Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 40

Heat Pump Concepts for Nearly Zero-Energy Buildings

Executive Summary

Operating Agent: Switzerland

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Executive Summary of IEA HPT Annex 40

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Executive Summary

1.1 Background of IEA HPT Annex 40

1.1.1 Political background

For the building sector after 2020, nearly or Net Zero Energy Buildings (nZEB and NZEB, respectively) are in the focus of political strategies. The political target of the EU is expressed in the EU Energy Performance Building Directive (EPBD recast of 2010), which states, that all new public buildings have to be nZEB by the beginning of 2019 and all new buildings have to achieve an nZE consumption by 2021. Moreover, the EU published a Cost-Optimality Guideline (2012), declaring that nZEB shall be reached at cost optimal levels, requiring thus both an energy-efficient and cost-effective building envelope to limit the loads and a technical building system to balance the remaining loads. In North-America, similar targets have been set, but the time schedule is a bit more extended, since introduction for all new buildings is intended by 2030. In Japan, a similar strategic plan has been set up for NZEB, starting with single new buildings by 2020 and reaching the NZEB target for all new buildings by 2030.

1.1.2 Experience with nZEB technologies

Despite this tight time schedule in the political strategies and directives, in particular in the EU, no uniform and consistent definition of nZEB exists. At the beginning of the IEA HPT Annex 40 in July 2012 only around 400-500 nZEB had been built worldwide. Furthermore, the majority of these built nZEB are new residential buildings, mostly single-family houses. Most of the buildings use solar PV to meet the on-site nearly zero energy balance, since for single-family houses the nearly zero energy balance is reached quite easily with PV and an efficient building envelope, since there is enough surface of the building envelope available in relation to the demand. On the other hand, these pilot and demonstration buildings are relatively expensive, since PV is still an expensive technology compared to other technologies like combined heat and power (CHP), at least in larger buildings. Many of the buildings use different technologies in parallel in order to get experience with real operation in nZEB.

A further aspect is that the building becomes a "prosumer" with an integrated local energy production, i.e. an energy producer and consumer at the same time. Additionally, technical storages (e.g. hot water storage) are installed in the building, and therefore, buildings have the capability to store heat actively in these installed storages or passively in the building structure. This can be used for demand response, if electricity surplus of the solar PV system or the electricity grid is stored as heating or cooling energy in the building. Thus, the integration of nZEB in future energy systems regarding self-consumption and demand response will become a more important aspect with rising number of nZEB after 2020.

Based on the tight time schedule for the introduction of nZEB as well as little experiences with nZEB and respective energy-efficient and cost-effective technologies, evaluation of systems solutions for nZEB is a topic of high interest in different countries.

Heat pumps have already reached large installation rates in realised nZEB, mainly due to some unique features particularly suited for the application in nZEB

- Heat pumps are highly efficient with an adequate system design, in particular in high performance buildings with low supply temperatures
- Heat pumps can cover multiple building functions with one generator, even in simultaneous operation with efficiency gains by internal heat recovery
- Heat pumps offer integration options with other building technologies, e.g. the ventilation system or solar components
- Heat pumps are often one of the main electricity consumers and offer therefore demand response options to store surplus electricity as heating or cooling energy, a concept often denoted as "power2heat".

1.1.3 Outline of IEA HPT Annex 40

Due to these features, heat pumps are an interesting technology for the applications in nZEB. Thus, the objectives of the Annex 40 in the Heat Pumping Technologies (HPT) Technology Collaboration Programme of the International Energy Agency (IEA) entitled "Heat pump concepts for nearly Zero Energy Buildings" were to

- Characterise the state-of-the-art of nZEB in the participating countries
- Compare different building technologies regarding performance and cost
- Further-develop heat pumping technologies for the application in nZEB
- Gather real world operation of heat pumps in nZEB from monitoring results
- Consider aspects like load match and grid interaction

leading to the following Tasks:

Task 1: State-of-the-art of nZEB and used building technologies

Task 2: Comparison of building technology systems in respect to energy performance and cost

Task 3: Technology development and field monitoring results of heat pumps in nZEB

Task 4: Integration of nZEB into energy systems

The nine countries Canada (CA), Switzerland (CH), Germany (DE), Finland (FI), Japan (JP), Netherlands (NL), Norway (NO), Sweden (SE) and the United States of America (US) have participated in the Annex 40. The project management of the Annex 40 was carried out by the Institute of Energy Technology (IET) of the HSR University of Applied Sciences Rapperswil in charge of the Swiss Federal Office of Energy (SFOE). Table 1 gives an overview of the contributions of the participating countries.

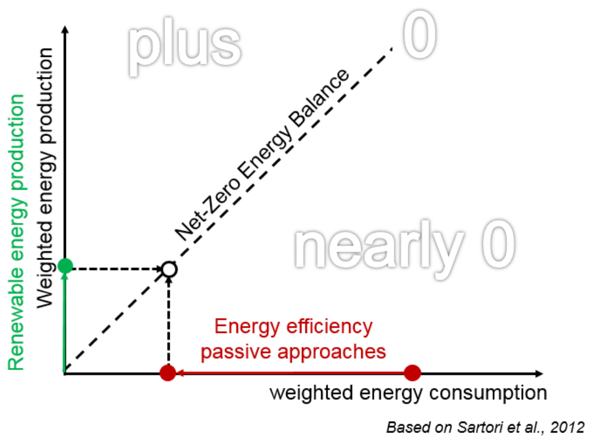
Table 1: Overview of the contributions of the participating countries

Country	Contribution to IEA HPT Annex 40
CA	Combination of heat pumps with other heat generators (solar technologies, CHP), Case studies for different building types and –uses, technology development: solar assisted heat pump system with ice-slurry storage
CH	Integration of solar absorber and heat pump for multifunctional operation in offices, system comparison of heating systems for MINERGIE-A®, field monitoring MINERGIE-A® with electro mobility, evaluation of load management options
DE	System integration and field monitoring of low energy office buildings, evaluation of load management options and grid-supportive operation
FI	Development of energy- and cost-efficient heat pump systems for nZEB in Finland by simulation of case studies for single- and multi-family houses
JP	Case studies for nZEB office buildings with heat pumps for Japanese and European load conditions, documentation of monitoring, technology developments for nZEB
NL	Field monitoring „Energy leap" for market implementation of nZEB, evaluation of user comfort and cost-effectiveness as well as retrofit concepts to nZEB
NO	Design software for heat pumps with natural refrigerants in nZEB-office buildings, documentation of field monitoring results of nZEB buildings in Norway
SE	System comparison of nZEB for single- and multi-family houses with Swedish weather conditions, prototype developments of adapted heat pump solutions for nZEB
US	Field monitoring of integrated and multifunctional heat pumps (IHP), Commissioning of NZEB test facility (Net Zero Energy Residential Test Facility – NZERTF) for testing of NZEB-technology under reproducible conditions, software development for comfort evaluation of low-ex heating and cooling systems

Focus of the research work in IEA HPT Annex 40 is on the one side a system comparison for the evaluation of technologies for nZEB and on the other side developments of prototypes with integrated heat pumps. Furthermore, field monitoring results of already built nZEB are documented as best practice systems. Also options for load management and load shifting in nZEB have been analysed for particular buildings in order to increase self-consumption and the energy flexibility of the building operation.

1.2 Task 1: Political framework and state-of-the-art of nZEB

Despite the emphasis on the nZEB concept, there is no consistent definition of an nZEB, yet. According to the EPBD recast (2010), 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”. In the EU, the implementation of the EPBD recast, and thereby the elaboration of a definition for nZEB is a task of the EU-Member states. Therefore, no consistent definition is expected in the first phase of the introduction. In the IEA EBC Annex 52/SHC Task 40 criteria for a uniform and consistent definition have been elaborated, which are shown in Fig. 1 with possible options for the single criteria and the most common implementation presently discussed.



System boundary:
Physical boundary (**Building,** Group, Neighbourhood)
Balance boundary (**Building technology**, **Plug loads**, embodied energy)

Weighting system:
Metric (**Primary energy**, CO_2, cost)
Symmetric Weighting (**symmetric**, asymmetric)

nearly Zero Energy Balance:
Balancing period (hour, month, **year**, life-cycle)
Type of balance (**Design** (**demand)**, Measurements (consumption))
Additional requirements (energy efficiency, energy production)

Temporal energy profile:
Load match (DCF, SCF)
grid interaction

Measurement concept and verification:
Verification of balance (**Design values**, consumption)

Fig. 1: Criteria for a consistent definition of nZEB (own depiction based on Sartori et al., 2012)

This definition shall lead to an alignment and a comparability of different national definitions due to the possibility of comparison between the different implementations of criteria.
The European Federation of Heating, Ventilation and Air-Conditioning (HVAC) associations REHVA elaborated a standard for certification of nZEB in collaboration with the European Standardization Committee CEN. According to the draft standard prEN 15603:2013, the balance includes building technology as well as lighting. Also besides own PV-production, renewable energies produced within the country’s frontiers (as far as a long-term connection to the building exists) are defined as nearby produced renewable energy. This definition of nearby production, however, is also a matter of national considerations, so may not be uniform in the first step. For the certification four criteria have to be fulfilled according to the CEN draft:

- <u>Space heating energy need</u> of the building as criterion for the efficiency of the building envelope
- <u>Total primary energy</u> as criterion for the total energy efficiency of the building
- <u>Non-renewable primary energy</u> as a criterion for the renewable share
- <u>Annual primary energy balance</u> as weighted balance criterion for the compensation of the energy demand (import) with energy production (export)

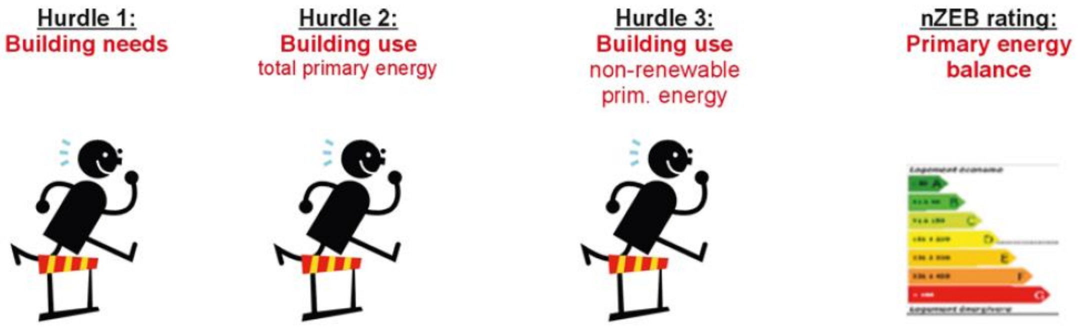


Fig. 2: "Hurdle race" for nZEB rating acc. to CEN draft standard prEN 15603:2013 (Zirngibl, 2014)

According to the draft standard, only the methodology for the certification is standardised, but the requirements for each criterion can vary on national level. Nevertheless, if the methodology is fix, results are still comparable when national requirements are taken into account. Fig. 2 shows the so-called hurdle-race, where each criterion has to be fulfilled.
In the USA and Canada nZEB shall be implemented between 2020 and 2030. The strategy of the USA is shown in Fig. 3. Based on today's common practice, 30-40% of energy shall be saved by more efficient existing technologies. Further 30-40% of energy shall be saved by new technologies developments. Thereby, total energy savings of 60-70% shall be reached, corresponding to the "Building America" goal by the Department of Energy DOE. The remaining energy needs shall be covered by on-site renewable energy.

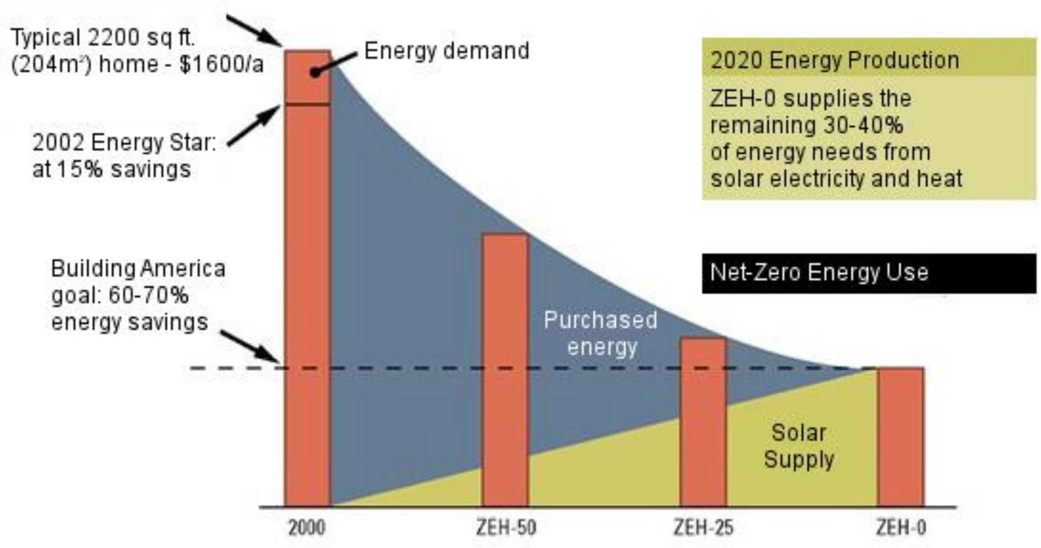


Fig. 3: Strategy of the USA to implement NZEB (ZEH)(source: DOE)

The original goal for implementation of NZEB was like in Europe 2020. Meanwhile, so called "Maximum Efficiency Homes" which also include retrofitted buildings are referred to. In September 2015 the DOE published a definition of NZEB which mainly corresponds to the CEN/REHVA definition. In Canada the implementation of NZEB as standard for new buildings is intended for 2030.
In Japan the implementation of NZEB as standard for new buildings is also planned for 2030. Therefore, an action plan which includes the steps shown in Fig. 4 until the full implementation for new buildings in 2030 has been made:

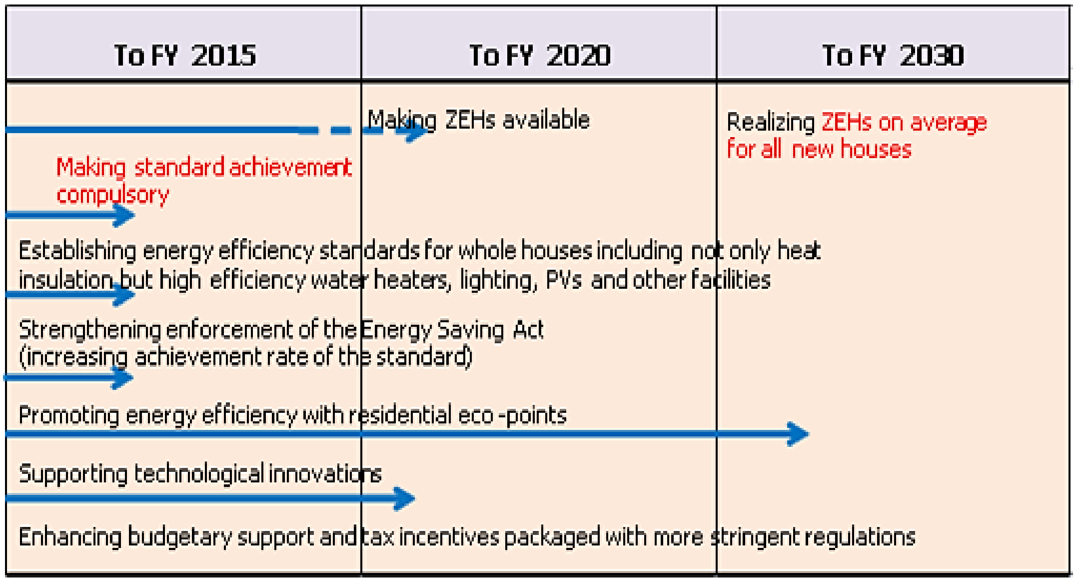


Fig. 4: Action plan for the introduction of nZEB (ZEH) in Japan (Okumiya et. al., 2013)

1.3 Task 2: System comparisons and case studies for nZEB

Different system comparisons and case studies, respectively, for building technology in nZEB were accomplished in IEA HPT Annex 40. Thereby, country specific boundary conditions in respect to weather data, load profiles and economic boundary conditions were considered. Residential as well as office buildings were evaluated.

1.3.1 System comparison Switzerland

As single-family building for the Swiss energy and cost comparison of different building systems, the reference framework of IEA HPP Annex 38/SHC Task 44 (Dott et al., 2013) was adapted. As multi-family building a five-storey building was taken. As example for an office building the headquarter of the Marché restaurants in Kemptthal was chosen. The results confirm that for Swiss boundary conditions of the MINERGIE-A®-label, which is a current implementation of nZEB in Switzerland, heat pumps in combination with PV are the most cost-effective systems for single-family buildings regarding energy efficiency and 20-year life-cycle cost, as depicted in Fig. 5 left. For low heat load at MINERGIE-P® level, air-to-water (A/W)-heat pumps reach the lowest annual cost due to the lower investments. For higher loads and larger buildings, ground-source heat pumps are more favourable regarding life-cycle cost. Systems with biomass, especially biogas, have the highest life-cycle cost.
In multi-family- and office buildings combined heat and power (CHP) and district heating reach similar life-cycle cost as the heat pumps under the set boundary conditions of system and energy cost, which is depicted in Fig. 5 right. While smaller office buildings with three storeys can still reach a nearly zero energy balance according to MINERGIE-A® with PV installed on the roof, larger buildings also need PV installation in the facade or even CHP as further electricity producing technology. Biomass systems, in particular biogas, are the most expensive system solutions like in single-family houses.

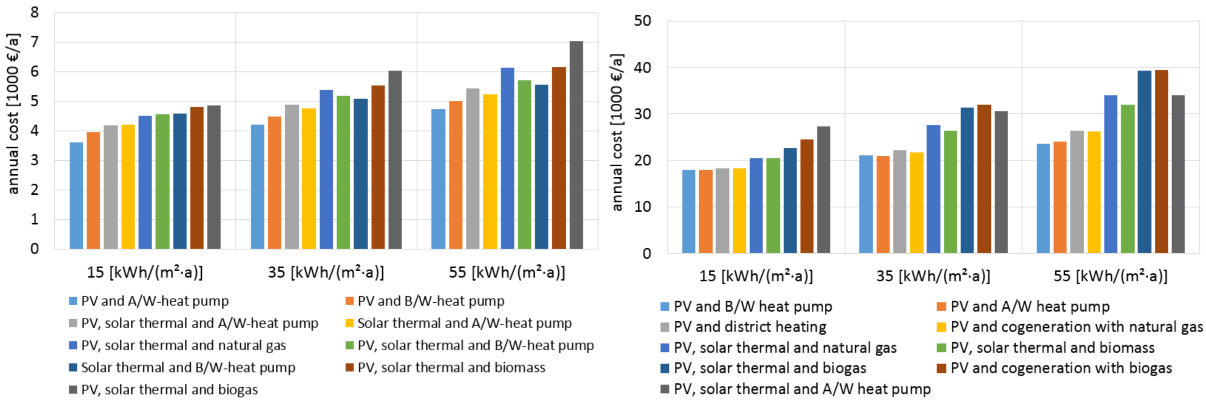


Fig. 5: System comparison for single-family (left) and multi-family houses (right) in Switzerland (Schwarz et al., 2015)

1.3.2 System comparison Sweden

In Sweden, the system comparison led to similar results as in Switzerland, as the cost comparison in Fig. 6 illustrates. It could be verified by the case study, that despite the higher investment cost, ground-coupled heat pumps can be an economic solution also for the lower space heating demand in nZEB. The system solution with ground-source heat pump combined with PV reached the lowest life-cycle cost, even lower than air-source heat pumps. 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 at low life-cycle cost.
Based on the results for single-family houses, ground-source heat pumps and district heating has been compared also for multi-family houses. In multi-family houses, 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 proposed requirements for nZEB in Sweden, and an additional technology like PV or solar thermal collectors is necessary.

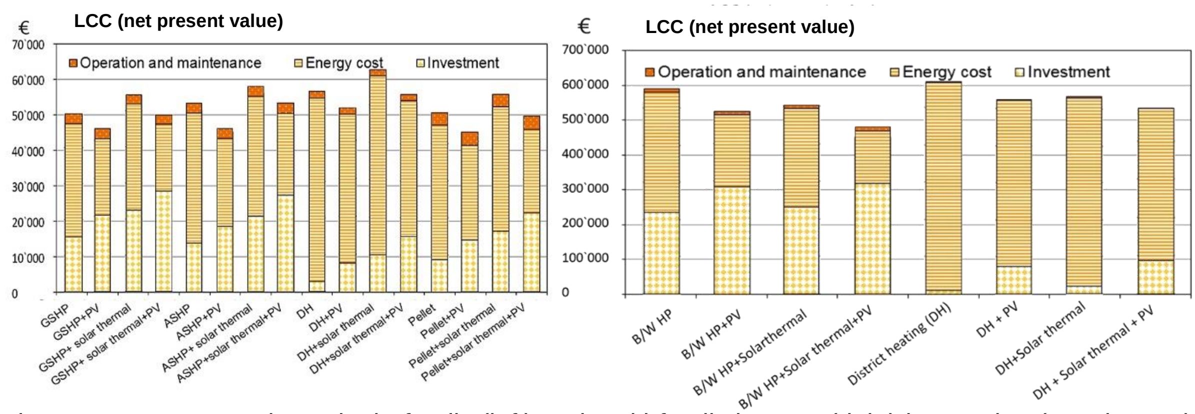


Fig. 6: System comparison single-family (left) and multi-family houses (right) in Sweden (Ruud, 2015)

1.3.3 System comparison Finland

In bigger cities, Finland has a well-developed district heating supply, so the role of heat pumps in future nZEB in Finland should be evaluated by the Finnish case study. In particular, it was a question, whether heat pumps can be a competitive solution for nZEB under Finnish boundary conditions. A Finnish definition for nZEB has been developed in parallel in the FInZEB project (Rautiainen, 2015). Results of the Finnish case studies already use the FInZEB recommendations as boundary condition. Investigations were done by simulations, and results confirm that A/W-heat pumps as well as B/W-heat pumps fulfil the requirements of the FInZEB limits, so called E-values. Regarding system configurations heat pump solutions are more cost-effective than district heating which is an important result of the project, since district heating systems are very common in the bigger cities in Finland. As well as in the Swedish case study also in the Finnish case study it was confirmed that despite the higher investment cost, ground-source heat pumps reach the lowest 25-year life-cycle cost. Fig. 7 shows the system comparison for the life-cycle cost of different heat pump systems and different E-values (ground-source with maximum solar energy systems (GSHP/S), ground-source (GSHP), outdoor air source (ASHP), Exhaust air (EAHP) and Air-to-Air (AAHP)).

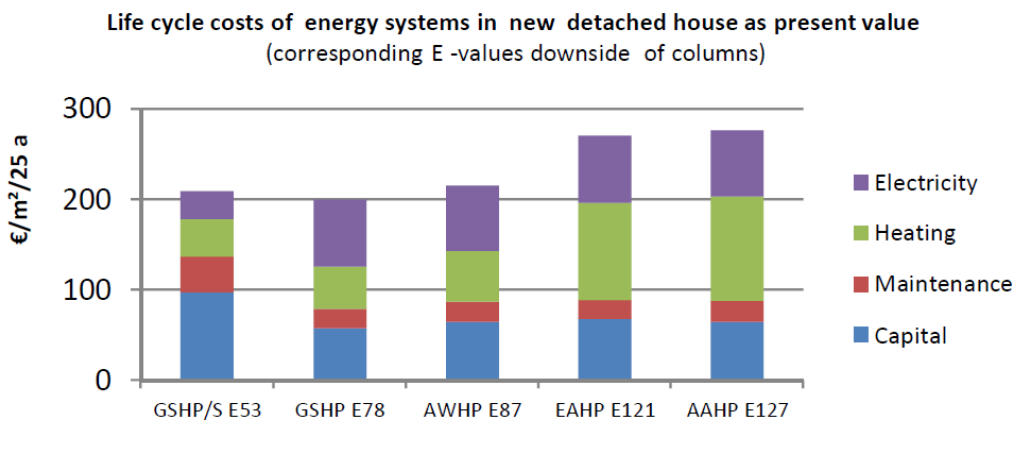


Fig. 7: System comparison in Finland for single family houses (Häkamies et al., 2015)

1.3.4 System comparison Canada

The system comparison in Canada does not show a uniform picture regarding preferable system solutions, but it reflects the influence of the market situation, i.e. the influence of the energy cost and prices, respectively, as shown in Fig. 8. While in the Eastern provinces represented by the cities Halifax and Montréal, ground-source heat pumps (GSHP) and special air-source heat pumps for cold climate conditions (CC ASHP) are the cheapest systems based on 20-year life-cycle cost, these system solutions are more expensive in the Western provinces represented by the cities Toronto, Edmonton and Vancouver due to very low gas prices. This underlines the dependency of the most cost-effective technologies on present energy prices.

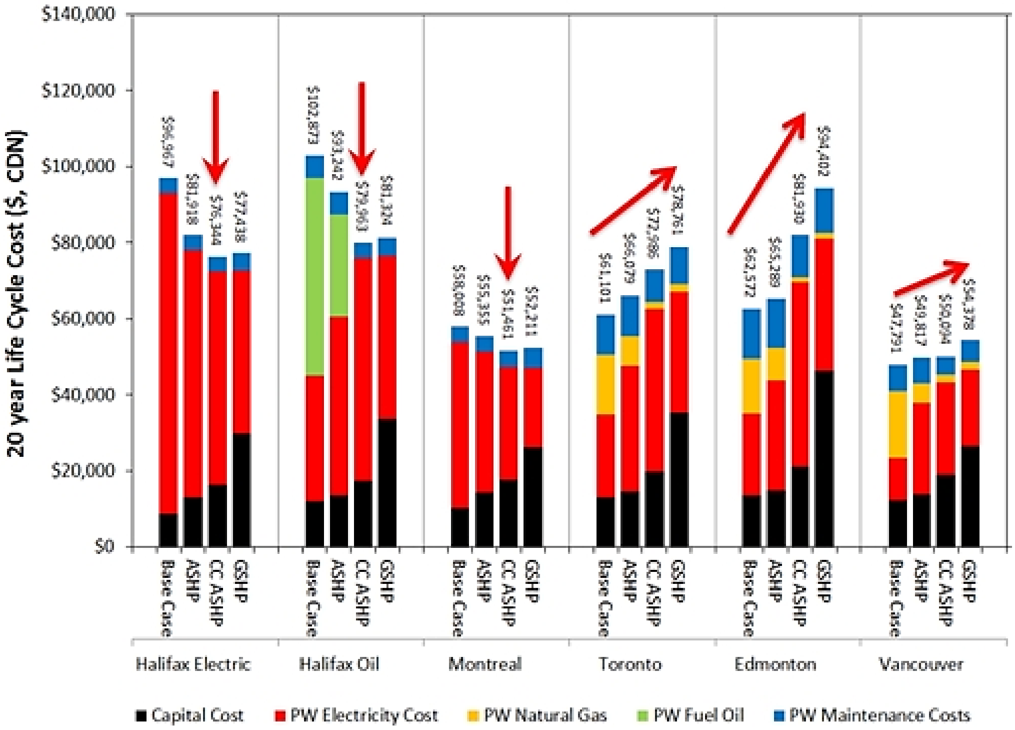


Fig. 8: System comparison by regions in Canada (Kegel et al., 2014)

1.3.5 Case study in Japan for nZEB office buildings

The balance boundaries for the case study in Japan includes the whole energy including the whole lighting and appliances. The different building types – standard, low energy and NZEB – as well as the results of the case study are shown in Fig. 9. The reference building is dominated by lighting and cooling demands. Compared to the reference building, the low energy building has a better insulation, energy-efficient windows and different efficiency technologies for lighting and appliances.

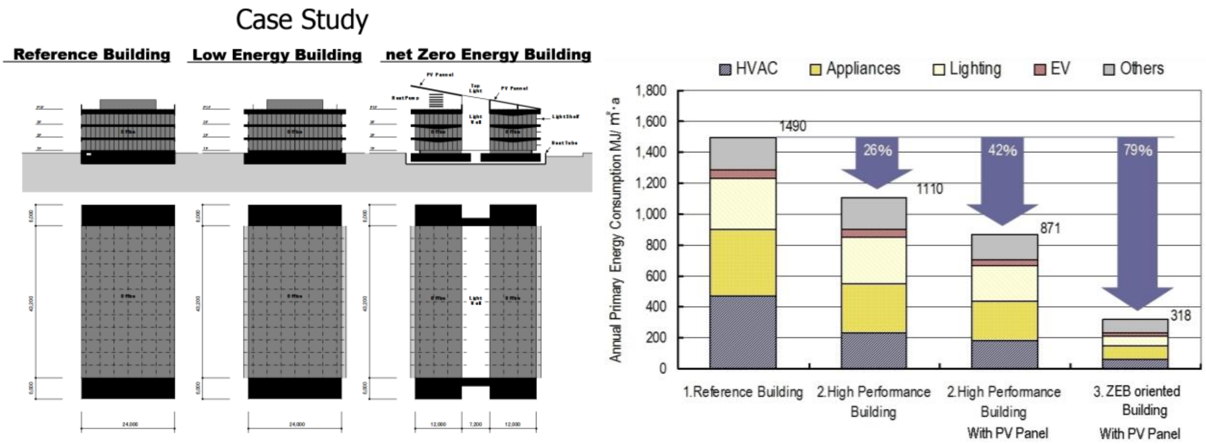


Fig. 9: Case study in Japan for nZEB office building (Okumiya et. al, 2015)

The energy consumption is 45% lower than in the reference building. Furthermore, the nZEB is optimised in respect to daylighting and energy generation on-site. The building is divided into two wings with an atrium inbetween. Due to the atrium, also in the former inner rooms daylight can be used. Furthermore, a highly efficient heat pump for heating and cooling as well as a PV-generator on the rooftop are installed. The energy needs, especially for the lighting, could be reduced by 65% in comparison to the reference building. Due to the PV-generation almost the total energy needs can be balanced on an annual basis. For office buildings up to three storeys, a zero balance and therefore a Net Zero Energy Building can be reached, if all energy reduction potentials are effectively used. Case studies for larger office building and case studies for European boundary conditions have also been performed.

1.3.6 Summary of case studies performed in Task 2

In Task 2 of Annex 40, case studies to compare system solutions in nZEB have been performed for different boundary conditions both for central European and Nordic climate conditions as well as in Japan, where pronounced air-conditioning needs occur. As building types both residential and office buildings have been considered. Thereby, the boundary conditions regarding the nZEB definition and economic aspects have been based on the current national state of definition and the present market conditions. Despite the partly different boundary conditions the case studies yield the results, that both in central European as in Nordic countries heat pumps are a favourable building system technology for the application in nearly Zero Energy Buildings both in terms of energy-efficiency and life-cycle cost. With the heat pump solutions, requirements of nZEB can be reached. Even though heat pumps may have higher investment cost compared to other heating systems on the national markets of the individual countries, heat pumps are among the systems with the lowest life-cycle cost.

Despite the differences in the nZEB balance definition, climate, and the economic boundary conditions, the resulting ranking of the different system solutions is quite similar, where heat pumps are among the most appropriate system solutions. This shows a certain robustness of the results regarding both the energy performance evaluation and the economic boundary conditions. For the energy evaluation heat pump solutions benefit from the high energy performance in nearly Zero Energy Buildings with good building envelopes enabling low supply temperatures. Thereby, the nZEB balance can be reached more cost-effectively, since less on-site generation is required for the compensation of the energy demand of the building. On the other hand, heat pumps may have higher investment cost on the national markets, but regarding the life-cycle cost, this initial disadvantage is compensated by less investment in generation technologies, e.g. PV systems can be designed smaller. Moreover, the higher energy performance of heat pumps reduces the operational cost, which is seen in the life-cycle consideration, too. According to these results, heat pumps are very favourable system technology for the application in future nZEB also for Nordic climate conditions.

1.4 Task 2: Development of design tools

In two of the projects within Task 2 of Annex 40 design tools were developed.

1.4.1 Design-Tool for comfort evaluation of surface heating- and -cooling systems

In the USA, at the Center of Environmental Energy Engineering (CEEE) of the University of Maryland, a tool to evaluate the thermal comfort of surface heating and cooling systems for rooms has been developed. Motivation of the tool development is the objective to reach the lowest possible supply temperature for heating and the highest possible supply temperature for cooling, respectively, in the room to optimise the Coefficient of Performance (COP) of the heat pump/chiller. The tool can display different comfort criteria for rooms with different geometries. The basis for the evaluation of a given room geometry are detailed computational fluid dynamic (CFD) simulations. By the proper orthogonal decomposition *(*POD) approach reduced order models are derived, which can be used for the investigation of the different comfort criteria in the given room with less computational expense than the full CFD simulations. Using the reduced models the comfort criteria Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) according to the Fanger algorithm, which is standardised in ISO 7730, as well as the influencing factors like room air temperatures, air velocities and radiative temperature can be evaluated in high spatial resolution.

Fig. 10 left shows a basic room configuration for the evaluation of a radiative wall-mounted cooling system and solar radiation entering the room by a window on the opposite wall. Due to the low temperature levels, surface heating and -cooling systems have been in the focus of the development, but also conventional convective cooling systems like inductive units or ducted air-handling systems as well as ductless room air-conditioners have been implemented in the design tool. Fig. 10 right shows an example of a case study regarding the temperature fields of a ducted air-handling unit and a ductless room air-conditioner with different supply temperatures.

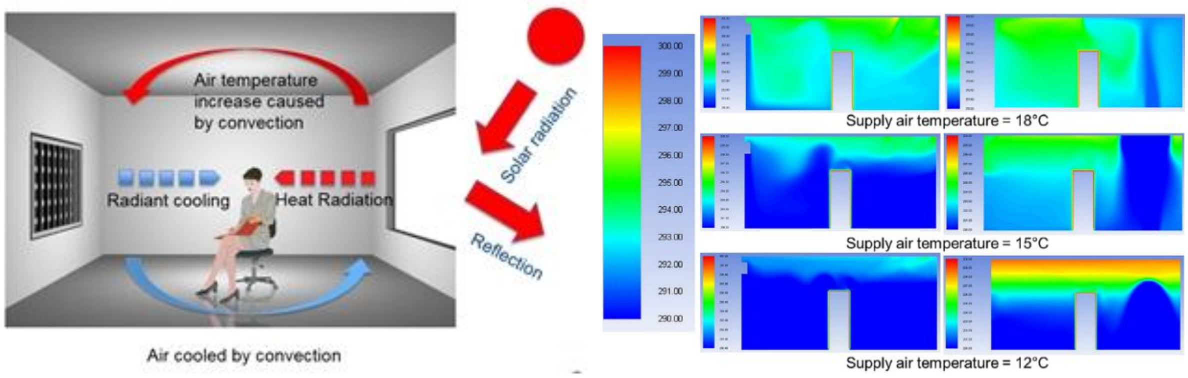


Fig. 10: Typical room of the design tool with surface heating and -cooling system for the evaluation of the indoor thermal environment (left) and evaluation of the temperature field of a ductless and ducted space cooling system for different supply air temperatures (Baxter et al., 2015)

1.4.2 Design-Tool for CO_2-emissions and cost in Norway

Simulations of CO_2-heat pumps for the application in nZEB as well as a development of a design tool for heat pumps and back-up heating regarding cost and CO_2-eq.-emissions have been accomplished at SINTEF Energy in Trondheim, Norway. Based on the load profile, which is generated in a pre-processing with standard building simulation software, the tool performs an iterative optimisation of the design of the system components to minimise CO_2-eq.-emissions and system life-cycle cost. Fig. 11 shows the current state of implemented system configurations. The system can be composed of the heat pump as main heat generator, a back-up heater, the storage and the emission system. As operation modes space heating and domestic hot water (DHW) operation as well as a free-cooling operation by a ground-source borehole heat exchanger and an active cooling operation by a heat pump in reverse operation mode shall be covered by the design tool. Based on the pre-processed load, the respective system configuration can be simulated and simulation results serve to iteratively optimise the design of the system components.

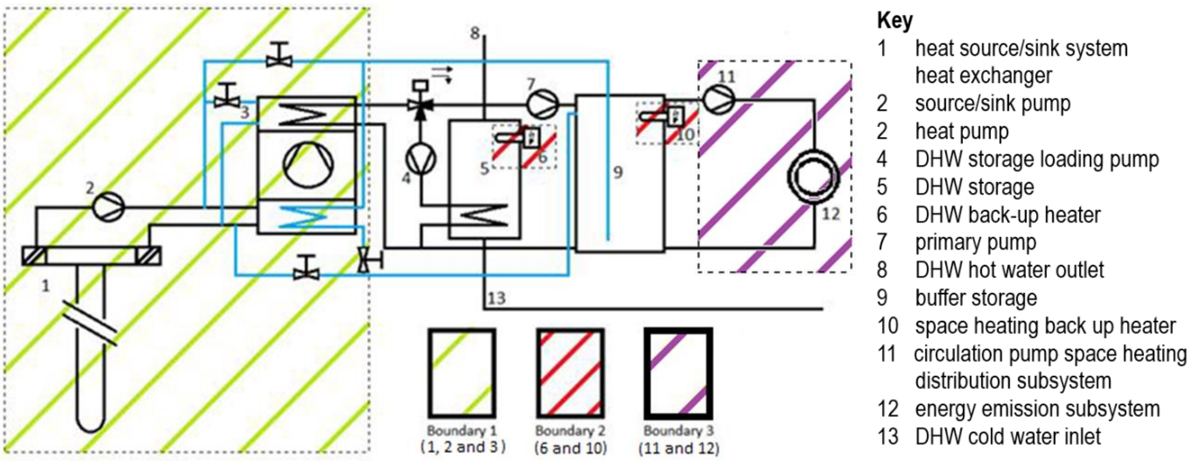


Fig. 11: Principle design of the modelled system: Boundary 1 – heat pump with heat source/sink, Boundary 2 – peak load system, Boundary 3 – DHW system and a heating/cooling system (Småland, 2013).

Fig. 12 shows the single calculation steps of the Net Zero Emission Programme (NZEP). After the pre-processing, the system configuration is chosen. The objective function for the optimisation is the design of the heat pump and a back-up system regarding minimal CO_2-eq.-emissions and life-cycle cost. Presently, the objective function is a cost-optimal design of the heat pump and the back-up system regarding a nearly zero CO_2-eq.-balance, i.e. a Net Zero Emission building. However, it is possible to change the weighting factors to a primary energy weighting to create nearly Zero Energy buildings.

As shown in Fig. 12 left, after the building pre-processing and definition of the system configuration, the parameters are set. In the next step the system simulation is accomplished.

Based on the simulation results, the optimisation variables system cost and CO_2-eq.-emissions are evaluated. Dependent on the results, the design of the system is adapted and another simulation is started. The current state of the tool, the optimisation is accomplished as a series of parameter variations of the system design in order to evaluate the minimum values of life-cycle cost and CO_2-eq.-emissions. However, since the entire calculation including the simulation has been transferred to a Matlab-Simulink® environment, also the optimisation algorithm available under Matlab® can be coupled to the simulation in order to perform automatic optimisation of the system design variables as shown in Fig. 12. The tool is still under development, and will be extended regarding the system configurations and the optimisation loop.

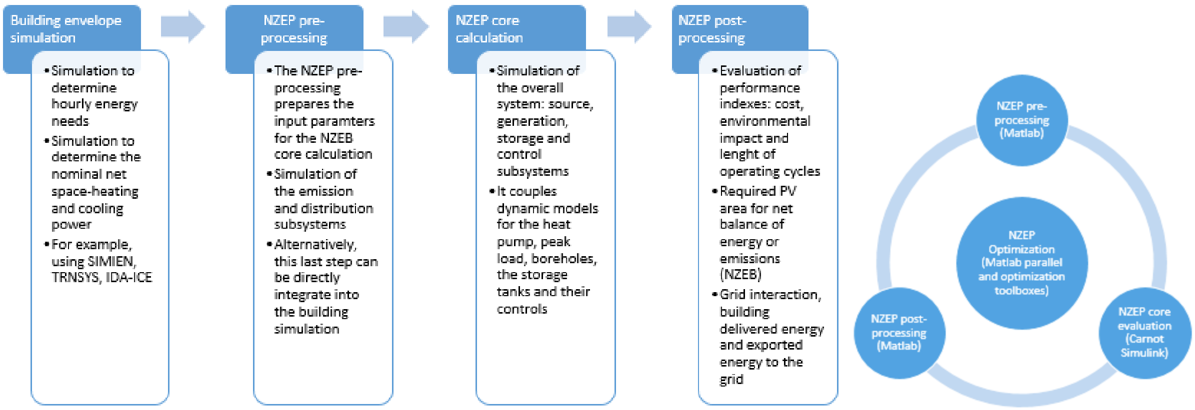


Fig. 12: The overall algorithm for the NZEP simulation tool and optimisation process by iterating on the three calculation phases: pre-processing, core calculation and post-processing, of which each step can be done in Matlab environment (Justo Alonso et al., 2015)

1.5 Task 3: Technology developments

In Task 3 prototypes of integrated heat pumps were developed and analysed in lab- and field tests. Field monitoring on built nZEB were carried out, in order to evaluate, whether the net zero energy balance was reached and to characterise and optimise the heat pump performance.

1.5.1 Integrated heat pump (IHP) development in the USA

The development of highly integrated heat pumps (IHP) 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 production and dehumidification, a function, which is essential in the southern states of the USA. Within the framework of Annex 40 the earlier developed prototypes were analysed in field monitoring and new variants of the IHP concept were evaluated.

A ground-source version of the IHP is already on the market, while for the air-source IHP (AS-IHP) three different embodiments have been developed and investigated in lab- and field-testing in the frame of the Annex 40. Two of them are electrically-driven, and the third is a gas-engine driven system configuration.

Fig. 13 shows the conceptual design and the field object as well as the results of the field monitoring in summer operation. The different combined operation modes are distinguished. As overall seasonal performance, values above 5 for cooling operation and 4.4 for DHW operation are reached. As expected the simultaneous operation modes reach higher performance values than the single operation modes. As variant of the AS-IHP system design also a so-called two-box system and a gas-engine driven system are under development. Several field-tests have already been performed, leading to improved prototype designs for the systems. The motivation for the two-box systems is the separation of the space heating and sensible space cooling function from the dehumidification (DH) and domestic hot water (DHW) production, i.e. a central high-efficiency air-source heat pump is coupled with a prototype water heating/dehumidification (WH-DH) module.

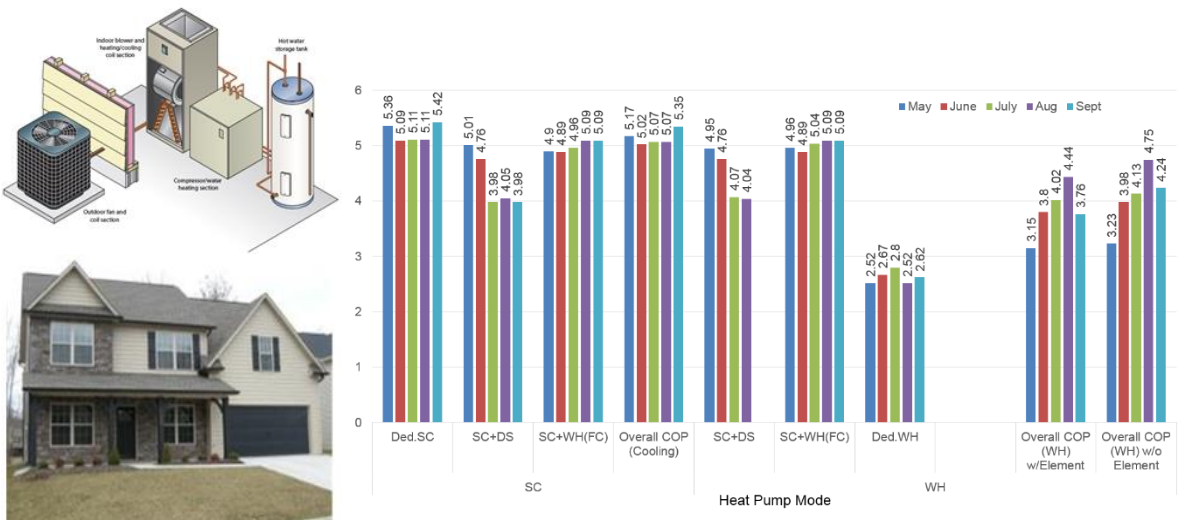


Fig. 13: Layout of the integrated heat pump (left, top) and field monitoring results (right) from Knoxville, TN (left, bottom)(Baxter et al., 2015)

The WH-DH module can be integrated with the air-source heat pump unit by a parallel secondary duct loop around the central air handler, receiving a portion of the central return air when the secondary (WH-DH) blower is operating and returning this air to the supply air stream. It also has an optional connection to an outdoor air intake to provide a means for conditioning and circulating ventilation air through the central duct system. A dedicated DH cycle addresses humidity control and integration of heat pump WH is expedient, since the small vapour compression components can perform double-duty. This integrated, yet independent operation of the WH-DH unit provides dehumidification of the central return and ventilation air as well as a central heat source for the WH mode.

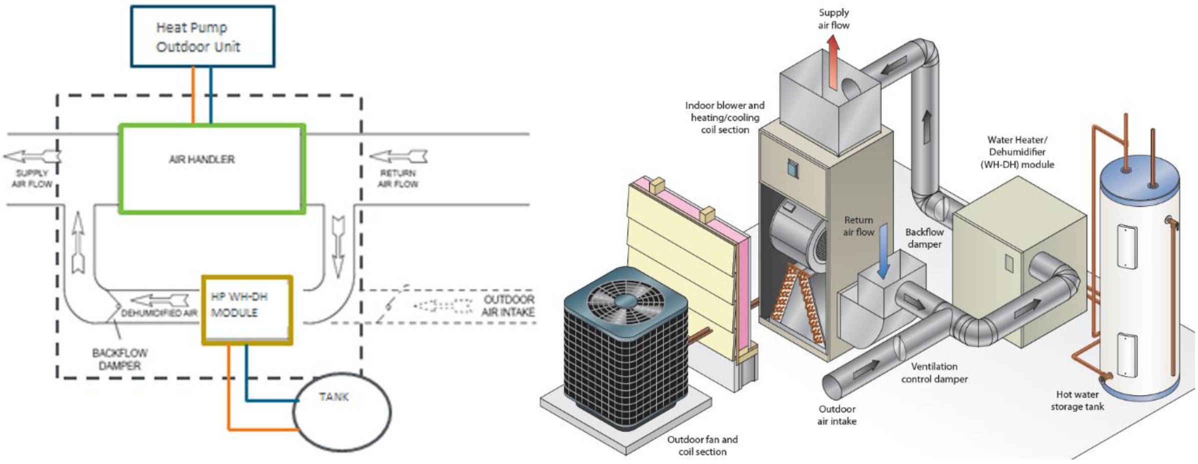


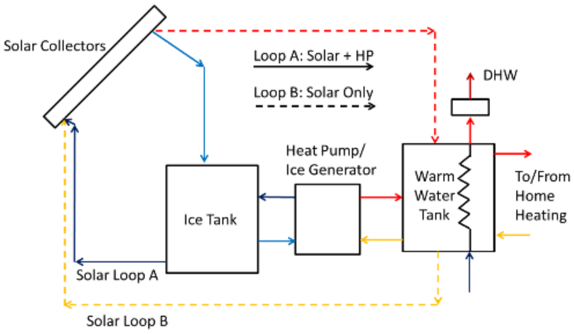
Fig. 14: Principle of the two-box design of the AS-IHP and layout for the field test of the unit (Rice et al., 2014)

The independent operation is especially useful in the shoulder months which often require dedicated DH, along with WH, but little or no SC or SH. The principle of the two-box system and a system layout for a field test are shown in Fig. 14 (Rice et al. 2014).
Another significant advantage is that this IHP approach can be relatively easily applied to retrofit/upgrade applications as well as new construction, utilising standard electric water heaters and a wide range of multi-capacity and variable speed air-source heat pumps. In retrofit applications, even if the tank is remote from the heat pump indoor section, the WH-DH unit can be located at the WH tank and the system will still retain most or all of the IHP advantages.

As a further variant, a Gas Engine-Driven Heat Pump (GHP) is developed. It can be an attractive economic choice in parts of the USA where the typical engine fuels such as natural gas, propane or liquefied petroleum gas (LPG), can be less expensive than electricity (Mahderekal et al., 2012). Compared to conventional fuel-fired furnace heating systems they are projected to reduce fuel consumption for space heating by 35% and for water heating by 80 % (Vineyard, 2014). They also significantly reduce summer cooling electric peak demand compared to electric air-conditioning (AC) systems. A GHP can be a more attractive climate control system than conventional single-speed electric heat pumps for a number of reasons, e.g. variable speed operation can be realized at high efficiency, thus well adapting to the load conditions and heat recovery from the engine can increase the winter capacity for space heating and be used for DHW preparation throughout the year. Moreover, lower gas prices exist in several regions of the USA, and by integration of a small power generator, the unit can be operated independent of the electricity grid and can provide basic electricity supply for the units auxiliary components and the base load of the home.

1.5.2 Solar assisted heat pump development in Canada

CANMET Energy of Natural Resources Canada is working on a solar assisted heat pump. The integration of solar components and heat pump is done by an ice-slurry storage. Similar to concepts with ice storages in Europe, the ice-slurry storage is integrated as source storage. The principle system configuration is shown in Fig. 15 left. The configuration has several advantages, namely an enhanced storage density by the phase change of the ice-slurry, a stable source temperature for the heat pump and improved efficiency and longer running time for the solar component due to the low temperature levels. The ice-slurry storage is charged by a solar component, which can be a solar thermal collector, but due to the low temperature in the ice storage this may also be a photovoltaic-thermal (PV/T)-hybrid collector. The heat pump discharges the storage and forms the ice while transferring the heat to a warm water storage, which serves for the space heating and DHW preheating. In times of sufficient solar irradiation, a direct heating of the warm water storage is also possible by the solar component. In summer operation, the source storage can be used as cold storage for cooling applications, while the condenser waste heat in cooling operation may be recovered for the DHW operation or is rejected to the ambiance by a separate heat exchanger. The DHW can be produced directly by the collector in summer operation with sufficient solar irradiation to reach DHW operating temperatures.



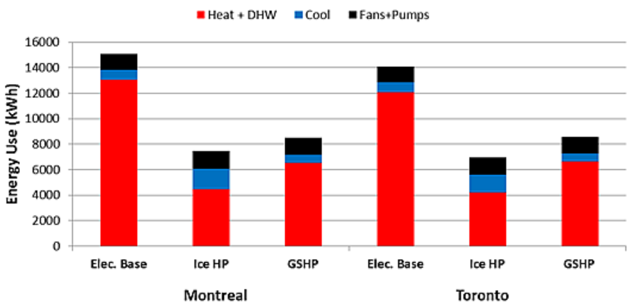


Fig. 15: Integration of solar collector with ice-slurry storage in Canada (Tamasauskas et al., 2015)

The system is intended to replace direct electric baseboard heating systems, which are still relatively common in Canada. For the investigation of the real behaviour of the single system components and the integration, a test bench has been built and commissioned. Besides characterisation of the component behaviour under different operating conditions, the test results have also been used to create and validate component models based on the test bench results. By integration of the component models in the system simulation software TRNSYS, whole year system simulations for a specified low energy building for different sites could be performed. Fig. 15 right shows the results of system simulations for the weather conditions of Montreal and Toronto.

The system simulations confirm that both in Montreal, which has a cold but clear winter climate with more solar irradiation in wintertime, and in Toronto significant energy reduction can be achieved compared to electric baseboard heating. The simulation results also demonstrate that the solar assisted heat pump system has even a slightly lower energy consumption than a ground-source heat pump.

1.5.3 Integration of heat pumps and solar technologies in Switzerland

The HSR University of Applied Sciences Rapperswil and the University of Applied Sciences Northwestern Switzerland FHNW have analysed the combination of an uncovered solar absorber and a heat pump for space heating and cooling operation. The principle of the system integration is shown in Fig. 16.

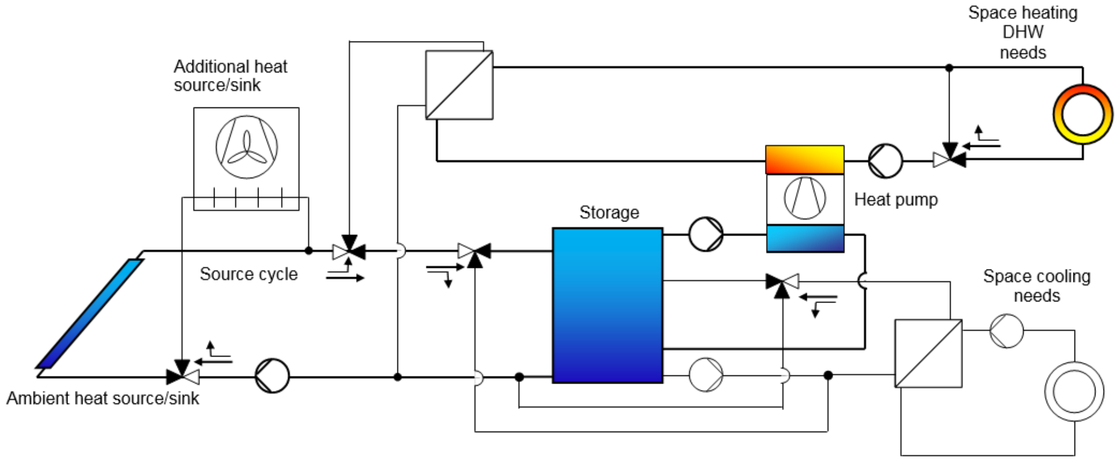


Fig. 16: System integration for space heating with absorber as heat source (Wemhoener et al., 2015)

In heating mode, the absorber works as heat source for a heat pump. The storage is operated as a source storage for the heat pump. With enough direct solar irradiation in the transitional period, also a direct solar heating can be performed.
In cooling mode, the absorber is used as an outside heat exchanger to reject heat to the colder ambient temperatures at night-time. In this mode, the cooling energy can be stored in the source storage, which acts as a cold storage in cooling mode, or directly coupled to thermally-activated building systems which are often installed in the room zones of an office building.

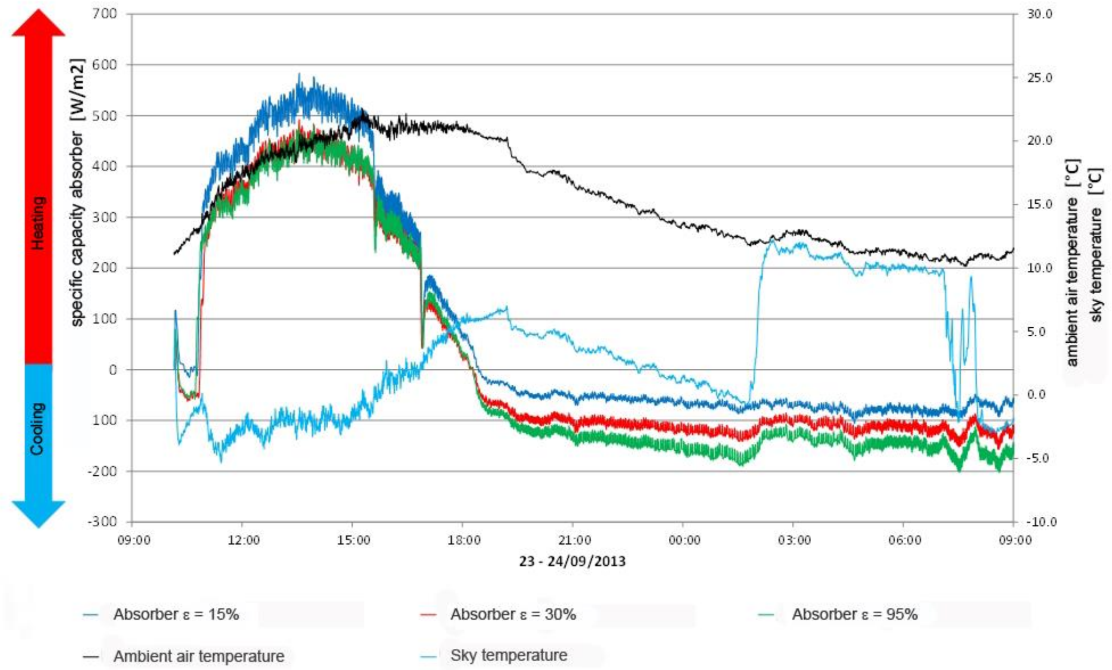


Fig. 17: Lab testing of uncovered absorbers with different selective coatings (Wemhoener et al., 2015)

Lab test measurements have been performed for three absorbers with different degree of selective coating of a long-wave emissivity of ε_{IR} = 0.15 (selective), ε_{IR} = 0.3 (faint selective) and ε_{IR} = 0.9 (non-selective).

Fig. 17 shows the lab measurement results for a sunny day followed by a clear night. The absorber inlet temperature is kept constant at 25 °C during the measurements. Heating capacities are in the range of 500-600 W/m^2_{abs} with direct solar irradiation during daytime, where the selective absorber reaches the highest values due to its reduced radiation losses. Cooling capacities during the clear night are in the range of 70-200 W/m^2_{abs}. In cooling operation, the non-selective absorber reaches the highest capacities due to the radiation losses, which are inhibited by the selective coating. The test results show that in the middle of the night, clouds appeared. This reduces the radiation losses to the sky, which caused the three absorbers capacities to approach each other. Thus, the absorber capacities depend on the selective coating of the absorber regarding the radiative fractions of the cooling capacity. Thereby, requirements for a high space heating and cooling capacity are contrary, since selective coating limits the radiation and environmental losses, which is good for the space heating operation, while it limits space cooling operation.

Based on lab-test measurements, a model of the absorber component was implemented in a simulation environment and validated with the test data. After validation annual system simulation of the space heating and cooling operation have been performed using weather data of Zurich Meteoschweiz for an average year for two office zones in north and south orientation and single office use. The office zones are equipped with thermally activated building systems (TABS) as concrete core activation, enabling a maximum supply temperatures of 29 °C in heating operation. The design of the collector is 33% of the energy reference area of the office space, which corresponds to the entire roof size of a three storey office building. The investigated absorber can be used directly as roof material.

Results show good seasonal performance factor (SPF) of an overall SPF in space heating mode between SPF_h = 4-5 for heating mode with heat pump and direct solar heating. The SPF differs depending on the absorber properties and inclination. While the selective coating is not as important in operation as heat source, it enables higher percentages of direct solar heating due to higher absorber temperatures. In summer operation 80-90% of the cooling load can be covered by free-cooling in moderate climate conditions of an average summer using Zurich weather data. This of course depends on the properties and inclination of the absorber. In free-cooling operation, the typical high performance factors of up to 30 are reached for an optimised hydronic integration. Non-selective coating is important in climates where the heat loss by convection is limited due to higher night-time temperatures, when radiative heat rejection is the main cooling mechanism.

1.5.4 Evaluation of HVAC system in Japan

In Japan a novel heating, ventilation and air conditioning (HVAC) system has been evaluated by testing in two office rooms. The HVAC system applies two innovative components, a heat pump (HP) Desiccant system and an enhanced temperature control of a variable refrigerant flow (VRF) heat pump.

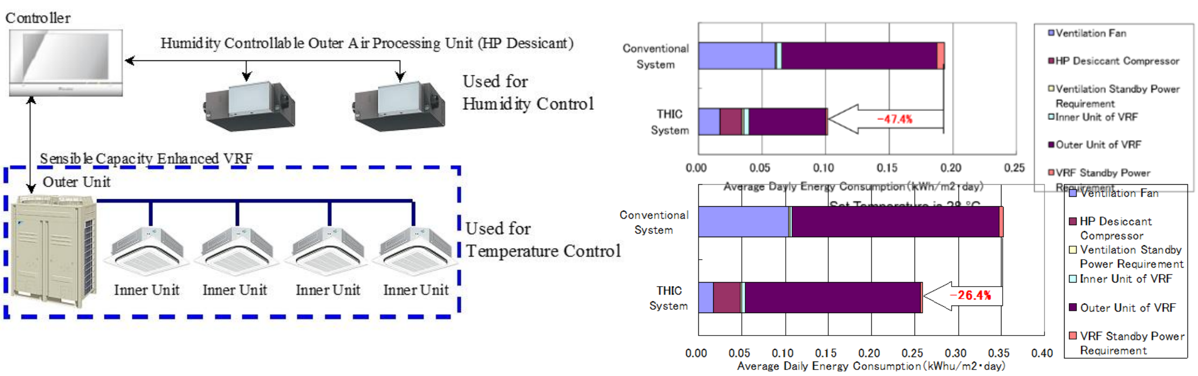


Fig. 18: Configuration of the HVAC system (left) and energy reduction in summer (right, top) and winter operation (right, bottom) (Okumiya et al., 2015)

The system denoted as Temperature and Humidity Individual Control (THIC) performs a separation of the sensible cooling load and the latent dehumidification load. The latent load is covered by a HP Desiccant system which has been further developed to decreased regeneration temperatures of the desiccant of 40-50 °C, so the regeneration can be accomplished efficiently with the heat pump. Adsorption and desorption are accomplished in parallel while the heat pump transfers the heat from the adsorption to the desorption process, which significantly increases the performance.

Due to separation of the latent load, pressure difference for the VRF heat pump can be decrease. The VRF heat pump has been optimised for low pressure differences. A new scroll compressor was developed which is far more tolerant for the operation with the small pressure difference operation, which makes it possible to notably reduce the pressure difference and increase the performance.

The test of the unit was accomplished in two office rooms in summer and in winter operation. Fig. 18 left shows the system configuration of the THIC and Fig. 18 right show the achieved energy savings during the summer and winter test. Despite the energy saving of about 50% the control of the indoor condition has been better by the THIC system than by the conventional system. In winter test, energy saving of about 25% have been achieved. Based on the measurements a model of the system was developed. The overall energy saving were determined by year-round simulations. Results of the overall energy saving are depicted in Fig. 19 yielding an energy saving potential of about 75%. Concluding, the impressive energy saving without any reduction of the indoor thermal environment conditions has been achieved by the reduction of air-conditioning loads by individual control of temperature and humidity, the development of the HP desiccant for efficient humidity control and the development of the sensible capacity enhanced VRF for efficient temperature control, especially in spring or autumn. By the energy reduction, it is much easier and more cost-effective to achieve an nZEB consumption due to reduced generation needs on-site to meet the balance. An nZEB can be reached by the application of the THIC relatively easy for 2-3 storey office buildings, but also in high-rise buildings, the technology offers a huge energy saving potential.

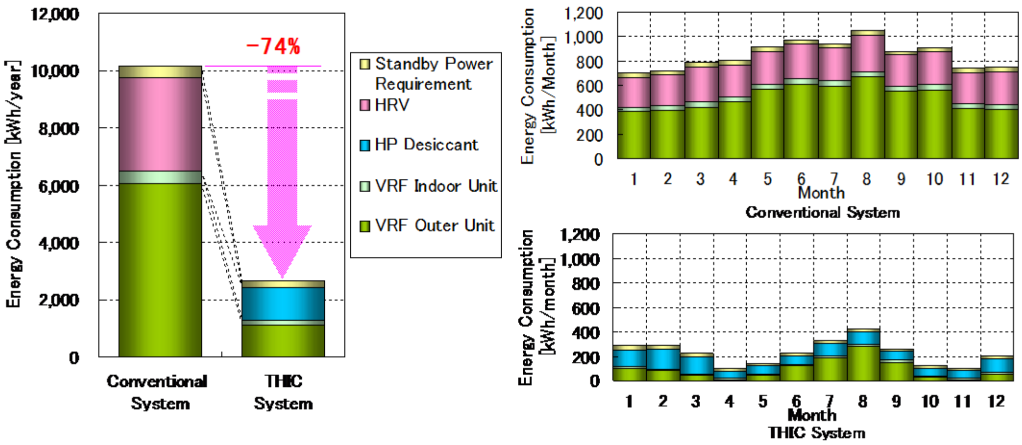


Fig. 19: Comparison of energy reduction by the THIC system with conventional air-conditioning systems without decoupling of sensible and latent loads (Okumiya et al., 2015)

1.5.5 Test platform for nZEB technologies on the NIST campus

The National Institute of Standards and Technologies (NIST) has built and commissioned a Net Zero Energy Residential Testing Facility (NZERTF). The test house is used for testing of NZEB technologies on the campus of the institute, which is shown in Fig. 20 left. The house is equipped with adjustable loads and extensive monitoring technologies in order to provide a reproducible test environment for real world testing of NZEB technologies. In the first year of operation the NZERTF was equipped with an air-to-air heat pump and a ventilation heat recovery. Fig. 20 right shows the energy balance of the first year of operation, which ended-up with a slight plus energy balance. Also the second year of operation achieved a plus energy balance. The test facility offer manifold opportunities for performance and comfort measurements and the testing and development of new technologies to be applied in NZEB.

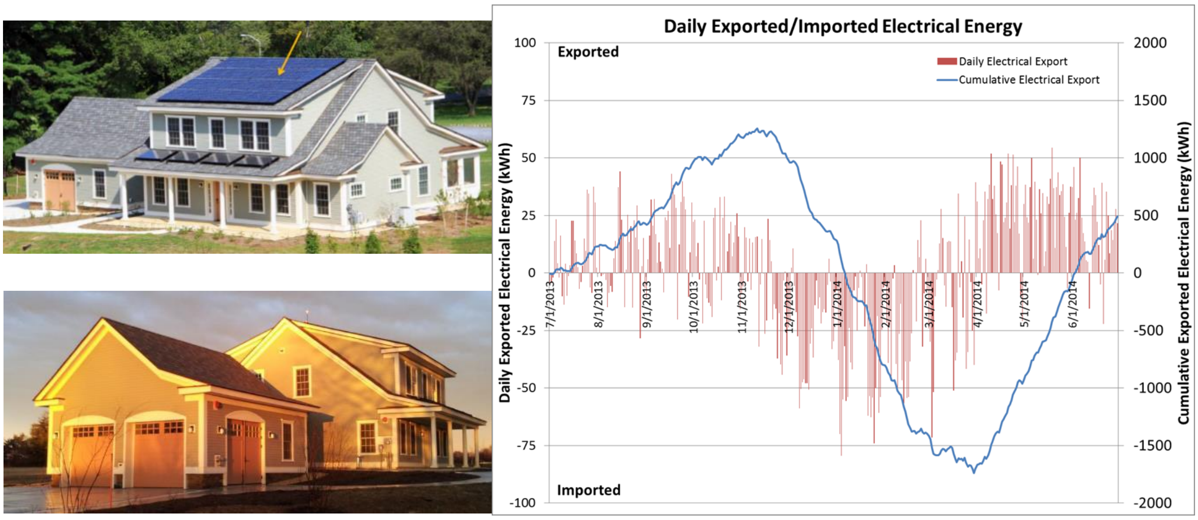


Fig. 20: Net Zero Energy Residential Testing Facility (NZERTF, left) on the NIST campus and annual balance in the first year of operation (right) (Baxter et. al., 2015)

1.6 Task 4: Field monitoring

1.6.1 Field monitoring of the first nZEB in Norway

Within the projects of the Research Centre on Zero Emission Buildings (ZEB) the first nZEB in Norway are being currently built and monitored as pilot projects for Norway. "Powerhouse Kjørbo" is one of the pilot and demonstration projects of the ZEB and has been monitored by the NTNU. The project refers to the retrofitting of an office building to a plus-energy building in Sandvika near Oslo. Fig. 21 shows the retrofitted building and a hydraulic scheme.

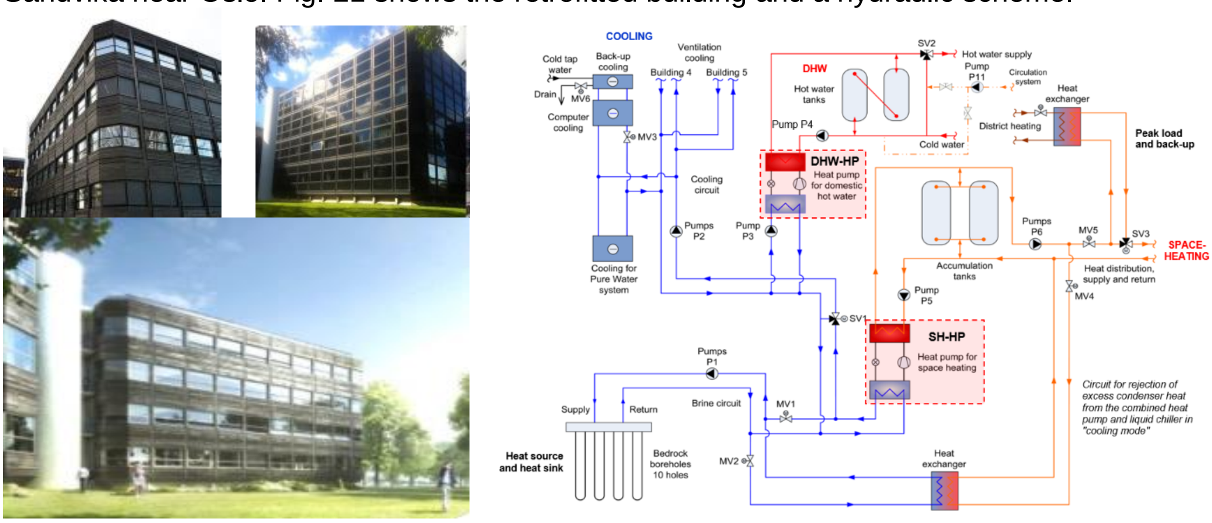


Fig. 21: View of Powerhouse Kjørbo (left, source ZEB) and hydraulic scheme of the building (right, Nordang, 2014)

The building with an energy reference area of 5200 m² has a calculated specific heating energy need of 19.1 kWh/(m²a), a design heat load of 52 kW and a DHW need of 4.8 kWh/(m²a) after the retrofitting. The cooling load is 65 kW and the specific cooling energy needs 1.8 kWh/(m²a). The heating and cooling needs are provided by a 64 kW brine-to-water (B/W) heat pump with 10 single U-tube borehole heat exchangers of 225 m depth each. The heat pump is also used as chiller for back-up cooling. For back-up heating the building has a connection to a district heating grid. Furthermore, an 8.5 kW B/W heat pump for DHW production is installed. For balancing the energy demand a solar PV-generator of 1,556 m² is installed, which yields a calculated electric energy of 225,000 kWh/a.

The measured heating energy demand of 24.6 kWh/(m²a) is 29% higher than the calculated value, the measured DHW needs are with 1.9 kWh/(m²a) about 60% lower as planned. The cooling energy is 11% higher with the measured value of 2 kWh/(m²a).

The measured peak load for heating of 14.4 W/m^2 is about 37% and the peak cooling load of 13.5 W/m^2 around 29% higher than the design values. Despite the high design temperatures of 50 °C for space heating due to retrofitted building, the monitoring shows a good SPF_{SH} of 3.9 including the auxiliary energy for the source pumps of the boreholes. In DHW mode an SPF_{DHW} of 2.9 is reached.

Optimisation potentials are seen in the dimensioning of the borehole field (only 5 boreholes to cover 90 % of the heating energy needs), frequency control instead of intermittent control of the compressors as well as in the use of buffer storages, application of natural refrigerants, and a better use of the waste heat from the active computer cooling.

Besides the Powerhouse Kjørbo, also monitoring projects of a CO_2 heat pump water heater (HPWH) installed in 3 blocks of flats of totally about 800 flats and an air-source heat pump installed in a new nZE office building in passive house standard were accomplished. The results of the CO_2-HPWH for the blocks of flats reached a SPF_{DHW} of 4.4 with 70 °C DHW supply temperature and an exhaust air heat source around 20 °C. These results are very good despite some identified optimisation potentials.

1.6.2 Retrofit projects in the frame of the Dutch field monitoring "Energiesprong"

Platform31 is responsible for the "Energiesprong" ("Energy leap") program, which is funded by the Dutch government. The objective of the program is to build good market conditions and to stimulating energy technology markets to increase the share of renewable energy use.

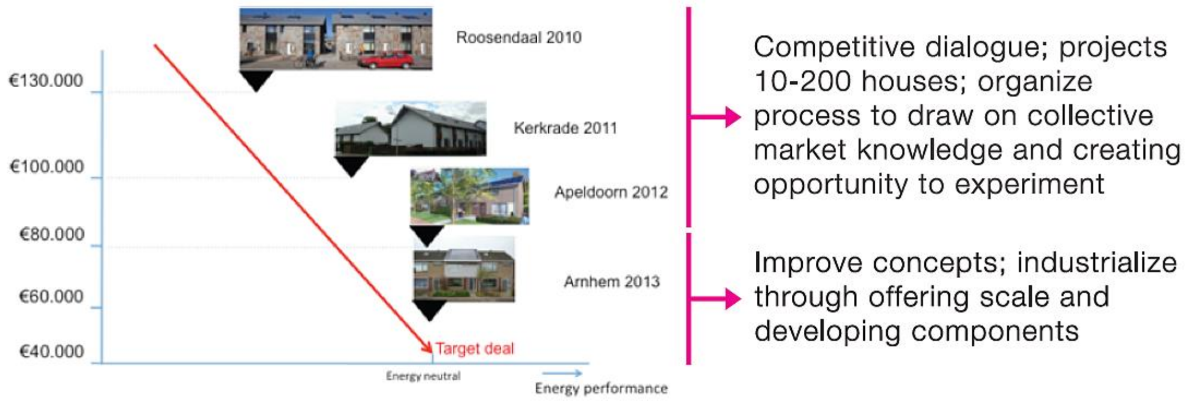


Fig. 22: Refurbishment projects in the framework of the "Energiesprong" monitoring in the Netherlands (Platform31, 2015)

Energiesprong initiated a deal between housing associations and builders to refurbish 111,000 houses to nearly zero energy level. The objective is to distribute technologies and make them competitive. The refurbishments are made within 10 days with pre-fabricated building components, which come with a 30-year guarantee. During the retrofitting, solar PV systems are also installed on the building roofs. Presently, a good feed-in tariff for PV electricity exists in the Netherlands, so parts of the refurbishment cost shall be covered by earnings from PV and decreased energy cost. Moreover, the cost for future refurbishments shall be further reduced. The cost of retrofitting have already decreased over the period from 2010 to 2013 as shown in Fig. 22. The idea of the Energiesprong is to generate a massive demand for these net zero energy retrofitting projects and to make financers and governments tune their funding and subsidy schemes and regulations towards these type of refurbishments. This shall lead to an innovation process in the Dutch building industry and to a decrease of fossil fuel applications. Within the framework of the Energiesprong project, also technology evaluations and analysis of user satisfaction have been carried out. In some of the new and refurbished buildings there is often a dissatisfaction due to the summerly overheating. Therefore, different measures for energy-efficient cooling by night-time ventilation or by ground-coupling have been applied. Besides the Netherlands, the concept shall also be applied in France and the UK in order to spread the experience of the Netherlands to other European countries.

1.6.3 Long-term monitoring of nZEB office buildings in Germany

The Fraunhofer ISE in Freiburg performs a long-term monitoring in 16 nZEB office buildings and schools. The buildings have an energy reference area of 1,000 m²-17,400 m² and are equipped with heat pumps. The majority of room emission systems are TABS. The evaluation is made according to five different system boundaries from the source over the heat pump up to the overall system. Fig. 23 left shows the evaluation for the space heating mode containing the seasonal performance factors (SPF) in the boundary of the heat pump and boundary II, which comprises the heat pump including the source pump. The SPF (including the source pump) in heating mode are in the range of 2.9-6.1 kWh_{th}/kWh_{el}.
In case of higher sink temperatures than required, problems with hydraulic integration could be identified, e.g. the integration by a common storage for emission systems with different supply temperature requirement.
The difference between the green and blue diamonds in Fig. 23 left depicts the difference in SPF caused by the source pump. Thus, auxiliary energy can have a substantial impact on the SPF, and the hydraulic design should be undertaken carefully. The auxiliary energy fraction of the source system is in the range of 6-25% of the total energy use, which demonstrates the optimisation potential of the hydraulic system design.

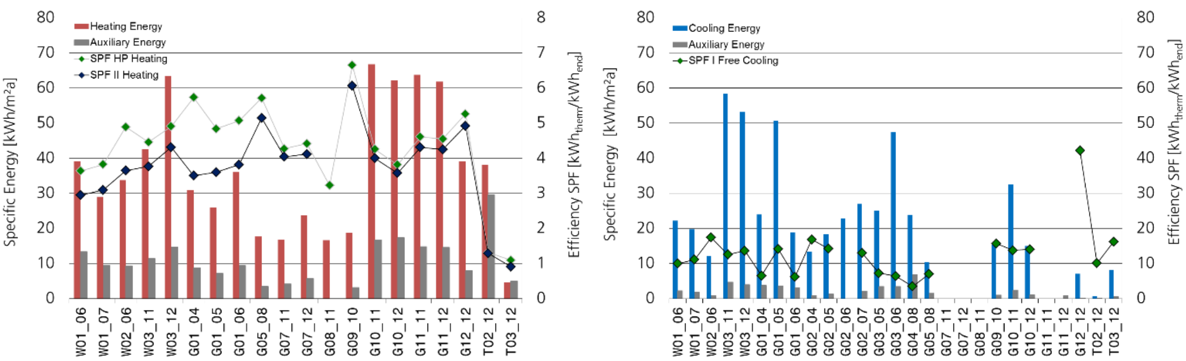


Fig. 23: Heating energy, auxiliary energy and SPF in space heating mode (left) and cooling energy, auxiliary energy and SPF in free-cooling mode (right) for monitored low energy office buildings in the German long term monitoring (Kalz et al., 2015)

Fig. 23 right shows the SPF I in the boundary of the source system in cooling mode, i.e. the performance of a free-cooling operation is depicted. The degree of coverage in free-cooling mode of 40-80% is reached. The seasonal performance factors are in the range between 3.5 and 42.1 kWh_{th}/kWh_{el} as depicted as green diamonds in Fig. 23 right.
On the other hand, also 16-56% of active cooling by reverse operation of the heat pumps were registered in systems with lower supply temperature requirements below 15 °C for the cooling operation. The respective seasonal performance factors of the heat pump in active cooling mode are in the range of 2.1 to 5.0 kWh_{th}/kWh_{el}.

1.7 Task 4: Integration of nZEB into the energy system

With the local energy production at the building site, the building gets a new role in the energy system. Besides the sole energy consumption, the building also acts as an energy producer what is often called a “prosumer”. By the installed energy storages and the building structure, the building can furthermore also store energy. In the future nZEB will get more widespread and can provide operation reserve for the so-called intelligent (smart) electricity grid. Therefore, the integration of nZEB into the connected energy grids gets an increasingly important aspect.
Within the framework of Task 4, options of load management to optimise the self-consumption of the generated PV-electricity were analysed both in simulations and as evaluation of field monitoring projects.

1.7.1 Evaluation of self-consumption in Swiss field monitoring objects

In two Swiss monitoring projects evaluations of self-consumption were performed. The options to increase local energy by load shifting have been investigated. Fig. 24 left shows the evaluated load shifting options in a MINERGIE-P-Eco® certified small multi-family plus energy building in Rupperswil. The all-electric building includes three apartments with an energy reference area of 396 m². The building is equipped with a 20 kW_p solar PV system (projected annual yield of 18,000 kWh/(m²a)) and an 8.9 kW B/W heat pump which uses a 180 m deep borehole heat exchanger as source. The heat pump with an electricity amount of about 27%, the shared electric car, which can be rented by the inhabitants or via a car-sharing service, and the dish washer with around 5% were identified as shiftable loads. By these load shifting option, mainly from the heat pump, a rise in the self-consumption of 10-15% could be evaluated, reaching a self-consumption of more than 30%, which is a good value for residential use.

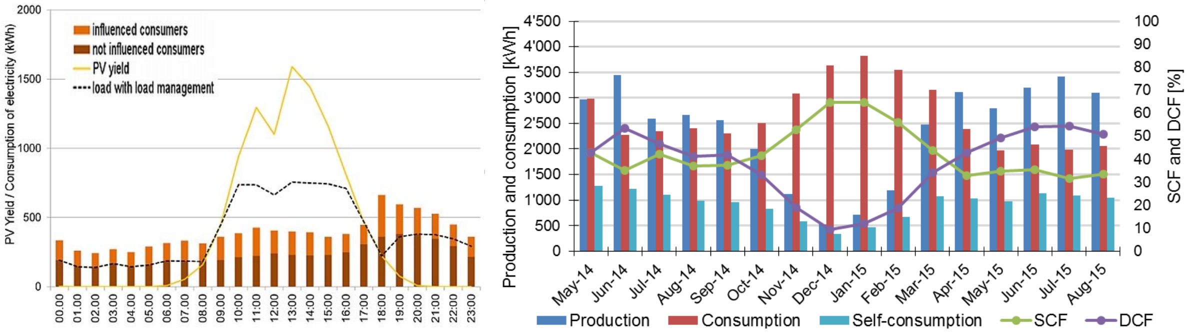


Fig. 24: Load shift in a multi-family building in Rupperswil (Dorusch et al., 2014) and load cover and supply cover factor of the MINERGIE-A® building with office use in Uster (Hässig et al., 2015)

Another evaluation of the self-consumption was accomplished at a MINERGIE-A® certified building in the centre of Uster. The building is one of the first MINERGIE-A® certified buildings with mixed residential and office use and is therefore used as a pilot project to further develop the MINERGIE-A® label for non-residential buildings. The energy reference area of the office part is around 30% of the whole energy reference area. The core component of the building technology is a 33.1 kW heat pump (at test point B0/W35) for space heating and DHW, which uses 11 boreholes of 79 m depth as source, and a 23.9 kW_p PV system. The evaluation of the first year of operation results in a MINERGIE-A® weighted delivered energy balance of -7.9 kWh/(m²a), which means the net zero energy balance regarding the building technology is surpassed. The SPF for the year 2015 has reached a value of about 4.3, the free-cooling operation in summer an SPF around 15. Potentials for optimisation have been identified by the field monitoring, so an increase of the seasonal performance factor in the second year of operation is expected. The office use is also interesting regarding the self-consumption due to a good load match of the PV production and office working hours during the day, which leads to self-consumption around 40% without particular load match measures. Fig. 24 right shows the monthly energy values of consumed and produced energy and the evaluation of the supply cover factor and demand cover factor on a monthly basis.

1.8 Conclusions

Nearly or Net Zero Energy Buildings are the target of political strategies for the next generation of high performance buildings. Heat pumps are already integrated in building concepts of built nZEB. The energy balance for smaller residential buildings is mostly met by PV-systems, in bigger residential buildings and office buildings, district heating and CHP are used as well.

Although there are already several hundreds of nZEB built, most of them are built as prototypes and pilot and demonstration (P&D) projects. These often use a variety of building technologies with the combination of PV-generators in order to evaluate the impact on a nearly zero energy balance. The prototypes help to gain experience with the operation of nZEB and allow the characterisation of the specific technologies.

Furthermore, there is not yet a consistent definition for nZEB and therefore, different levels of ambition exists in regard to requirements for generated energy for the zero energy balance.

Hence, these pilot buildings are not optimised regarding design of the components and cost, and tend to be still expensive buildings due to the use of PV.
As archetype of built nZEB, so called “All Electric Buildings”, that only use electricity as delivered energy, have established on the market. The heating systems in these buildings are heat pumps, i.e. heat pumps and PV are already a kind of standard combination in nZEB.
In Annex 40, heat pump concepts for nearly zero energy applications were analysed in the framework of case studies and monitoring projects. Moreover, prototype technologies were tested in laboratory and in field monitoring and further developed by the lab and field results.
The results of simulations as well as field experience confirm that heat pumps reach a good performance for the application in nZEB and are favourable regarding to life-cycle cost compared to other heat generator technologies. In Annex 40, also development of design tools for heat pumps in nZEB have been started, although these developments have not yet finished.
Furthermore, some development potentials regarding cost-optimised systems as well as improved self-consumption have been identified. An improvement of on-site electricity use can be achieved by load shifting and storage integration, which has been evaluated by simulations and field measurements.
Second to the household electricity consumption, heat pumps are the biggest electricity consumers in the buildings, which leads to opportunities of a higher self-consumption of on-site PV-electricity by adapted operation times of the heat pump.
Indeed, an additional criterion for future building technology could be the possible self-consumption and thereby provided flexibility for the connected energy systems, respectively. Further research issues in that sense are the investigation of optimal design of heat pump systems regarding performance, costs and flexibility of the building system technology. It should be assessed which designs lead to cost-optimised system solutions, which are also capable to perform system services in order to work in synergy with the connected energy grids. Thereby, the requirements to future system technology may get wider and more complex and heat pumps may also enable grid-supportive operation due to the link between the electric and thermal infrastructure for a flexible operation of the building technology. Under these boundary conditions, an integration of storage systems – with the prognosticated cost degression in the future eventually also electric storage systems – and solar technologies can yield further performance and cost advantages.
Moreover, there is a trend to extend the considerations from single buildings to groups of building or whole neighbourhoods for the energy balancing and rating. This perspective broadens the scope of nearly Zero Energy Buildings, and system technologies which can use synergies of different load structures in larger energy systems are an interesting aspect for further investigations. Also in larger energy systems heat pumps can play an important role enabling on the one hand decentralised temperature adaptations to the use, but on the other hand also central generation of required building needs, covering different building services in simultaneous operation. Thereby, heat pumps have the advantage to link the different infrastructures of electricity, heating and cooling to enhance a flexible operation on a larger scale. Systems optimisations of the heat pump with other installed generators are promising to increase the overall performance of the single components by optimised operation conditions which should be addressed by future research projects.
Summarising, heat pumps in connection with nearly zero energy buildings will play a particularly important role for a future sustainable energy system with high percentage of renewable energy, which will be required to reach the climate protection target.
The results of the IEA HPT Annex 40 have been summarised in four final reports. Information on the Annex 40 work is contained on the project website at http://www.annex40.net.

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