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Results of IEA HPT Annex 40 on Heat Pumps in Nearly Zero Energy Buildings

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Abstract

Political strategies are focusing on nearly Zero Energy Buildings (nZEB) as next step for high performance buildings to be introduced in the time frame of 2021-2030 in different parts of the world. Therefore, solutions for the technical building system are required.

Annex 40 in the Heat Pumping Technologies (HPT) Implementing Agreement of the International Energy Agency (IEA) has investigated the application of heat pumps in nZEB in the nine participating countries Canada, Finland, Germany, Japan, the Netherlands, Norway, Sweden, Switzerland and the USA.

Investigations have been performed both as case studies and by lab testing and field monitoring of new prototypes. Case studies to compare system solutions have been performed for Canada, central and Northern Europe as well as for Japan. Results confirm that heat pumps range among the most energy-efficient and cost-effective heat generators, both in central European and in Northern climate. For multi-family buildings and offices, also combined heat and power and district heating are in the same range of life-cycle cost.

Monitoring projects, among these the first nZEB in Norway, confirm that the nearly Zero Energy balance is reached efficiently with heat pumps even in Northern climate. Thereby, heat pumps offer further options for load management. Increase of self-consumption by 10-15% has been confirmed in field monitoring projects and simulations by the shift of the heat pump operation to hours with on-site PV production.

Keywords – nearly Zero Energy buildings; multifunctional heat pump; solar integration; system simulation; field monitoring

1. Introduction

As a political target for the building sector after 2020, Nearly or Net Zero Energy Buildings (nZEB and NZEB, respectively) are in the focus of strategies. Due to the EU-directive EPBD recast of 2010 [1], from 2021 on all new buildings have to fulfill nZEB requirements.

Despite the emphasis of the nZEB concept, there is no consistent definition of an nZEB, yet. According to the EPBD recast, an nZEB is a "building that has a very high energy performance [..]. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby".

Heat pumps are seen as promising candidate for the building technology for the following reasons:

- With adequate system design heat pumps are highly efficient, enabling a nearly zero energy balance with less on-site generation
- Heat pumps can cover both heating and cooling needs with the same generator in multifunctional use
- Heat pumps can convert surplus electricity of on-site generation to heat or cold, which can be stored locally, a concept called "power2heat"

Therefore, IEA HPT Annex 40 has investigated heat pump application in nearly or Net Zero Energy buildings in order to confirm feasibility of different heat pump operation for nZEB application, to further develop heat pump systems for the application in nZEB and confirm the nZE balance by field monitoring. Moreover, load management options for the integration into connected energy grids have been investigated in order to reduce grid interaction or enhanced self-consumption.

2. Outline of the IEA HPT Annex 40

Annex 40 in the Heat Pumping Technologies (HPT) Implementing Agreement of the International Energy Agency (IEA) entitled "Heat pump concepts for nearly Zero Energy Buildings" has been carried out from July 2012 until December 2015 with nine participating countries and about forty institutions from the countries Canada, Finland, Germany, Japan, the Netherlands, Norway, Sweden, Switzerland and the USA. The HSR University of Applied Sciences Rapperswil has been accomplished the project management as operating agent on behalf of the Swiss Federal office of Energy SFOE. The Annex has been structured into four Tasks: Task 1 is to gather the state-of-the-art of the definition of nZEB and heat pump application in realized nZEB. Task 2 deals with the comparison of system technologies regarding performance and system cost in nZEB, while Task 3 is on heat pumps developments and field monitoring. Task 4 opens the investigations for the integration of nZEB into connected energy grids. Table 1 gives an overview of national contributions in IEA HPT Annex 40.

Table 1. Overview of national contributions in IEA HPT Annex 40

	contribution
CA	• Combination of heat pumps with other heat generators (solar, CHP) • Case studies for different building types and –use • Technology development: solar and heat pump system with ice-storage
CH	• Integration of solar and heat pump for multifunctional use in offices • Case studies and system comparison for MINERGIE-A® • Field monitoring of MINERGIE-A® buildings with electro-mobility • Evaluation of load management options
DE	• Long-term field monitoring of nZEB office buildings • Evaluation of load management options and grid-supportive operation
FI	• Case studies of energy- and cost-efficient heat pump systems for nZEB for single- and multi-family houses in Finland by simulation
JP	• Case study of nZEB office buildings with heat pumps • Documentation of monitoring and technology developments for nZEB
NL	• Field-monitoring project “Energy leap” in residential and non-residential buildings for market stimulation of Net Zero Energy Buildings
NO	• Design tool for heat pumps in nZEB-office buildings • Field monitoring results of three nZEB buildings in Norway
SE	• System comparison of nZEB for single- and multi-family houses • Prototype developments of adapted heat pumps for nZEB application
US	• Prototype testing and field monitoring of integrated heat pumps (IHP) • NZEB test facility for technology testing under reproducible conditions • Comfort evaluation of surface heating and cooling systems

3. State of nZEB and heat pump application

In the EU, the implementation of the EPBD recast, and thereby the elaboration of a definition for nZEB is task of the EU-Member states (MS). Even though the time schedule is quite tight, since already by the beginning of 2019 all public new buildings shall be nZEB, a definition does not yet exist in all member countries. Just 15 MS (incl. Brussels region) have a definition, while in further 3 MS the definition is in approval, and in 12 further MS (incl. Norway), it is still under development. The existing definitions, though, are not uniform, but differ both in criteria and limits. Therefore, no uniform definition is expected in the first phase of introduction. In IEA EBC Annex 52/SHC Task 40 criteria for a uniform and consistent definition have been worked out. Fig. 1 shows the basic principle of nZEB and criteria for a comprehensive definition including the presently most common assignment of the criteria based on [2].

In the European standardization committee CEN, an nZEB rating procedure has been elaborated in the frame of the overarching standard of the EPBD prEN 15316, which is currently elevated to prISO 52000-1 [3].

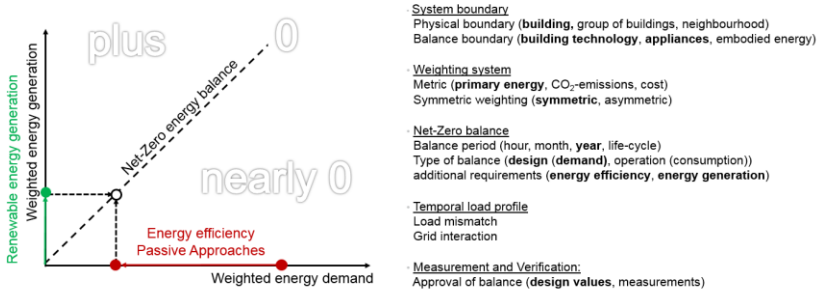

Fig. 1 Principle of nZEB (left) and definition criteria with most common assignments (right)

It defines four criteria for the nZEB rating, which have to be passed one by one. Therefore, the procedures is also denoted as "hurdle race" depicted in Fig. 2.

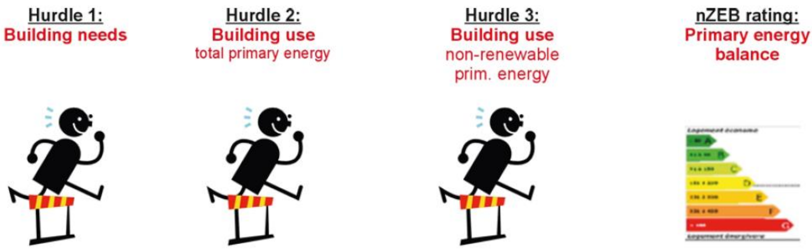

Fig. 2 nZEB rating procedure according to prEN 15316 or prISO 52000-1, respectively [4]

The European standardization committee CEN also elaborated an nZEB definition in co-operation with European Federation of Heating, Ventilation and Air Conditioning Associations REHVA [5]. In Sept. 2015 the US Department of Energy has published a definition of NZEB, which is similar to the CEN/REHVA definition [6]. Both definition set primary energy, which is denoted as source energy in the DOE definition, as metric for the balance and physical boundary is set to the site energy, i.e. the balance of delivered and exported primary energy on an annual basis. As balance boundary, all energies used in the building including lighting and appliances are stated in DOE definition.

Regarding applied systems in built nZEB heat pumps are already quite common. In the currently most common Swiss implementation of an nZEB, the MINERGIE-A® label [7], for instance, about 90% of the 600 certified buildings are equipped with heat pumps. With electrically-driven heat pumps only electricity as delivered energy is used, which is denoted as "all-electric building" and became a kind of archetype for built nZEB. The balance is often reached by on-site PV production.

In the Nordic countries, the first nZEB are in the construction phase, and within the Annex 40 evaluations of suited buildings systems and verification of the nearly zero energy balance are evaluated by case studies and field monitorings.

4. Case studies for nZEB technologies

In order to characterize nZEB technologies regarding performance and cost, case studies have been performed.

In Switzerland, system comparison have been performed for both residential use as single and multi-family buildings and for office buildings [8] based on the MINERGIE-A® balance. The MINERGIE-A®-label is based on weighted end energy of the building technology, i.e. lighting and appliances are not included. The PV area is design to meet the MINERGIE-A® balance. Fig. 3 shows the comparison of different building systems for the multi-family case, which has been defined as 5 storey building with an energy reference area 1500 m^2. Different insulation levels are expressed as annual space heating needs in Fig. 3.

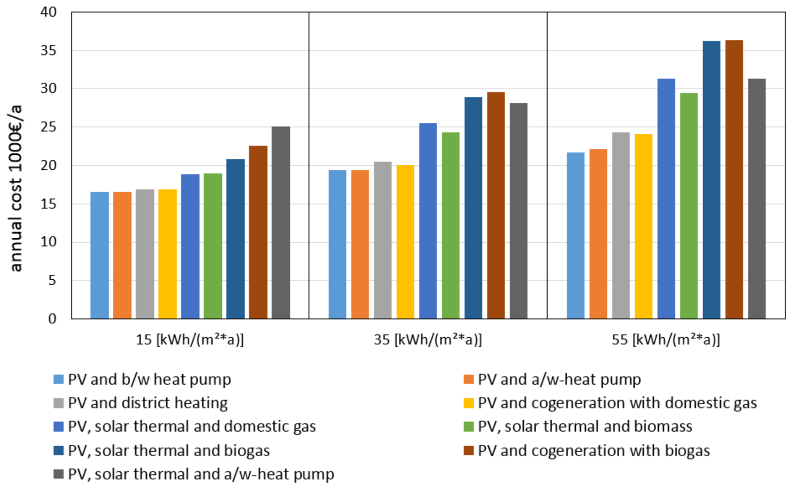

Fig. 3 Cost comparison of building systems for multi-family houses in Switzerland [8]

While in single-family houses heat pumps are the most cost-effective systems in Switzerland based on 20-year life-cycle cost, in multi-family houses also district heating and CHP reach the same cost level for low space heating needs.

With increasing space heating needs, heat pumps are getting more cost-effective, and ground-source heat pumps reach lower life-cycle cost than air-source heat pumps despite the higher initial investment cost. Biogas systems are among the most expensive systems at current market prices.

Despite the different climate conditions, results of a case study in Sweden and Finland result in a similar ranking as in Switzerland. Fig. 4 shows the life-cycle cost of single-family houses in Sweden for different building systems.

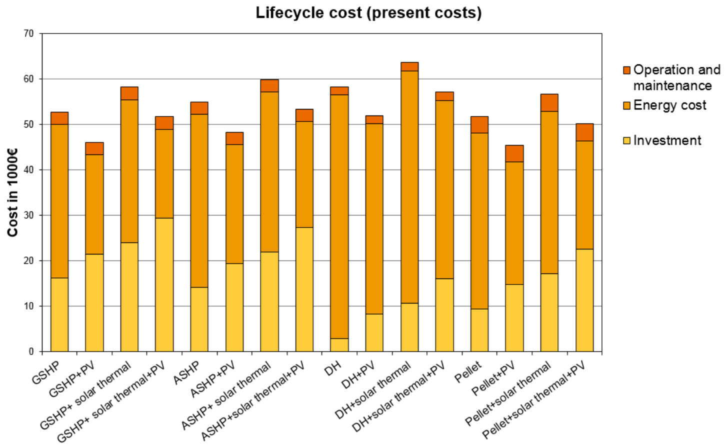

Fig. 4 Cost comparison of different building systems for single-family houses in Sweden [9]

The system solution with ground-source heat pump combined with PV reach the lowest life-cycle costs [9]. District heating is more expensive in single-family buildings. Pellets combined with PV reach similar life-cycle cost and are an alternative for nearly zero energy balance. In multi-family buildings, ground-source heat pumps are preferable to district heating due to lower costs and higher independence from future developments in energy prices. District heating alone does not reach the requirements for nZEB in Sweden, and an additional technology like PV or solar thermal collectors is necessary.

In Finland, the supply of district heating is well developed in cities. Nevertheless, heat pumps in nZEB yield lower delivered energy than the district heating [10]. Also in Finland, ground-source heat pumps reach better values than air-source heat pumps despite low space heating needs in nZEB.

Besides the case studies, also tools have been developed in Task 2 of the Annex 40. At SINTEF energy research in Norway a design tool for heat pump and additional heat generator has been developed, which performs an iterative optimization regarding CO_2-emissions and cost for nZEB office buildings. The development will be continued regarding further systems configurations to be covered [11].

At the Center of Environmental Energy Engineering at the University of Maryland, a tool for comfort evaluations in high spatial resolutions for rooms and automotive cabins has been developed. The background is a detailed evaluation of surface heating and cooling room emission systems in order to decrease supply temperature requirement for the heat pump. Despite this background, the tools covers also convective heating and cooling [12].

5. Heat pump developments and field monitoring in nZEB

In Task 3 of the Annex 40 developments of heat pumps for nZEB have been accomplished. The development of highly integrated heat pumps at the Oak Ridge National Laboratory (ORNL) in the USA has already begun in 2005. The integration includes the functions space heating, space cooling, DHW and dehumidification. While a ground-source system is already on the market, the air-source prototype is analyzed in field monitoring in Annex 40 and new variants of the concept are evaluated. For the air-source prototype an overall seasonal performance factor SPF of different simultaneous operation modes, values above 5 for cooling operation and 4.4 for DHW operation during a summer monitoring period from May – Sept. 2015 in Knoxville, Tennessee are reached [13].

Moreover, in Canada, the integration of solar components by an ice slurry storage is investigated by lab-testing and in Switzerland, the integration of unglazed solar absorber and heat pump for space heating and cooling has been investigated by test-rig measurement and simulations.

At the National Institute of Standards and Technologies (NIST) a test facility for NZEB technologies has been built on the campus of the institute. The houses has been designed on NZEB targets and is equipped with tunable load generators and detailed monitoring equipment, so reproducible load profile can be generated for the equipment testing. NZEB-technologies can be integrated into the test house and be tested in real condition. In the first year of operation the house has been equipped with a highly-efficient air-to-air heat pumps. The energy balance of the first year of operation reaches a positive balance [13].

At Fraunhofer Institute of Solar Energy systems in Germany, a long-term monitoring in 16 nZEB office buildings and schools is performed. The buildings consist of an energy reference area of 1’600 to 17’000 m² and are supplied by heat pumps. The majority of the buildings is equipped with thermo-active building system. The evaluation is performed with five different system boundaries from the source over the heat pump into the overall system. In cooling operation degree of coverage of 40-80% in free-cooling mode are reached. The SPF ranges from 8-18 and the defined goal of 20 is achieved for three systems. The SPF (inclusive the source pump) in heating mode range from 2.3-6.1.

Optimization potentials are found in the optimization of auxiliary energies and the integration of storage, which partly cause higher operation temperature than required by the application and thereby lower the SPF of the heat pump operation. Moreover, investigations of a grid-supportive operation has been performed by simulations. With a shift of heat pump operation times from night- to daytime operation, the share of PV and wind electricity use can be increased by 10-15% [14].

In Switzerland, load management options to increase self-consumption have been evaluated in monitoring projects of a small multi-family plus energy house and one of the first MINERGIE-A® certified buildings with office use. It was confirmed that the heat pump is the electricity consumption with the highest potential to shift. Typical self-consumption of about 30% in residential and about 40% with office use have been confirmed. By load shifting, self-consumption can be increased by 10%-15% consistent to the simulations results in Germany [15].

6. Conclusions

IEA HPT Annex 40 has investigated heat pump applications in nZEB. Even though political target focus on nZEB as standard for the next generation of high performance buildings, and an ambitious time schedule for the broad introduction of nZEB is set, no uniform definition of nZEB exists, yet. However, some steps are taken by CEN, REHVA and DOE to harmonise the definition of nZEB.

In built nZEB, heat pumps have already a large diffusion due to the high performance. However, the majority of built nZEB are single family houses where the balance can be reached quite easily by PV due to sufficient area in the building envelope. But, many of these buildings have been built as pilot and demonstration projects for the approval of the nearly zero energy balance, and are not cost-optimally designed, as the EU requires.

In Annex 40 system comparison of different building technologies for nZEB has been performed in case studies for the different boundary conditions in the participating countries. Results confirm that heat pumps are both energy-efficient and cost-effective systems for the application in nZEB in central European and Nordic climate conditions. In larger building like multi-family and office buildings, also district heating and CHP may reach comparable life-cycle cost depending on market prices. Furthermore, two design tools for heat pumps applications in nZEB have been developed.

Moreover, different technology developments of heat pumps for nZEB regarding highly integrated heat pumps for multifunctional use of different building services and integration options of solar components have been performed. A prototype development in the USA yielded an SPF above 5 in space cooling and dehumidification mode and 4.4 in DHW mode in the summer period field monitoring.

With the politically intended broad introduction of nZEB by 2021 also aspects of the integration of nZEB into connected energy grids regarding grid interaction will gain importance. The implementation and the grid interaction will also be determined by the definition of nZEB in the different member states of the EU and outside Europe. NZEB or even plus energy buildings by PV tend to produce a higher surplus of electricity and may cause higher grid interaction than nZEB, and may therefore require larger demand response capabilities. Therefore, by simulations and field evaluations first evaluations of demand response capabilities of heat pumps have been accomplished. Heat pumps are often the main electricity consumer besides the plug loads, and thus offer a load shift potential to grid supportive operation. Self-consumptions of 30% in residential and 40% in office use and increase of self-consumption of 10-15% by load shifting of the heat pump operation were evaluated in simulations and field monitorings.

Based on the Annex 40 results, it can be conclude that heat pumps are both an energy efficient and cost-effective building system technology in nZEB application and will play an important role in future high performance buildings fulfilling nZEB requirement, not only due to the energy and cost aspects, but also due to demand response capabilities to support operation of connected energy grids. However, further research issues are the optimal design of systems under consideration of performance, cost and demand response. Moreover, storage integration options both on thermal and on electrical side and the extension of the concept to the neighborhoods or even communities are further research topics.

IEA HPT Annex 40 is presently concluded. Final reports are expected to be published after review in summer 2016. Information on the Annex 40 is found on the Annex 40 project website at http://www.annex40.net.

Acknowledgment

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