power consumption of 1.25 kWh/MWh, there is no significant increase of the PV self-consumption anymore.
However, the measures for augmented self-consumption will increase electricity demand by up to 4.5% due to the increased running time of the heat pump and the higher flow temperature with dedicated PV control. On the basis of the selected component variants, it can already be shown that the share of electricity self-consumption and the load cover factor can be increased with only a small amount of effort and few technical components. Even the implementation of a night-time set-back or the implementation of the PV surplus regulation will result in an increase up to 40%. Without the use of an electrical storage unit, but with adaptation of the control strategy for electricity self-consumption and a buffer storage extension, the supply cover factor can be increased to 38% and the load cover factor to 45%. At the same time, grid purchases are reduced by around 13% as depicted in Figure 31.



Simulation combination	Basis								
total power consumption	11.227 kWh	- 2,4 %	0 %	- 2,4 %	+ 1,3%	+ 1,3%	+ 4,5%	+ 4,5%	+ 4,5%
direct use of PV-output	27 %	28 %	31 %	31 %	34 %	37 %	38 %	41 %	48 %
fraction on power consumption	34 %	36 %	37 %	39 %	42 %	45%	45 %	48 %	54 %
grid power	7.420 kWh	- 5,4%	- 4,6%	- 9,9%	- 11,2%	- 15,5%	- 13,3%	- 17,0%	- 28,0%

Figure 31: Results of storage integration variants concerning supply and load cover factor increase

5.2 Load management in group of single family houses Herzo-Base

In the project Herzo-Base described in chap. 3.4.1 investigations of demand side management (DSM) for increased on-site PV self-consumption and reduction of grid interaction have been performed by simulations. The rule based control strategy is modulating the speed controlled heat pump and charging the central thermal storages and decentral DHW storages to higher temperatures in case of PV yield and reduces storage charging at low PV yield.

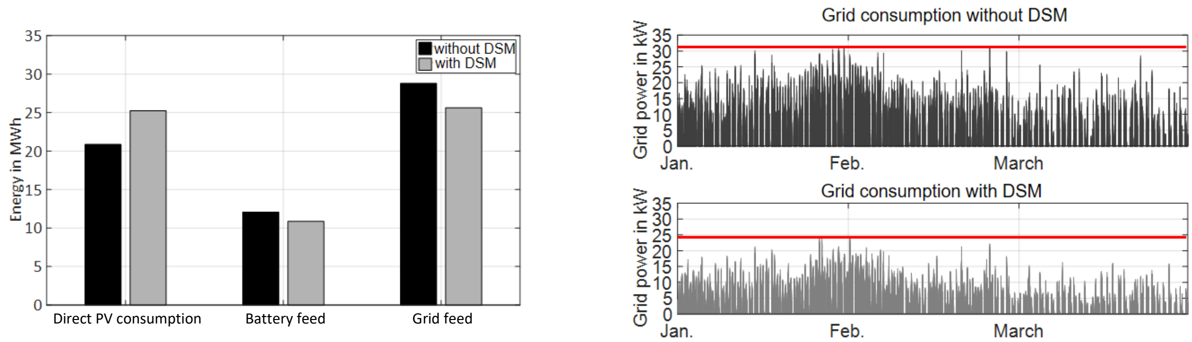


Figure 32: Change of direct PV consumption, battery and grid feed (left) and reduction of load peaks (right) by rule based control in the project Herzo-Base

Figure 32 shows an evaluation of the simulation results for the winter period January to March. The direct PV consumption could be increased up to 21% and thereby, the electric battery feed-in could be decreased by 10% and the grid feed by 11%. As a consequence, also grid interactions could be decreased, since load peaks of the grid could be reduced by up to 24%. Ongoing investigations also evaluate advanced control strategies using model predictive control (MPC).

5.3 Optimisation of nZEB system technology in Vögelebichl

Based on system models which have been calibrated and validated with the four year monitoring data of the two multi-family houses Vögelebichl in Innsbruck described in chap. 3.1.2, detailed system analysis has been accomplished to optimise the building technology of the two buildings. Figure 33 shows the two investigated system configurations. In both cases PV replaces the solar thermal (ST) collectors, since a slightly better energy balance resulted in the comparison, see Figure 34 left. Case A denoted "direct SH" connects the space heating directly to the floor heating. The smaller storage serves the DHW operation and capacity is controlled by variable speed pumps instead of mixing valves. No desuperheater is considered for the DHW operation.

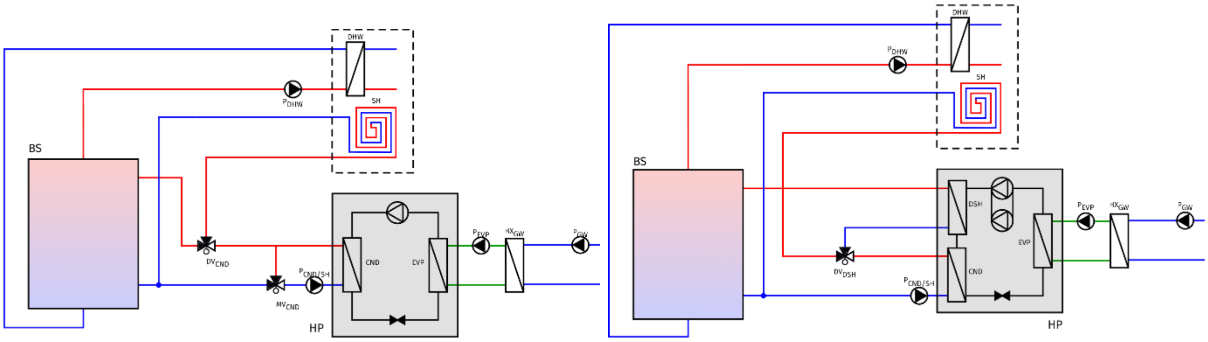


Figure 33: System variant without ST collectors, Case A: "direct SH" (left) and Case B: CND-DSH series" (right)

Case B denoted "CND-DSH series" connects the condenser and the desuperheater in series, so the DHW is produced simultaneously during space heating operation which enables lower condensation temperatures in the condenser. Figure 34 left shows a comparison of the reference with the variant without ST and respective scaled, i.e. increased PV system. It can be seen, that without ST system more electricity is required, in particular in summer, but also up to 6% in January. However, since the ST area could be replaced by PV, the scaled PV yield can compensate for the higher electricity demand.

The annual balance yields 2.3 kWh/(m^{2}yr) for the reference, 7.7 kWh/(m^{2}yr) for the reference w/o ST and 2.2 kWh/(m^{2}yr) for reference w/o ST and scaled PV, i.e. a slight advantage for the PV system. However, the scaled PV system configuration is not optimised, so a higher difference could be expected, but also grid round-trip efficiency and on-site thermal or electric storage must be considered and optimized for a complete comparison. Figure 34 right shows the results for Case A and B. In both system variants the SPF rises to 4.1 compared to SPF of 3.9 in the reference variant. Both variants need more energy for the heat pump due to the lack of the solar thermal systems, but the PV production also increases. Thereby, for both optimised variants, the nZE balance is reached, while it is not reached for the reference. Due to the simpler hydronic scheme and a slightly lower energy consumption in Case A of 10.9 kWh/(m^{2}yr) compared to 11.4 kWh/(m^{2}yr) in Case B, Case A is the recommended optimisation.

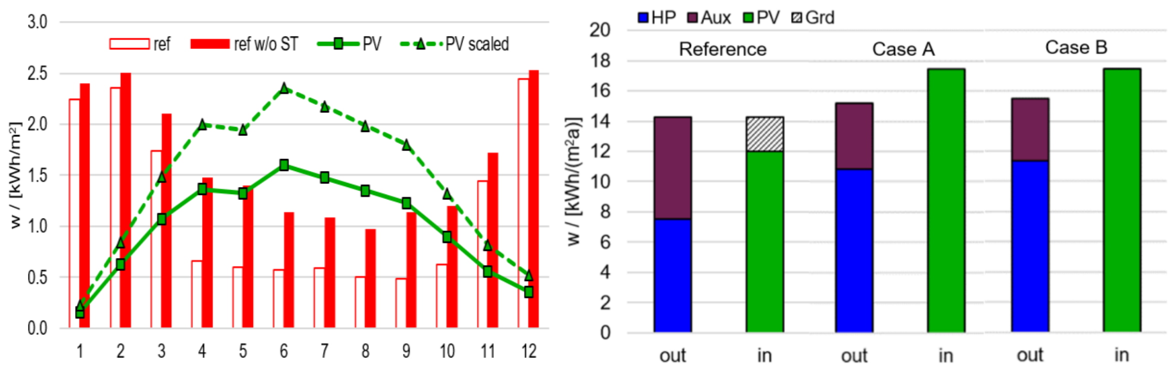


Figure 34: Comparison of variants with and without solar thermal system (left) and annual electric energy balance for the reference case, Case A and Case B (right).

5.3.1 Desuperheater use in high performance buildings

In addition to the system configuration shown in Figure 33 right, also the benefits of an integrated desuperheater (DSH) has been investigated. In Figure 35 left, the different operation modes for the two stage heat pump installed in the building are shown for the space heating and the DHW mode. Figure 35 right gives the trend of the electric energy saving, highlighting the typical values of heating to DHW energy demand ratios for a low energy house (LEH), the Passive House (PH) standard for single-family house (SFH) or multi-family building (MFB). As it is clear from Figure 35, the energy-saving due to the DSH is larger as the DHW to heating demand (HD) is lower; therefore, the largest benefit is expected for buildings less performing than passive houses.

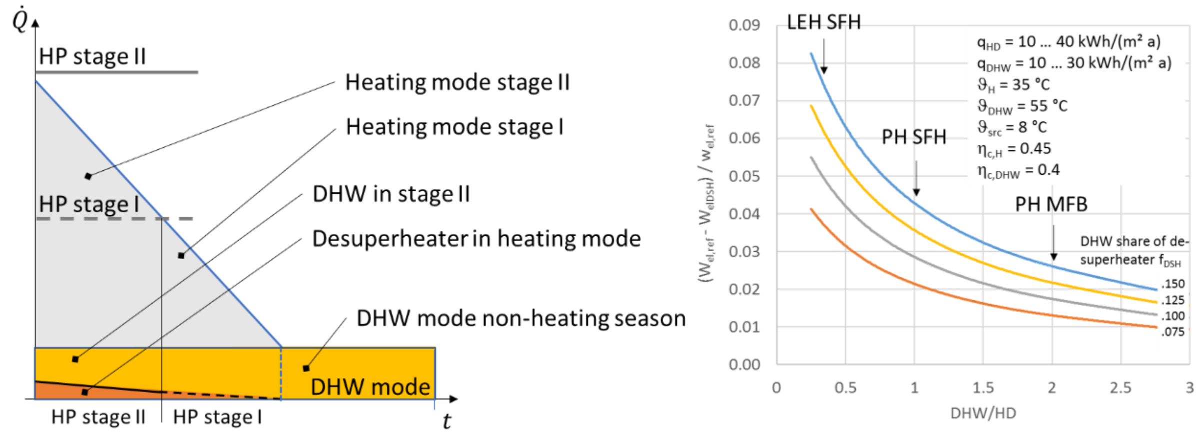


Figure 35: Sorted load duration curve (baseload DHW and peak load heating) with double stage HP with possible share of DHW contribution from DSH in heating mode (left) and theoretic reduction of electricity consumption by using a DSH depending on DHW and HD ratio with DHW share of DSH f_{DSH} as parameter.

5.4 Storage in the building structure

At IWT of TU Graz an investigation by simulation of storage of PV electricity converted to heat by the heat pump or of ST heat in the building structure by thermally-activated building systems (TABS) was performed. System A is the reference system with an air-to-water heat pump which does not have PV or ST installed. The system comprises a buffer storage which supplies the TABS and a fresh water station for DHW heating. System B amends the reference by adding a ST collector which is connected to a buffer storage. System C amends the reference with a solar PV system. Simulations did not consider the household electricity consumption. On the one hand, this would lead to less available PV energy for the heat pump, but on the other hand, it would result in an overall higher self-consumption of PV and substitution of grid electricity. Figure 36 shows the results of the simulated cases.

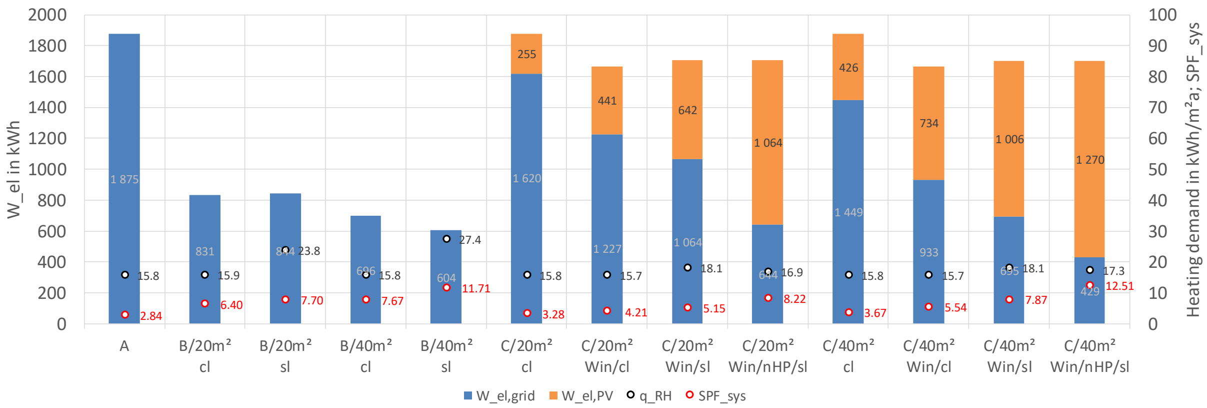


Figure 36: Simulation results for investigated systems variants A, B and C, for 20 and 40 m² collector area, conventional loading (cl) and solar loading (sl)

For reference system A, a SPF_{sys} of 2.84 is achieved, which means an electricity consumption from the grid $W_{el,grid}$ of 1875 kWh.

For the variant B with a ST system conventional loading (cl) with 20 m² of ST collectors the electricity consumption from the grid can be reduced by 56% to 830 kWh. If the solar loading (sl) of the TABS is activated, $W_{el,grid}$ remains almost unchanged, but SPF_{sys} increases from 6.4 to 7.7, which, however, with the used definition of SPF_{sys} is mainly due to an increased heat demand due to solar loading. Thus, the SPF_{sys} alone is not meaningful, since it does not evaluate electricity consumed from the grid and electricity costs. With 40 m² collector surface, the electricity from the grid drops further to 696 (cl) and 604 (sl) kWh, which corresponds to additional 16% and 28% savings, but absolute savings in [kWh] are low for the doubling of the collector area.

System C was also simulated with 20 and 40 m² PV area and four control variants. With conventional loading (cl), $W_{el,sys}$ is 1620 kWh for 20 m² PV and 1449 kWh for 40 m².

HP and PV are operated in parallel, which means that the heat pump only uses PV electricity, if it happens to be operated, when PV yield is available. If a time window is used for DHW charging (Win), the electricity drawn from the grid can be reduced to 1227 (-24 %) with 20 m² and 933 kWh (-36 %) with 40 m², because DHW charging only takes place at times, when PV yield is potentially available. The simulation results have shown that this time limitation for DHW charging does not cause any loss of comfort concerning the hot water temperature. For smaller DHW storages, comfort could be ensured by "emergency charging" outside the time window.
As in system B, $W_{el,sys}$ decreases further to 1064 (20 m²) and 695 (40 m²) kWh with additional solar loading of the TABS (sl). If, as a last additional measure, a variable speed compressor with a corresponding control is used (nHP), $W_{el,sys}$ can be reduced to 644 with 20 m² and 429 kWh with 40 m² of PV. This corresponds to a saving of 66 and 77 % respectively compared to the system without PV (system A).
Results show that coupling a heat pump with a PV system, the PV share can be significantly increased and grid consumption reduced by simple control measures. Slightly better results can be achieved with PV than with ST of the same collector or module area. For this reason, the use of PV as a whole currently appears more attractive than ST, primarily due to the relatively low investment, but also due to the possibility of feeding surplus energy into the grid. Further work should also include the cooling operation with TABS, since sustainable and energy-efficient cooling is an increasing demand due to rising outdoor temperatures.

5.5 Design of speed-controlled heat pumps

Due to high performance building envelopes in nZEB, capacity-controlled heat pumps may be advantageously used. Depending on the compressor control, capacity-controlled heat pumps have the opportunity of increased COP in part load operation. In particular speed-controlled heat pumps with inverter show higher COP in part load than in full load operation. Thus, the questions arises, how to design the heat pump in order to best use the higher part load COPs. A slight oversizing could thus be an advantage, if full load operation can be avoided and part load COPs can be optimally used. Thus, a simulation study of the application of speed controlled heat pumps in nZEB have been carried out at the HSR Rapperswil.
Figure 37 left shows the SPF for space heating and DHW operation depending on the design heating capacity of the heat pump based on a fixed heat load of the building for two investigated speed-controlled heat pumps. It can be seen that efficiency decreases with increasing heating capacity of the heat pump. This has the following reason: The larger the design of the heat pump, the earlier the cyclic operation starts, i.e. in case of an oversizing, the cyclic operation already starts at higher heat loads of the building and capacity control by the inverter is limited to highest heat loads. This is also illustrated in Figure 37 right with a plot of the performance map of heat pump 1 for two designs, an oversized design (red curve) and a design according to the building design heat load (blue curve).

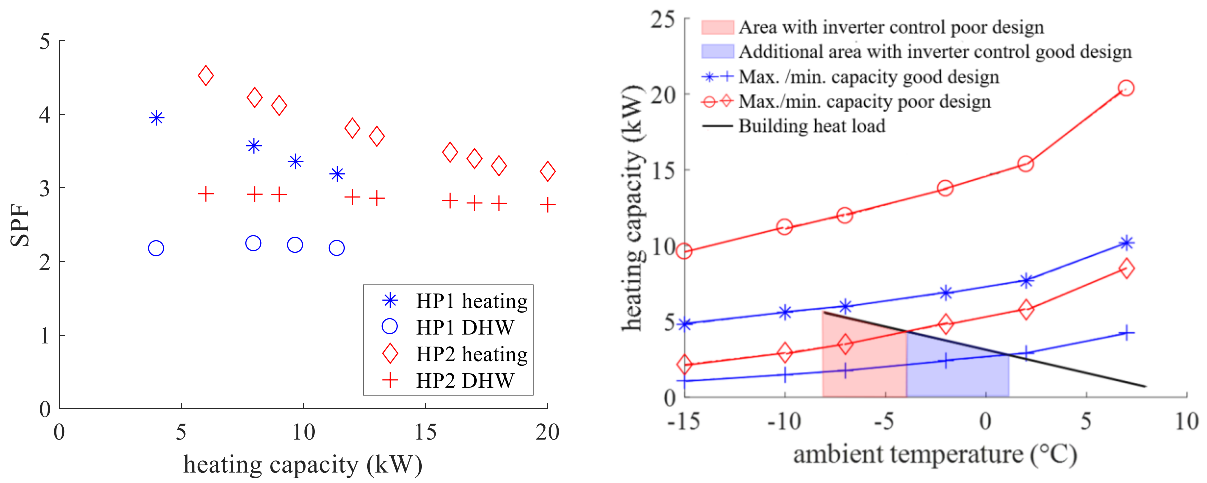


Figure 37: Influence of sizing of the HP on SPF (left) and heating capacity and building load dependent on ambient temperature (right)

The decrease of the building heat load is depicted idealised as linear black line dependent on the ambient temperature in Figure 37 right. With oversized design of twice the building design heat load the building load curve (black line) crosses the lowest capacity that can be achieved with the inverter control (red line with diamond markers), which is typically at about 30% of the capacity, and the cyclic operation starts already at an ambient temperature of -4 °C (red area in Figure 37 right). On the other hand, with a design according to the design heat load of the building, cycling starts significantly later above an ambient temperature of 2 °C, as shown by the crossing of the lowest capacity (blue line with plus markers) with the building load curve. That means, that between -4 °C and 2 °C (blue area in Figure 37 right), a temperature range, which has a high frequency during the year, inverter control and thus the better part load COP can be additionally used with the smaller design, while with oversizing, the heat pumps is already in cyclic operation in this temperature range. Thus, a rather scarce design is recommended, since the standard heat load calculation of the building is already on the safe side compared to the real heat load.

5.6 Energy flexible buildings

In Norway, demand response measures to unlock energy flexibility of residential buildings heated using heat pumps has been investigated. Demand response is applied to support the electricity grid and uses the thermal energy storages of the building, namely the building fabric (i.e. thermal mass activations) as well as of the DHW and buffer water tanks. Different predictive rule-based controls have been tested, each control strategy targeting a specific objective: the reduction of (1) the operational costs (CSP control), (2) the yearly CO_2-emissions to operate the heating system (CSC control) and (3) the energy use during peak hours (CSS control). These three controls are compared to a business-as-usual control scenario where the temperature set-points are kept constant (BAU). In the simulation study in IDA ICE, the case building and the heating system configuration is based on the ZEB Living Lab located in the Gløshaugen campus of NTNU. It is a highly-insulated single-family house of 105 m^2 heated floor area. The air source heat pump (AS-HP) is connected to a combi storage tank where the upper part serves for DHW heating and the lower part for space-heating. Moreover, the building is equipped with 4 m^2 of solar thermal collector and a 12 kW_p PV system. Results are presented for a modulating heat pump system (MHP), for an on-off heat pump system (OHP) and for direct electric heating, where space heating is covered by electric radiators and DHW heating by an electric resistance heater. Some exemplary results in Figure 38 show the influence of the three control scenarios (CSP, CSC and CSS) on the annual electricity use for heating for the modulating heat pump system. In general, all scenarios lead to an increased annual electricity use for heating, which is not only due to longer periods with higher temperature set-points, but also due to an increased use of the direct electric back-up heaters (for all three control strategies). The investigated strategies reduce the energy use for heating during peak hours, except for CSP. CSS is very effective for load shifting away from peak hours, but, as it simply moves the electricity use from peak to pre-peak hours, it may create new peaks.

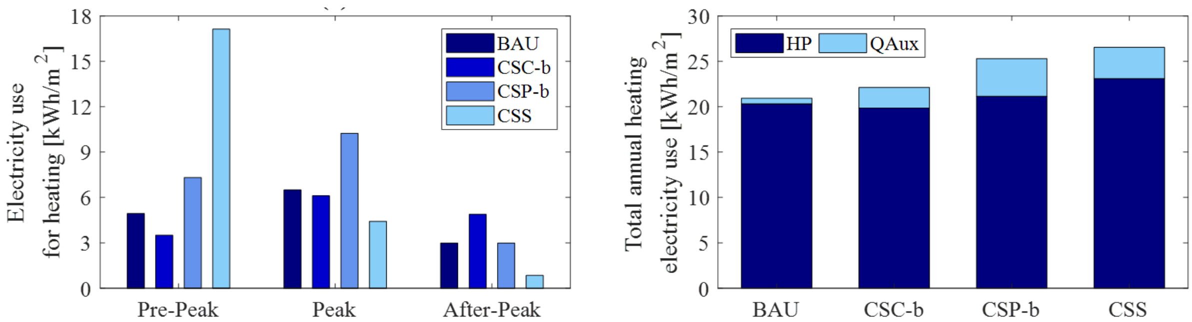


Figure 38: Electricity use for heating of the ZEB for modulating heat pump (Clauss et al., 2019)

In this study, the CSP control leads to an increased heating electricity use during peak hours because of the strict prioritization of DHW heating over SH. Extended periods for DHW heating by the heat pump lead to a more frequent use of the direct electric back-up heater to charge the space heating buffer tank, since the heat pump is not able to heat both simultaneously.

Even though the CSP control forces the heating system to use electricity when it is cheaper, the CSP control was not able to reduce the energy costs because of the resulting increase of the energy use. The spot price of Norwegian bidding zones has been taken for the study and is characterized by limited fluctuations (volatility). Results are different for other countries or other price signals with larger fluctuations. Finally, the project also evaluated the impact of the modelling complexity on results (Clauss and Georges, 2019) and found that modelling details have a strong impact. A detailed modelling is thus required to evaluate the heat pump system performance with demand response in a reliable way. For example, it was shown that the details of the regulatory control (at the component level) may impact the overall system performance.

6 Conclusions IEA HPT Annex 49

The following conclusions and perspectives can be derived from the Annex 49 work regarding the following aspects:

State of the art and implementation of nZEB in EU member states

- At current state of the implementation of the EPBD in EU MS different implementations and ambition levels of nZEB prevail in EU member states, which differ both in system boundaries, requirements and linked metrics and limits.
- Some EU member states implement a step to higher efficiency in the new built sector, while others virtually remain at the state that existed before the introduction of nZEB
- Some EU member state's implementations seem not ambitious enough and remain below the EU benchmarks, which have been published as recommendations for the required nZEB energy performance
- Due to the different implementations of the EPBD in the EU member states a comparison of ambition levels in different countries is hindered and sophisticated. Thus, a common methodology for comparison of ambition levels would be useful to motivate less ambitious countries to set higher performance requirements as intended by the EPBD. The developed methodology in Annex 49 shall thus be further tested and developed to enable a harmonised comparison.
- The all electric building concept, as a combination of heat pump and PV, is an archetype for nZEB implementation, which is found often in realised nZEB and is a market driver for heat pumps with the introduction of nZEB requirements in the new built sector.

Monitoring experience of heat pumps in nZEB

- In general the numerous long-term monitoring projects show a high performance of the heat pump operation in nZEB as result of the field monitoring. However, most of the monitored buildings set higher targets for the ambition level than would be required by the national nZEB implementation in the building regulation
- Nevertheless, the monitoring projects also show that, in particular in larger buildings an ambitious nZE balance remains a challenge despite the high performance of the heat pump, which requires optimised building envelope and system technology as well as large-scale integrated renewable production, which may be limited by the available building surface, though
- Due to the high performance of heat pumps in nZEB, ambitious nZEB requirements can thus also be a market driver for heat pumps in larger buildings, since otherwise, ambitious nZEB targets may not be reachable
- First experience with nZEB with mixed use and groups of buildings show positive results regarding waste heat use and load balancing, which should be further investigated

Prototype developments

- All prototype developments in the Annex 49 were dedicated to highly integrated units, both regarding integrated functionalities to cover all building services with one unit and regarding compact design, e.g. an integrated recooling storage or a compact façade integrated unit
- Prototype developments and testing had a focus on integrated space cooling operation, since with rising outdoor temperatures, the need for sustainable space cooling options will increase.
- Besides development also component and system testing of prototypes in the lab and in field testing has been contributed to Annex 49.

Accompanying investigations by simulation on design and control

- Monitoring systems with long-term results of several years have also been used to extend the investigation of the system regarding to integration, design and control strategies
- Accompanying investigations were used to optimise the system configuration regarding the performance and the nZEB balance as well as to investigate design and control of the heat pump and storages

- A smart heat pump operation and the demand response capability of heat pumps is a further unique selling point for heat pumps in nZEB and all electric building concepts
- Results from different projects in the Annex 49 confirm that adapted and advanced controls can increase self-consumption and unlock demand response potentials
- Based on the monitoring results and simulations design and control recommendations for integrated thermal and electric storages for increased on-site electricity self-consumption and grid supportive operation were derived
- In some monitoring projects, an oversizing of the heat pump was observed. Also speed-controlled heat pumps should be designed to closely match the load to benefit from longer running time at good part load COPs. Since design standards are already on the safe side, a scarce design of the heat pumps is recommended.
- Control for peak shaving are relatively easy to develop while price-based or CO_2-based controls are significantly more sophisticated.
- Price-based or CO_2-based controls require minimum fluctuations (volatility) of the penalty signal (i.e. price or CO_2-intensity of the electricity grid) in order to meet their control objectives.
- For the evaluation of control strategies, a detailed modelling of the heat pump system is required while simplified models may lead to incorrect conclusions (mostly overoptimistic).
- With increasing importance of energy flexibility, demand response capability may become a design criterion besides the current criteria mainly based on energy efficiency and costs. However, at current market conditions, investment in flexibility, e.g. by larger storage design or electric battery integration, is often not economically feasible and there is little incentive to unlock the energy flexibility potential.

<u>Perspectives</u>

- With the background of rapidly progressing climate change, ambitious energy performance targets shall be pursued for the built environment as intended by the EPBD recast.
- Thus, a further harmonisation of nZEB implementations among the EU countries is recommended to support high ambition levels and facilitate standardised system solutions and technologies across European countries, which can further reinforce the good market position of heat pumps for nZEB applications
- From a general perspective the nZEB concept on annual energy balancing may be misleading due to load mismatch and seasonal effects (intermittent renewable energy production, overproduction in summer and lack of production in winter). Adequate Key Performance Indicators shall be further developed to entirely assess these concepts including grid-interaction effects in order to optimise local consumption and grid operation.
- Limitations to reach nZEB requirements, particularly in larger buildings, may be overcome by moving the nZEB assessment boundary from one to groups of buildings and neighbourhoods. Thereby, the ambition levels for single buildings shall still be high, but load and on-site production profiles and balancing, both for thermal and electric loads, can be facilitated to reach ambitious targets. Research shall thus be extended to groups of nZEB and neighbourhoods.

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8 Abbreviations

Abbreviation	Meaning	Remark
AS	Air source	
BAU	Business as usual	Scenario NO energy flexibility
BPIE	Buildings Performance Institute Europe	
BREEAM	Building Research Establishment Environmental Assessment Method	UK sustainable Building label
BTES	Borehole Thermal Energy Storage	
CEN	Committee Europeen des Normalisation	EU Standardisation Organisation
CND	Condenser	
COP	Coefficient Of Performance	
CSC		Scenario NO energy flexibility
CSP		Scenario NO energy flexibility
CSS		Scenario NO energy flexibility
DHW	Domestic hot water	
DOE	US Department of Energy	
DSH	Desuperheater	
DSM	Demand Side Management	
EC	European Commission	
EERE	Energy efficiency and renewable energy	DOE office
EnEV	German Energy saving directive	EnergieEinsparVerordnung
EPBD	Energy Performance of Buildings	EU Directive
EU	European Union	
GS	Ground source	
HD	Heat demand	
HP	Heat pump	
HPT	Heat Pumping Technologies	IEA TCP
HVAC	Heating, Ventilation and Air-conditioning	
IEA	International Energy Agency	
IHP	Integrated Heat Pump	
IPEEC	International Partnership for Energy Efficiency Cooperation	
ISO	International Standardisation Organisation	
JRC	Joint Research Centre	
KfW	Kreditanstalt für Wiederaufbau	German bank for funding a. o. high performance buildings
LCF	load cover factor	
LEH	Low energy house	
MFB	Multi-family building	
MHP	Modulating heat pump	
MPC	Model predictive control	
MS	(EU) member state	
MuKEn	Model ordinance of the cantons in Energy	Swiss building regulation
MVHR	mechanical ventilation heat recovery	
NIST	National Institute of Standards and Technology	
NS	Norge Standard	
nZE	Nearly Zero Energy	
nZEB	Nearly Zero Energy Building	
NZEB	Net Zero Energy Building	
NZERTF	Net Zero Energy Residential Testing Facility	
OIB	Austrian Institute of Construction Engineering	Österreichisches Institut für Bautechnik
ORNL	Oak Ridge National Laboratory	
OVN	Otto Nielsens vei	Monitoring Building in NO
PCM	Phase change material	
PH	Passive house	

Abbreviation	**Meaning**	**Remark**
PV	Photovoltaic	
PV/T	photovoltaic/thermal	
RE	Renewable energy	
REHVA	Federation of European HVAC associations	
SC	Space cooling	
SCF	supply cover factor	
SFH	Single family house	
SH	Space heating	
SPF	Seasonal performance factor	
ST	Solar thermal	
TABS	Thermally activated building system	
VSD	Variable speed drive	

Appendix List of publications in IEA HPT Annex 49

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