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Heat pump integration for nZEB–results of IEA HPT Annex 49

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Abstract

Heat pumps are a promising building technology, especially in nearly Zero Energy Buildings (nZEB), which is believed to be the future building standard in many countries. In IEA HPT Annex 49, participants of nine countries are investigating design and integration options for heat pump application in nZEB. In Task 1, current implementations of nZEB are analysed and a methodology to compare ambition levels in the countries is developed. In Task 2, improvements of the heat pump performance by system integration are investigated by simulations, which are also coupled to the evaluation of real world performance of monitored heat pumps in nZEB in Task 3. In Task 4, the design and control is investigated, which also covers control for demand response. Besides single buildings, also clusters of buildings are included.
Results indicate that heat pumps reach a high performance in nZEB, which is necessary to reach ambitious nZE targets in particular in larger buildings. Furthermore, by simulation and monitoring, further optimization potentials of the heat pump operation have been identified. It is also confirmed that adapted controls can improve self-consumption and grid interaction of on-site electricity generation.

Keywords: Integrated heat pumps; nZEB, system design; energy flexibility; field monitoring

1. Background of nZEB

The recast of the Energy Performance of Buildings Directive [1] in Europe sets the objective that all new public buildings shall be built as nearly Zero Energy Buildings (nZEB) from 2019 on and all new buildings from 2021 on. Also in the USA and Canada Net Zero Energy Buildings (NZEB) are in the focus of the political strategy for high performance buildings, in order to be widely introduced between 2020 and 2030 and in Japan, NZEB are planned to be the standard building by 2030.

Even though political strategies strongly refer to the nearly or Net Zero Energy objectives, there is limited available knowledge and experiences about standardised cost- and performance optimized building technologies to reach nearly or Net Zero Energy consumption. While low- and ultra-low energy houses, e. g. according to the passive house standard, already show considerable market penetration and growth in several European countries and worldwide, nZEB are rather in the pilot and demonstration phase in order to prove a nearly zero, net zero or even plus energy balance. In plus energy buildings a surplus of produced energy compared to the consumed energy is achieved by installed renewables on-site on an annual basis. Especially in the non-residential sector, the nZEB balance can be challenging. Residential buildings have rather moderate energy loads and consumptions, and in particular for single family buildings, there is enough space in the building envelope to reach the balance by on-site renewable production.

In larger buildings, though, both loads may be higher and building envelope may be limited regarding the on-site renewable production, challenging the achievement of the balance and emphasizing the application of high performance components and operation.

Due to the common understanding, an NZEB is a grid-connected building with highly reduced energy needs where the weighted consumed energy can be produced by weighted renewable production on-site on an annual basis. However, this definition is incomplete, e.g. regarding the system boundary (what does on-site mean,

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since the EPBD also considers nearby energies), the energies taken into account (including plug loads or just building technology, including mobility, life-cycle consideration) and the weighting system. Moreover, with a broad introduction of the concept as intended in the political objectives, aspects like load match between locally produced and consumed energy as well as interaction with energy grids, in particular the electricity grid should also be considered and buildings should be designed to work in line with the needs of the connected energy grids. Last but not least, the definition of the nZE building has an impact on design and the system configuration.

2. Project outline IEA HPT Annex 49

IEA HPT Annex 49 entitled "Design and integration of heat pumps for nZEB" is carried out in the Heat Pumping Technologies (HPT) Technology Collaboration Programme (TCP) of the International Energy Agency. It deals with integration options and design/control of heat pump application in nZEB, which is investigated both by simulation and monitoring of realized nZEB. Moreover, prototype developments of new integrated heat pumps are included in the Annex 49.

The IEA HPT Annex 49 started in October 2016. The nine countries Austria, Belgium, Estonia, Germany, Norway, Sweden, Switzerland, UK and the USA have joined the Annex 49. The Annex 49 is dealing with a more in-depth evaluation of integration options as well as the design and control of components. Moreover, the building technology may get new tasks, e.g. the provision of flexibility to the connected energy grids, in particular the electricity grid. This may have an impact on future system design and on storage integration. But not only a short-term flexibility, but also the seasonal mismatch has to be taken into account for a holistic assessment of the system solutions.

Furthermore, also the economic boundary conditions are rapidly changing. For instance, PV prices and subsidy schemes are changing, which affects the design and layout of systems and reduction of feed-in tariffs lead to a higher importance of the self-consumption to guarantee an economic operation of the PV system. Decreasing prices of electrical batteries due to e-mobility may additionally have an impact on self-consumption and demand response.

As a further aspect, the investigations in Annex 49 extend the system boundary to clusters of buildings or neighbourhoods. For instance, collective systems connected by micro-grids and load balancing between buildings are implemented.

The work in Annex 49 has been structured into the following tasks:

- Task 1 deals with the state-of-the-art of heat pump application in nZEB in the participating countries. Thereby, the impact of the national definitions on the ambition level in the countries is a topic. Furthermore, implications of the definitions on heat pump use shall be characterized by comparing system solutions and characterizing favourable system layouts and configurations.
- Task 2 is dedicated to an in-depth analysis of integration options of heat pumps in nZEB both on the source side like the ground and active components in the building envelope as well as thermal and electric storage. Moreover, also the integration and coupling to electric and thermal grids shall be considered in terms of load management and grid supportive operation. Thereby, also clusters of buildings and neighbourhoods are evaluated regarding their integration potential for load shift between buildings.
- Task 3 is dedicated to the development of prototype systems and the monitoring of heat pump operation and performance in nZEB, which also includes larger buildings like multi-family houses and non-residential buildings like office buildings, a school and a kindergarten, a hotel and a supermarket in Germany and Norway.
- Task 4 is dedicated to the design and control of heat pumps in nZEB and is closely linked to the system integration in Task 2. Both the on-site control as well as design implications for higher self-consumption of solar energy produced on-site and demand response for grid-supportive operation are aspects of the control. Thereby, potentials of model predictive control are partly assessed, as well.

An overview of the different participating institutions in the countries and the national project contributions is given in Table 1.

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	• Monitoring and simulation of two nZEB buildings for performance optimization • Development of a prototype of a façade integrated heat pump • Evaluation of larger nZEB buildings and districts
Belgium Free Univ. Brussels	• Evaluation of heat pump in office nZEB with sewer heat recovery heat source
Estonia Tallinn Technical Univ.	• Modelling and simulation of ground-coupled heat pumps (energy piles, horizontal collectors) • Design of heat pumps and heat emission systems for the nZEB application
Germany TH Nürnberg, IGS of Univ. of Braunschweig, TEB GmbH	• System integration, design and field monitoring of different nZEB building types • Development of control strategies for smart grid integration
Norway SINTEF, NTNU, Cowi AS	• Developments of heat pumps with natural refrigerants • Investigation/monitoring of nZE demonstration buildings and neighbourhoods in Norway
Sweden RISE	• Monitoring and comparison of heat pump systems in two equal test houses
Switzerland IET HSR	• Integration and design options of solar and heat pump systems • Field monitoring of nZEB with façade integrated PV
UK Glen Dimplex	• Evaluation of design and control of nZEB model houses
USA ORNL, NIST, CEEE Uni Maryland	• Field monitoring of integrated heat pump variants (IHP) • Technology testing and comfort evaluation in NZEB test facility (NZERTF) • Evaluation of a prototype of a personal cooling device to reduce loads in NZEB

In the following, specific results of the single Tasks and national contribution are given as overview of the outcomes of the IEA HPT Annex 49.

3. Results of the different Annex 49 Tasks

3.1. Task 1 on the state-of-the-art of nZEB

In Task 1 the state-of-the-art of nZEB in the different participating countries of the Annex 49 is analyzed. nZEB definition in Europe is elaborated by the EU-member states (MS) and current definitions in the EU-MS vary both in system boundaries, metrics, limits and rating systems as outlined in [2], [3] for different states of implementation. Thus, in the first step, there will not be a common definition of nZEB, even though the EU institutions REHVA and CEN have prepared different documents to support a harmonized definition and implementation of nZEB in the EU. In the USA, a similar system boundary as of the REHVA definition has been proposed by US-DOE [4].

However, current implementations of nZEB may still updated before requirement for all new buildings are enacted on January 1, 2021, even though the deadline for the requirements for all new public buildings is already passed and thereby, definitions are in application.

The different definitions of nZEB are also related to national rating procedures, which use national calculation methods in order to approve compliance with the nZEB requirement according to the national implementation. As consequence, even with a common definition, the implementation in the single countries would vary due to different national boundary conditions, national climate data and calculation methods. Thus, it is hard to compare the ambition level of the different countries to achieve high building performance values in the new sector, which would be a useful information for policy makers to set high ambition levels in the new built sector.

Therefore, in the Task 1 of Annex 49, a methodology to compare the ambition levels of different nZEB definitions is worked out. The term ambition level refers to the ambition of the nZEB rating to reach very high energy performance of the building. For instance in Denmark, there is an ambitious requirement to reach a building envelope in the range of passive house level for the nZEB implementation, thus for the building envelope, Denmark has a high ambition level. The development of the methodology is still in progress, thus in the following, the current state is shortly summarized, details on the state of the methodology can be found in [6]. The methodology is based on a single family building as outline in [5] with some modification in order to turn the building into an nZEB. Since a heat pump is applied as heat generator for space heating and DHW operation, the building corresponds to an all-electric building. As next step, based on the common design, boundary conditions and site of the reference building, the building is transferred to the local conditions.

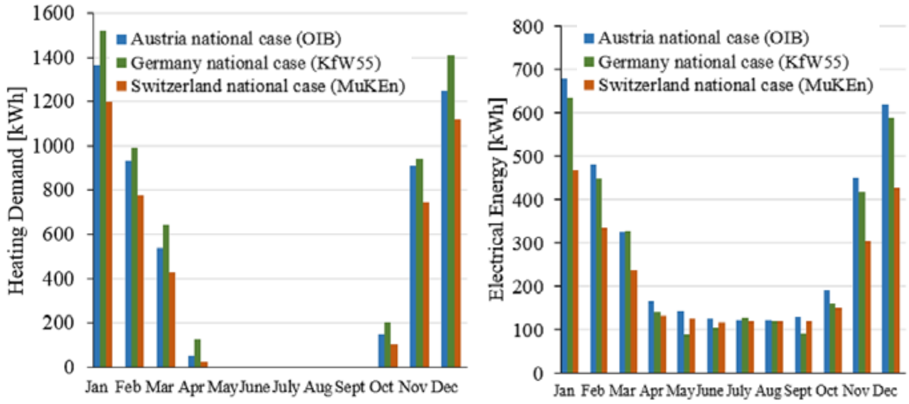

Fig. 1. Comparison of the space heating demand (left) and the electrical energy (right) for the nZEB requirements in the D-A-CH countries Germany, Austria and Switzerland

Thereby, the national nZEB layout related to the national boundary conditions by the rating procedure in the different countries can be evaluated. Afterwards, the building parameters are transferred to a simulation model of the buildings, and boundary conditions and climate data are changed back to the common ones.

This enables the comparison of the national buildings for common boundary conditions regarding internal loads, climate and DHW tapping profiles. Finally, the space heating demand and the delivered energy can be compared in order to get a ranking of the ambition level in different countries. Fig. 1 shows a comparison for the D-A-CH countries Germany (D), Austria (A) and Switzerland (CH), which are in the same climate zone, for the space heating demand on the left and the delivered electrical energy on the right according to the national definitions. It can be seen, that requirements for the nZEB rating in Switzerland results both in a lower space heating demand and in a lower electricity consumption than in the two other countries. Thus, a relative order of ambition levels among the three countries can be evaluated. However, present limitations of the methodology are that only countries in the same climate zone have been compared and the method focuses on the building envelope, while for the nZEB concept, also the on-site renewable production shall be included for the ranking. Thus, the methodology shall be further developed and extended to other examples.

3.2. Task 2 on heat pump integration for nZEB

Task 2 is dedicated to the integration options of heat pumps for nZEB application. The work in Task 2 is carried out by simulation, but is also linked to monitoring projects carried out in Task 3. An example for this link of the implementation of optimization potentials derived by simulations in monitored buildings is a project contribution of the Unit for Energy Efficient Building of the University of Innsbruck

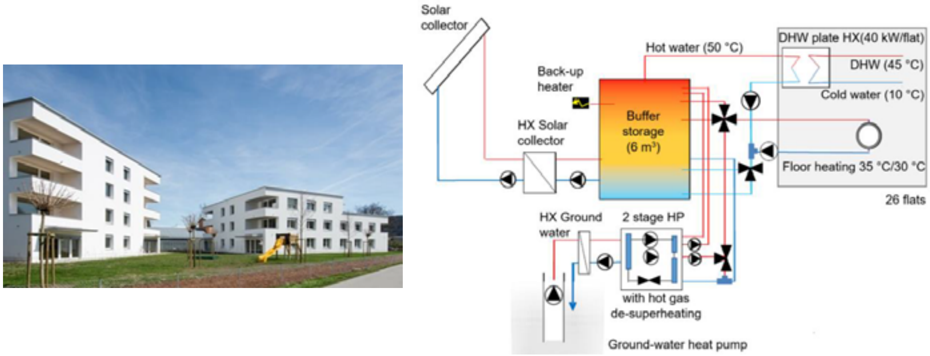

Fig. 2. Two multi-family houses in passive house standard of the project Innsbruck Vögelebichl (left, photo: "NHT Tirol") and principle sketch of the installed system technology (right)

An example for this link of the implementation of optimization potentials derived by simulations in monitored buildings is a project contribution of the Unit for Energy Efficient Building of the University of Innsbruck.

The case study deals with two multi-storey multi-family buildings in passive house standard of the social housing company NHT in Tyrol, Austria (see also [8] for more details). In the following, the main facts are summarized. Fig. 2 left shows a photo of the two buildings in Innsbruck Vögelebichl and Fig. 2 right depicts a principle sketch of the building system technology.

The buildings consist of 10 or 16 flats, respectively, with a total treated area of 2149 m^2 and are designed for a Net Zero Energy balance in terms of space heating, domestic hot water (DHW) production and auxiliary energies for the building technology (i.e. without taking into account appliances and plug loads). The design heat load for both buildings is 24 kW (according to the Passive House Planning Package – PHPP) and additional 12 kW for DHW. The buildings are equipped with 73.6 m^2 solar thermal collectors and a solar PV installation, which covers the entire roof of the one building with an area of 99.8 m^2 and a part of the other roof with 52.5 m^2 besides the solar thermal installation. The system consists of a ground-water source two compressor heat pump of a nominal heating capacity of 58 (52) kW at W10/W35 (W55) and respective COP values of 6 (3.7). The heat pump and the solar thermal system supply heat to a central 6 m^3 thermal buffer storage. The storage is charged at the top in DHW mode and at a relative height of 67% in space heating mode. The combined return flow enters the storage at a relative height of 33% or at the bottom depending on the temperature level. The installed direct electrical back-up heater is currently not in use. The storage delivers the heat to a floor heating system in the flats and the decentralized fresh water systems with plate heat exchangers for the DHW supply at use temperatures of 45 °C, using a primary inlet temperature of 50 °C from the storage.

Additionally, the heat pump is equipped with a de-superheater for simultaneous heating and DHW preparation. The de-superheater is located between the compressor outlet and the condenser inlet and uses the higher temperature of the refrigerant discharge gas for a DHW production at lower condenser pressure level in simultaneous space heating operation (e.g. for a floor heating with typical design temperature of 35 °C/30 °C) instead of the higher pressure level of the DHW-only mode. Thereby, the higher DHW temperature can be produced at high efficiency and no interruption of the space heating operation is necessary. However, the heat extraction is limited to the de-superheating fraction before the condensation begins, see also Fig. 4 below. Furthermore, the actual hydraulic integration is not optimal, see [8] for more details.

The investigations by simulation comprises different aspects of the system as operation modes of the two-compressor heat pump including the evaluation of the performance map, which is not available for all operation modes by the manufacturer. Furthermore, the de-superheater operation, the monitoring system, the nZEB balance including the auxiliaries, the storage stratification and the control of the building technology are investigated. For a detailed analysis, a system model has been set-up, which consists of a simplified refrigerant cycle model of the two-compressor heat pump. Using the model, the performance maps of the missing operation modes have been identified with the monitoring data. Moreover, a model of the central storage has been set-up and compared to monitoring data. There are some deviations, but for the use of investigating the configuration, design and control of the system, the model is applicable. Using the developed system models, the integration of the system functions and the respective control can be simulated and optimized. Selected results are presented in the following, more details are found in [7, 8].

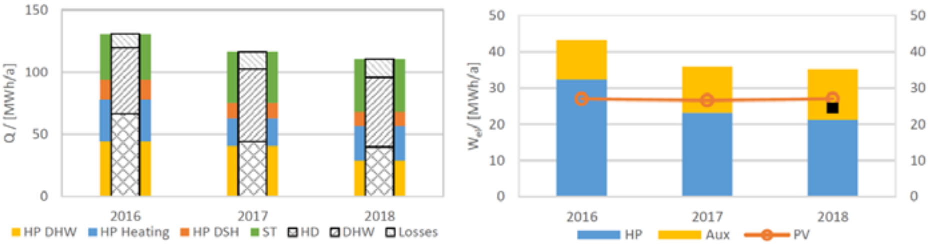

Fig. 3. Monitored heat balance (left) and electrical energy (right) of the three year measurement period of the multi-family buildings Vögelebichl Innsbruck

Results of the monitoring a three-year period are shown in Fig. 3. Operation of the buildings started in winter 2015. The demand for space heating of the buildings was 20.5 kWh/(m^2yr) in 2017 and 18.5 kWh/(m^2yr) in 2018 and thereby slightly higher than the planned 15 kWh/(m^2yr) according to the passive house standard.

The DHW demand was 25 kWh/(m²yr) and thereby in the expected range. Both the space heating demand and the electricity consumption could be successively decreased from year to year.

However, the thermal losses slightly increased in absolute numbers leading to an increased relative contribution of 14%, which is one of the major reasons, why the NZE balance related to the balance boundary of the building technology and the onsite PV production could not be fulfilled, yet. In 2018, for instance, the electricity consumption of the HP was 21 MWh and auxiliary energies were responsible for 14 MWh. The PV field produced in average around 27 MWh, as shown in Fig. 3 right of the electric energy balance for the years 2016 to 2018.

Despite the reduced total energy demand in 2018 (mainly because of the decreased heating demand), the NZE balance was not achieved. Thereby, the PV production was 24.5 MWh in 2018 due to a technical failure of the inverter of the PV field of the north building. A yield between 26.6 MWh and 27.2 MWh can be predicted based on data of 2016 and 2017 for the case without the failure.

Fig. 4, left hand side, shows a more detailed theoretical estimation of the system operation by de-superheating. Potentials for electricity savings are dependent on the ratio of DHW heat demand and space heating demand, which depends on the building standard. While in low energy houses (LEH) the space heating demand is still dominating, the fraction can increase to 50% of the total heat demand in single family passive houses (PH SFH) and even reach a ratio of about two in multi-family passive buildings (PH MFB). The given curves are parametrized by the DHW share produced by de-superheating, which might range from 7.5% to 15%. With increasing DHW fraction, the potential electricity saving decrease from 8% in the best case to about 1% to 2%, since with dominating DHW demand, the simultaneous operation with space heating decreases and thereby also the potential for combined heat production for both building services. In this configuration, the de-superheater could always supply the heat to the buffer storage in the top zone.

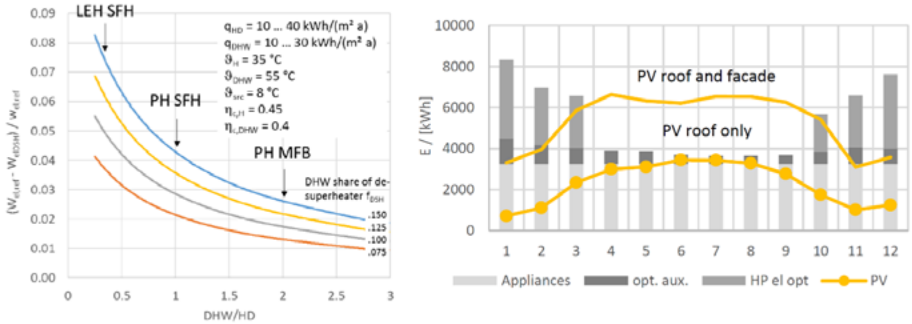

Fig. 4. Theoretical potential of the DHW electrical energy saving by desuperheating for different building types and DHW shares (left) and simulated annual energy balance with improved control and reduced auxiliary losses (right)

Fig. 4, right hand side, depicts a prediction of the monthly energy balance with reduced auxiliary energy consumption for the building equipment (e.g. pumps, fans etc.) and optimized control strategy. A multi-dimensional performance map was developed in Matlab/Simulink environment and is integrated in a system model that allows to simulate different heat pump operation strategies with and without de-superheating, single and double-stage operation as well as optimized hydraulic integration. In this optimal case, the nZE balance for heating, DHW and auxiliary energy for the building equipment can be met with the yield of the PV on the roof. However, it is noteworthy that PV in the façade is required, if also household appliances and plug loads are considered, too, as shown in Fig. 4 right. It is obvious, that the contribution to the winter load is not significant if the annual energy balance is met. A monthly net balance could only be achieved by integration of (very cost intensive) long term energy storage. This demonstrates the importance of reducing the winter load.

3.3. Task 3 on heat pump prototyping and monitoring of heat pumps in nZEB

Task 3 is dedicated to the development of prototype technologies and monitoring of nZEB with heat pumps. Different participating countries in the Annex 49 perform field monitoring projects in order to evaluate the real performance of heat pumps in nZEB.

Fig. 5: Building Black & White with roof and façade integrated PV system in the city centre of Pfäffikon SZ (left) and building use (right, orange – commercial use, green – office use, blue – residential use) (source: AWIAG)

In the following results of a monitoring project in Switzerland are given, which refers to a 5-storey building with mixed commercial (basement, 615 m^2), office (1^{st} and 2^{nd} floor, 615 m^2) and residential use (3rd and 4th floor and attic, 1520 m^2) energy reference areas in the city centre of Pfäffikon (SZ), that has been monitored for one year. The building and the uses are depicted in Fig. 5.

Fig. 6 shows a sketch of the building technology system. As counterpart to the efficient building envelope on passive house level also an efficient building technology was planned and an active solar electricity production was designed to high yields of a net zero energy balance. Therefore, a major part of the building outer surface is used for the solar PV-production. In order to meet a nZE balance, the roof comprises 26 kW_p of monocrystalline PV modules. In the south, east and west direction, thin-film PV modules of a total installed capacity of 48 kW_p are integrated in the façades. The efficiency of the roof modules is with 21% notably higher than the thin film CIS-module in the façade with an efficiency of 11%. Moreover, the building is integrated in the city centre, so that the facades are temporarily shaded by surrounding buildings.

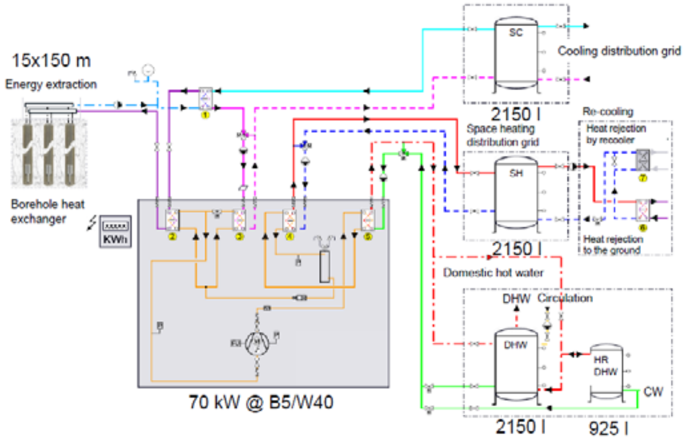

Fig. 6: Building technology concept of the Black & White with ground-coupled heat pump and waste heat recovery in space cooling operation (source: Andy Wickart Haustechnik AG)

As innovative building technology concept, the core component of a 70 kW (B5/W40) ground coupled heat pump has been planned, so that the building corresponds to an „All-electric building“. The heat source is a borehole heat exchanger field of 15 Duplex-ground probes of 40 mm diameter and a depth of 150 m each, which guarantees an efficient space heating and DHW operation, but is also integrated in the cooling concept. For the space cooling operation, a 5-phase-concept is considered: The system is planned in that way, that both the ground and a heat recovery for the DHW and space heating operation cover the re-cooling of the heat pump in cooling operation, i.e. also for the active cooling operation, no re-cooler to the outside air is required.

However, the focus of the cooling concept is a high degree of coverage in ground-coupled free-cooling (phase 1), and only at higher cooling loads, the active cooling with reverse operation of the heat pump is used. The maximum cooling capacity in active cooling mode is 53 kW. Thereby, the re-cooling heat is transferred primarily into the DHW preheating storage (phase 2). At simultaneous space heating and cooling demand, the recooling heat is transferred into the heating buffer storage (phase 3), and only in case of a surplus heat, which cannot be used in the heating buffer or DHW storage, the ground is regenerated (phase 4). If the ground cannot absorb the surplus heat anymore, a re-cooler to the outside air has to be operated (phase 5). For balancing the load and production a heating and cooling buffer storage of each 2,150 l are installed. Additionally, two DHW storages are installed, a preheating storage of 925 l for the use of re-cooling heat and a DHW storage of 2,150 l.

Moreover, for the different uses, ventilation systems with heat recovery are installed, which supply the building with an overall volume flow rate of 8,450 m^3/h. The commercial areas are cooled by cooling ceilings, which enhances the free-cooling use due to the higher possible temperature levels, and henceforth the reverse operation of the heat pump for space cooling can be limited to peak loads in summer. Additionally, the ground probes are used to preheat the ventilation air in wintertime in order to avoid ice formation on the heat recovery heat exchangers.

The year-round monitoring was evaluated from Oct. 2016 – Sept. 2017 and the balance is depicted for the single energy uses in Table 2. The measured energy consumption mainly corresponds to the calculated design values of the building. The space cooling demand is yet a bit lower, since one of the server rooms has not been operated as planned.

The projected production did not reach 20 kWh/(m^2yr) energy reference area (ERA), which would have balanced the energy consumption of the building technology. Reasons are the different type of modules, so the façade could deliver more energy with higher efficiency of the modules. The system performance factors reaches high values of 4.97 in space heating operation and 3.1 in DHW operation at 60 °C charging temperature of the storage. The space cooling operation reaches a seasonal performance of 5.9, whereby the re-cooling heat is entirely used in the space heating and DHW storage or for the regeneration of the ground, so no re-cooler to the ambient air is installed. The PV yield of the façade-integrated modules, though, has not reached the projected values, since different modules than considered in the planning have been used in the real building.

Table 2. Yearly balance of the Black & White building with mixed use in urban environment

Balanced energy	Calculation/Design value	Monitoring value
Space heating and DHW	11.4 $kWh_{el}/(m^2yr)$	9.9 $kWh_{el}/(m^2yr)$
Ventilation	3.2 $kWh_{el}/(m^2yr)$	5 $kWh_{el}/(m^2yr)$
Space cooling	5.2 $kWh_{el}/(m^2yr)$	2 $kWh_{el}/(m^2yr)$
Total electricity building technology	19.8 $kWh_{el}/(m^2yr)$	16.9 $kWh_{el}/(m^2yr)$
Total electricity consumption	49.1 $kWh_{el}/(m^2yr)$	44.4 $kWh_{el}/(m^2yr)$
Electricity yield solar PV	20 $kWh_{el}/(m^2yr)$	13.4 $kWh_{el}/(m^2yr)$
nZEB balance (weighted with 2)	-0.4 $kWh_{el}/(m^2yr)$	7.0 $kWh_{el}/(m^2yr)$

Thus, despite a building envelope on ultra-low energy house level and a good system performance with an overall seasonal performance factor of 5.2 including free-cooling, the net balance based on the system boundary building technology (excluding plug loads) is not entirely reached. Nevertheless, 95% of the energy for the building system is produced on-site on an annual basis including the ground source. The reasons for not reaching the nZE balance is the PV yield of the façade modules, which is below the design values. With an increased efficiency of the façade modules, though, the nZE balance for the boundary of the building technology could be reached, while it would be hard to reach the nZE balance including plug load, which would require a total on-site production of 44.4 kWh/(m^2yr). Since already a large fraction of the façade and roof is covered with PV and the system performance is already high, it would be hard to reach the balance including plug loads for this type of building, since the building envelope is limited and PV yields are also affected by the urban environment due to temporary shading by surrounding buildings.

3.4. Task 4 on Design and control of heat pumps in nZEB

Task 2 on the integration of nZEB building technology and Task 4 on the design and control of heat pumps for the application in nZEB are interlinked. If integrated systems are considered, also the design and control is an important feature to achieve the maximum performance.

The integration also includes the integration of nZEB into connected energy grids in terms of thermal grids or the electrical grid. As example of grid integrated nZEB, a project contribution of Germany is presented which consists of a new built neighbourhood.

At the energy campus of the TH Nürnberg, Germany, the electric and thermal integration is considered for the example of eight single family terraced houses of each 150 m^2 energy reference area, which is called "Herzo Base". The system concept contains two modulating central ground-coupled heat pumps, which are equipped with inverter control and are distributing the space heating energy by a low temperature grid on the level of the supply temperatures for the space heating operation, which is thereby centrally supplied. In contrast, the domestic hot water (DHW) is produced in decentralised 200 liters DHW storages in each house, which are supplied each by decentral 2 kW booster heat pumps, that use the low-temperature grid as heat source.

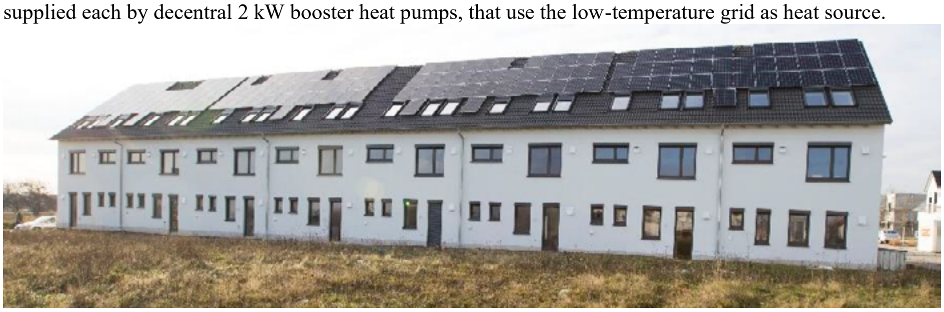

Fig. 7. Terraced houses of the project "Herzo Base" in Germany

In summertime, the ground source is used for free-cooling. The system is also equipped with an electrical battery storage that is installed centrally at the two modulating ground-source heat pumps. Fig. 7 shows a picture of the eight terraced houses.

At daytime, the PV mainly covers the household appliances and plug loads. In case of PV surplus, the battery is charged to mainly cover the illumination of the buildings and electric consumers in the evening.

Additionally, also central thermal buffer storages are installed. Besides a monitoring of the system, it is also investigated by simulations. One task of the simulation study is to evaluate control concepts, how the different storage options and heat pump modulation enhances self-consumption of the on-site generated PV electricity, since thermal storage and electric storage can be combined to increase on-site PV use and diminish grid interaction and grid import as well as to reduce peak loads. Details on control strategies are found in [9].

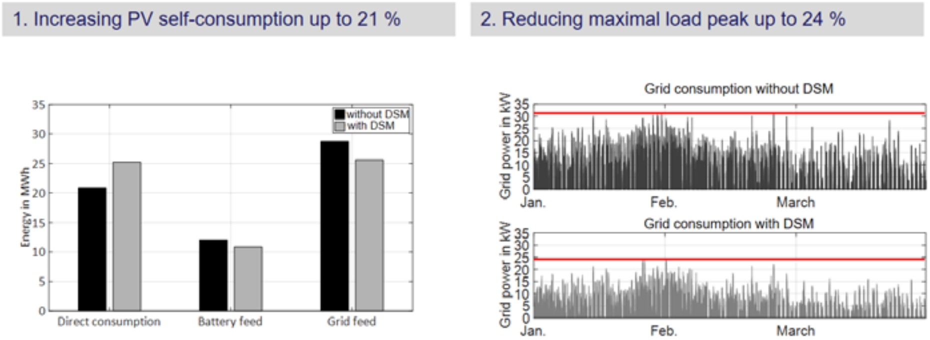

Fig. 8. Simulation results of Demand Side Management (DSM) to increase self-consumption and decreased load peaks and grid import

In Fig. 8, simulation results for the increase of self-consumption are depicted. The direct consumption could be notably increased by 21% due to the control optimisation. Thereby, also the battery feed-in could be decreased by 10%, while grid import is reduced by 11%. Moreover, the impact of the DSM on the grid also led to a reduction of the load peaks in the grid, which were reduced by 24% in the three winter months January to March.

Monitoring results of the system for the year-round monitoring period of April to March confirm the plus energy design of the building. The measured energy for space heating is with 33.2 kWh/(m²yr) slightly higher than the design value of 23.4 kWh/(m²yr) and also the measured DHW energy of 21.8 kWh/(m²yr) surpasses the design value of 18.5 kWh/(m²yr).

The space cooling, though, is with measured 7.3 kWh/(m²yr) a bit lower than the calculated 8.6 kWh/(m²yr). The overall balance in terms of delivered energy, primary energy and CO_2-emissions is given in Fig. 9. In the annual balance a surplus of the delivered energy by the PV production of 26.6 kWh/(m²yr) is achieved, and weighted values of primary energy and CO_2-emissions lead to 47.9 kWh/(m²yr) and 14.0 kg/(m²yr), respectively. This surplus can also be explained by the good performance values of the installed heat pumps, which is depicted in Fig. 10 for different system boundaries.

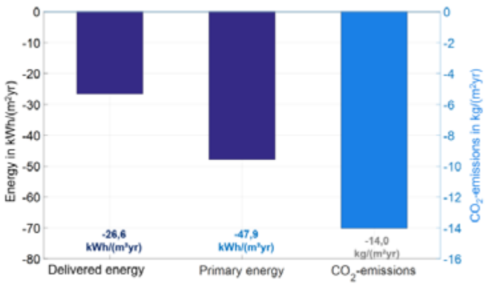

Fig. 9. Annual monitoring results for the Herzo Base system in terms of delivered energy, primary energy and CO_2-emissions

Even higher values than in the simulation have been measured. The two central heat pumps reach values of 5.4 and 6.0 in the boundary of the COP, and including the source system a value of 5.6. The source system by itself reaches a measured performance of an ETA of 175, where ETA refers to the electro-thermal amplification by extracted heat related to pumping energy. The booster heat pumps for the DHW operation reach performance values around 4.

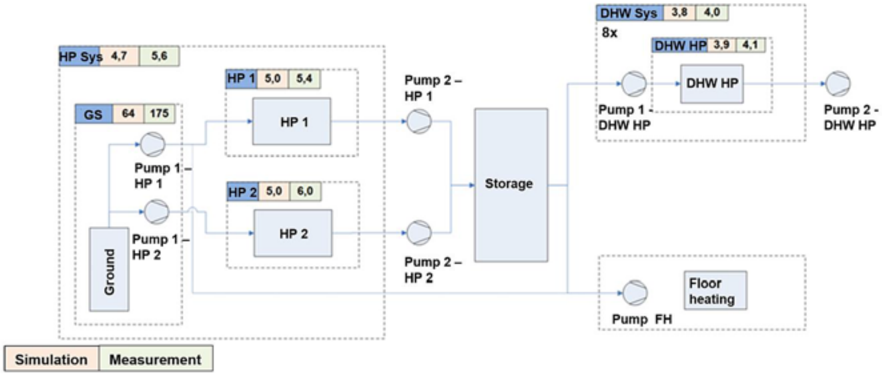

Fig. 10. Seasonal performance factors based on produced energy of the heat pumps

4. Conclusions

IEA HPT Annex 49 has the objective to perform investigations and analysis of the integration options and adapted design and control of heat pumps for the application in nearly Zero Energy Buildings, which are considered as future building standard in many countries around the world. nZEB requirements have already been introduced in the EU member states by Jan 1, 2019 for all new public buildings, which will be extended to all new buildings by the beginning of 2021. Nevertheless, despite different attempts for a harmonisation among countries, the implementations presently differ in metrics, limits and rating procedures, which impede a comparison of ambition levels and the development of standardised system solutions.

Moreover, in this step, not all countries require the nZE balance, but some countries only set requirements on the building envelope or primary energy consumption or have separate requirement for on-site renewable production without explicitly requiring a balance between energy consumption and on-site production.

IEA HPT Annex 49 has set a scope on integration options of the heat pump for nZEB. Regarding the monitoring, integration option yield positive results regarding the energy performance. The monitored integrated heat pumps reach high seasonal performance factors in the range of 5-6, which is also due to internal waste heat recovery by combining different building service in simultaneous operation of the heat pump as well as the integration of sources for free-cooling and regeneration. However, despite a high system performance and a high-performance building envelope, reaching an annual nZE balance may still be challenging in larger buildings, where the building surface area is limited for the renewable production on-site. Thus, a high system performance and an optimised system operation is a prerequisite for approaching the nZE balance in these buildings.

Regarding the design and control, besides the conventional aspects of performance and cost, additional aspects may affect the design of the building technology in nZEB, namely the energy flexibility, which becomes more important in nZEB for two reasons. On the one hand, the economy of on-site PV systems, which are often installed in nZEB to achieve the nearly zero energy balance, is positively affected by a higher degree of on-site consumption of the produced electricity in times of decreasing feed-in tariffs.

On the other hand, with increasing renewable energy in the electricity grids, buildings may also play a role to provide energy flexibility to the grid by reduced or increased consumption according to the grid needs. In this context also the control strategies are an important feature, since future buildings should contribute to a reduction of grid interaction and reduce the stress put on the grid by the increased renewable energy production. Thus, buildings are already seen today as one player for a future smart grid and the nZEB concept of on-site renewable production to balance the building's energy demand can be considered as turning point for buildings from a passive to an active component in the energy system. Design and control of the building technology should thus take into account demand response capabilities. An increase of electrical storage side by side with thermal storage installations raise the question of improved system and building integration of heat sources, generators, storages and sinks, on the single building level as well as on the neighbourhood and district level, where buildings with different use profiles and needs can be integrated by thermal and electrical grids. Presented results of a load shift and peak load reduction, which can be achieved by electric and thermal storage integration are positive from the energy perspective, but it has still to be proven, if this is also economically feasible for the building owners, since currently in most cases the building owner is not refunded for providing energy flexibility. Exception may be found in particular tariff structures, where e.g. a benefit for peak load reduction is granted. However, especially in smaller buildings like single family houses, designing the building technology to larger demand response capabilities, e.g. by larger storage design may not pay off with current electricity tariffs.

Summarising, nZEB are a next step to high performance buildings including renewable energy production, but reaching the balance can still be a challenge in larger building. The high-performance values reached with heat pump integration options and optimised design and control help to achieve ambitious targets of nZEB, and also enhance energy flexibility, which has been proven by the different simulation and field monitoring results of IEA HPT Annex 49.

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