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Design and integration of heat pumps for nZEB in IEA HPT Annex 49

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Abstract. Heat pumps are a promising building technology, especially for nearly Zero Energy Buildings (nZEB) to be introduced in the EU by the beginning of 2021 for all new buildings. Despite heat pumps already range among the most efficient heat generators, further efficiency and cost optimisation is seen in system integration as well as in adapted design and control for the application in nZEB. IEA HPT Annex 49 investigates heat pump application in nZEB by simulation and field monitoring in order to evaluate integration options with other building technologies, thermal and electrical storages, the building envelope and the ground. Moreover, design and control for the loads in nZEB and the integration of nZEB into connected energy grids are considered. The investigations are accompanied by field monitoring of heat pumps in different nZEB applications and climate conditions in order to relate calculation results to the real operation and identify optimisation potentials. Expected results of the Annex 49 are recommendations regarding heat pump integration options and related design and control as well as real world heat pump performance in monitored nZEB. The paper gives an overview on the Annex 49 project and national contributions and will present first interim results of the Annex Tasks.

1 Background

1.1 State of nearly Zero Energy Buildings

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, in order to be widely introduced between 2020 and 2030 and in Japan, NZEB are planned to be the building standard by 2030.

Even though political strategies strongly refer to the nearly or Net Zero Energy objectives, there is little available knowledge 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.

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, 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.

However, nZEB definition in Europe is done by the EU-member states (MS) and current definitions in the EU-MS vary both in system boundaries, metrics, limits and weighting systems as outline 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 [5] [6]. In the USA a similar system boundary as of the REHVA definition has been proposed by US-DOE [6].

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Table 1. Overview of possible contributions of participating and interested countries to Annex 49

Country/Institution	Contribution to IEA HPT Annex 49
Austria Uni Innsbruck, IWT of TU Graz, AIT	• Monitoring and simulation of two nZEB buildings for performance optimization • Development of prototypes of façade integrated heat pump • Monitoring and simulation of nZEB office buildings and neighbourhoods
Belgium Univ. Libre Brussels	• Monitoring of nZEB office buildings with heat source wastewater • Design of modular nZEB concept
Estonia Tallinn Techn. Uni	• Modelling and simulation of ground-coupled heat pumps (energy piles, horizontal collectors) • Design of heat pumps and heat emission systems for nZEB application
Germany TH Nurnberg, Uni Braunschweig, TEB	• System integration, design and field monitoring of 8 terrace houses and passive house • Long-term field monitoring of plus energy single-family, multi-family and school building • Design and control strategies for smart grid integration
Norway SINTEF, NTNU, COWI AS	• Design and control for cost-effective heat pumps with natural refrigerants • Investigation/monitoring of nZE demonstration buildings and neighbourhoods in Norway
Sweden SP	• Monitoring and comparison of heat pump system in two equal test houses • Design and control of heat pumps with storage and different emission systems
Switzerland IET HSR	• Integration and design options of solar absorber and heat pump system • 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 personal cooling methods to reduce loads in NZEB

Due to approaching deadlines for the introduction of nZEB in new public buildings by the beginning of 2019 and 2021 the interest in cost-effective system solutions for nZEB is continuously high. Research of preceding IEA HPT Annex 40 [7] proved that heat pumps are an attractive building technology for the application in nZEB due to several unique features, among others:

- Heat pumps reach high performance values, in particular with low temperature levels in buildings with low loads in nZEB, which reduces the amount of energy to be produced on-site to meet the balance.
- Heat pumps can cover different building services with the same generator, e.g. space heating, domestic hot water (DHW) and space cooling needs, even in simultaneous operation.
- Since heat pumps are one of the main electricity consumers besides appliances, load shift of the heat pump can unlock demand response potentials in combination with thermal and electric storage in order to optimize on-site solar PV self-consumption and a grid supportive operation.

In fact, all-electric buildings which are only supplied with electric energy are an archetype implementation of an nZEB building, and the combination of solar PV and heat pump has both energy and economic benefits.

1.2 Objectives of IEA HPT Annex 49

Thus, research is continued in IEA HPT Annex 49 entitled "Design and integration of heat pumps for nZEB". On the one hand, developments and investigations which have begun in Annex 40 shall be further developed. On the other hand, a new focus is set.

The IEA HPT Annex 49 started in October 2016. Currently, the eight countries Austria, Belgium, Germany, Norway, Sweden, Switzerland, UK and the USA have joined the Annex 49. Furthermore, Estonia has already kept close contact to the work in the Annex 49 and is interested to join after joining the Heat Pumping Technologies (HPT) Technology Collaboration Programme (TCP).

The investigations in Annex 40 were related to the system assessment. Based on that 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. In this regard, the ground may be an interesting option to transfer source energy from the summer to the winter months by ground regeneration of borehole fields during summertime.

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 give a higher importance to a high self-consumption rates 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 rates and demand response.

As further aspect, the investigations performed in Annex 40 were limited to single buildings, but an extension to groups of buildings or neighbourhoods may open the consideration. For instance, collective systems connected by micro-grids and load balancing between buildings can be implemented.

The work in Annex 49 has been structured in the following Tasks

- Task 1 is on the state-of-the-art of heat pump application in nZEB in the participating countries. Also the impact of the national definition on heat pump use and the ambition level in the countries is a topic of Task 1.
- 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 and other building technology like the ventilation system. Moreover, also the integration and coupling to electric and thermal grid shall be considered in terms of load management and grid supportive operation. Thereby, also groups of buildings and neighbourhoods shall be evaluated regarding their integration potential for load shifts between buildings.
- Task 3 is to further develop prototype systems and monitoring of heat pump operation 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, a hospital 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 shall be assessed, as well.

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

2 Interim results of Task 1

In Task 1 the state of implementation of nZEB in the different countries has been updated. While in some countries, the implementation of nZEB is already on its way, other countries like Norway or Germany do not have a fixed definition, yet, but Norway is not bound to introduce nZEB by 2019 for all new public buildings, since it is not a member state of the EU.

In Germany, the decision on the ambition level is currently taken, which will most probably refer to the current building code in operation, the EnEV 2016, but may also become the more ambitious kfw55 standard, which refers to a primary energy use of 55 kWh for the building technology and is currently used as requirement for funding by "Kreditanstalt für Wiederaufbau" (kfw).

In Austria, the current implementation of the ÖIB is considered as nZEB. Both the German EnEV and the ÖIB use a reference building, and the requirements are formulated related to this reference building.

In Switzerland, the MuKEn 2014 is in the implementation phase in the different cantons (federal states in Switzerland), which shall be finished in 2020. While some cantons have already implemented the new requirements, other cantons are rather in the beginning of the implementation process, so even within countries, there might be difference in the speed of implementation of the future nZEB requirements. Also for Switzerland, the time schedule given in the EU directive is not binding, but Switzerland has harmonised implementation schedules to the EU deadline of beginning of 2021 for the implementation.

Heat pumps are in many countries a dominating solutions for nZEB in combination with solar PV. In Switzerland, for instance, more than 90% of the buildings certified according to the Swiss MINERGIE-A® label, which is the voluntary certification of an NZEB, are equipped with heat pumps, and solar PV has to meet the total annual energy consumption as a label requirement. While the MINERGIE-A® standard applies a balance criterion of weighted energy consumption and weighted energy production, the MuKEn 2014 as future legally binding implementation of an nZEB only sets an efficiency criterion of weighted energy consumption and has a separated requirement of a minimum installed electricity production capacity on-site, which is currently set to 10 W/m^2 energy reference area. However, there is no balancing between on-site consumption and production.

This short overview without going into details of the national implementations already illustrates that it is hard to specify the ambition levels across the different countries, since different climate boundary conditions, but also national loads and calculation methods are applied besides the different definitions, metrics and limits. Therefore, within the Annex 49 a methodology is in development based on simulations in order to compare ambition levels across the participating countries on a common basis. As contribution of Estonia, an evaluation of an office building at four sites across Europe, namely in Estonia, Finland, France and Belgium has been performed and a methodology has been proposed, which is currently tested and further developed in the Annex 49 group. One result of the study is that national boundary conditions and calculation methods have a larger impact on the ambition level than the climate data, at least for the considered office building among the four considered countries. Thus, a lower primary energy value is not necessarily an indicator of a higher ambition level on a normalised basis across different climate and calculation boundary conditions [7]. Within the Annex 49 the residential building described in the Reference framework [8] is simulated in order to develop and evaluate a methodology for residential buildings to determine and compare the ambition level in the participating countries. Thereby, different simulation programs are used, as TRNSYS, IDA-ICE and Matlab-Simulink.

In order to compare the different programs and model implementations a calibration among the programs has been accomplished by common simulations of the framework building. The evaluation of the methodology is still ongoing. One approach is a comparison of the simulation results for the framework building based on the used standard design software to define the building envelope settings according to the national nZEB requirements. Another reference building for the comparison could be the internationally widespread passive house approach.

The building is then compared by the subsequent simulation results for the building under the national and a common climate boundary conditions. Another approach to be evaluated is to compare the performance to a common reference building at the same site.

3 Interim results of Task 2 and Task 4

Task 2 on the integration of heat pumps into building technology system configurations and Task 4, the design and control of heat pump systems in nZEB are linked. If integrated systems are considered, also the design and control is an important feature to achieve the maximum performance. As example of the interim results of Task 2, a project contribution of Germany is presented. As extension of investigations in Annex 40 a transfer from single buildings to group of buildings or neighbourhoods is made in Annex 49. Thereby, both the integration in thermal as in electric grids is a topic.

At the energy campus of the TH Nuremberg, Germany, the electric and thermal integration is considered for the example of eight terraced houses of each 150 m^2 energy reference area called Herzobase. The system concept contains two capacity-controlled central ground-coupled heat pumps, which are distributing the space heating energy by a low temperature grid. In contrast to the space heating operation, the domestic hot water (DHW) is produced in decentralised 200-l DHW storages in each house, which are supplied each by a decentral 2 kW booster heat pump, which uses the low-temperature grid as heat source. In summertime, the ground source heat pumps are used for free-cooling. Figure 1 shows a picture of the 8 terraced houses.

Figure 1. Terraced houses of the project Herzobase in Germany

The system is also equipped with electrical storage. A battery is installed centrally at the heat pumps.

The PV systems on the roof of the single houses is oriented in east-west direction, which enables a more evenly yield. During daytime the PV mainly covers the household appliances and plug loads. In case of PV surplus, the battery is charged and covers mainly the illumination of the buildings and electric consumers in the evening. One task of the simulation study was to evaluate, how the storage options enhances self-consumption by the heat pump, 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 reduce peak loads. In Figure 2 the simulation results concerning the increase of self-consumption are depicted. The direct consumption could be notable increased by the control strategies by 21%, and thereby, even the battery feed-in could be decreased by 10%, while grid import was reduced by 11%. Moreover, the impact of the demand side management on the grid also includes a reduction of the load peak, which could be diminished by 24% in the three month January – March.

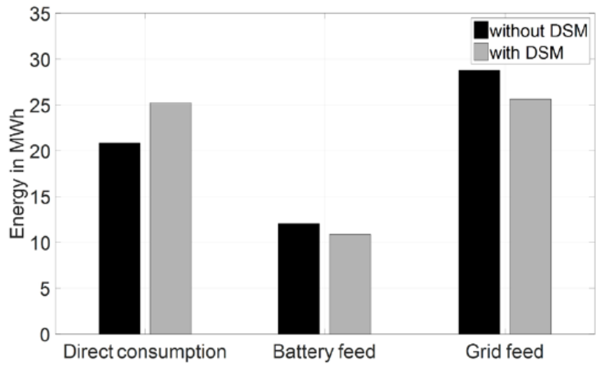

Figure 2. Increase self-consumption by favourable control strategy

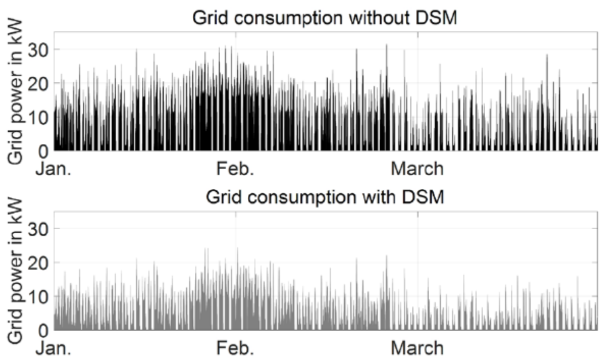

Figure 3. Simulation results of Demand Side Management (DSM) to increase self-consumption and decrease grid import

4 Interim results of Task 3

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 project in order to evaluate the real performance of heat pumps in nZEB.

In the following results of a monitoring project in Switzerland are given, which refer to a 5-storey building with mixed commercial (basement, 615 m^2), office (1-2 storey, 615 m^2) and residential use (3-4 storey and attic, 1520 m^2) energy reference area in the city centre of Pfäffikon (SZ), that has been monitored for one year. The all-electric building is equipped with a high performance building envelope approaching ultra-low energy house level and a ground-source heat pump as core generator for space heating, DHW and space cooling with a heating capacity of 80 kW at B0/W35. The cooling operation, though, is mainly covered by free-cooling operation of the borehole field, which consists of 15 ground probes of each 150 m. Moreover, the ground is used for preheating/-cooling of the mechanical ventilation system, which prevents the heat recovery from frosting.

Figure 4. Monitoring building with mixed residential and commercial use in Switzerland

In order to meet a net-zero energy 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 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 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. While the yield of the modules on the flat roof is with 970 kWh/kW_p in a typical range for Switzerland, the south façade only yield about half of this values, and the west and east integrated façade module only yield about 200 kWh/kW_p. Thus, the projected production does not reach 20 kWh/m^2 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 performance of the modules. Thus, despite a building envelope on ultra-low energy house level and a good system performance with a measured overall seasonal performance factor of 5.2, the net balance based on the system boundary building technology (excluding plug loads) is not entirely reached. However, 95% of the energy for the building system is produced on-site on an annual basis.

Different monitoring projects in Annex 49 are also linked to simulations of the buildings in order to compare simulated performance values to the results of the real building operation and to implement optimisation measures derived by the simulation.

5 Conclusions

IEA HPT Annex 49 has been started in the end of 2016 in order to accomplish more in-depth analysis of the integration options and adapted design and control of heat pumps for the application in nearly Zero Energy Buildings. Besides the conventional aspects for performance and cost, in nZEB also the energy flexibility is a criteria for the design and control of the systems, 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 nZEB mark the turning point for the buildings from a passive to an active component in the energy system by the integrated renewable production as part of the concept. 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 sink, 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.

IEA HPT Annex 49 sets as scope on integration options of the heat pump for nZEB with associated design and control. Presented first results of a load shift and peak load reduction, which can be achieved by electric and thermal storage are positive. Further evaluation will be made, which can also be compared to monitoring results of the real operation.

On the other hand, by the accompanied monitoring, the real performance of prototype developments and marketable heat pumps shall be evaluated. Interim monitoring results in the Annex 49 confirm that nZEB are high performing buildings. However, depending on the balance boundary it can be hard to reach an nZEB consumption in larger buildings even with a high performance of the building system and the building envelope, since the surface for the energy production at the building site is limited. Consideration of a group of buildings or neighbourhoods may be a viable solution to overcome limitations of the surface on the energy generation of single buildings. Moreover, by different load structures, synergies on the neighbourhood level may be used.

IEA HPT Annex 49 is a collaborative research project and the contribution of all participating countries as well as the good collaboration in the Annex 49 are acknowledge.

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