

## Annex 40

### Heat Pump Concepts for Nearly Zero-Energy Buildings

Task 4: Field monitoring projects and integration of nZEB into energy systems

Final Report

Operating Agent: Switzerland

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## **Preface**

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

## **The IEA**

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

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

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the Heat Pumping Technologies Programme. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

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

## **The IEA Heat Pump Centre**

A central role within the HPT TCP is played by the Heat Pump Centre (HPC). Consistent with the overall objective of the HPT TCP the HPC seeks to advance and disseminate knowledge about heat pumps, and promote their use wherever appropriate. Activities of the HPC include the production of a quarterly newsletter and the webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the IEA Heat Pumping Technologies Programme and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:

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## IEA HPT Annex 40

## Heat pump concepts for Nearly Zero Energy Buildings



## Heat pump concepts for Nearly Zero Energy Buildings

Field monitoring projects and integration of nZEB into energy systems

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# Imprint

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## **IEA HPT Annex 40 "Heat pump concepts for nearly zero energy buildings"**

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# Abstract

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Since the mid of the 1990ties low energy buildings with a significantly reduced energy consumption down to ultra-low energy standard (typical space heating energy need of 15 kWh/(m<sup>2</sup>a)) have been realised.

Based on the political strategies for the building sector in terms of meeting the Kyoto targets, the buildings concepts are currently extended to derive a nearly zero energy balance, which requires on the one hand an energy-efficient building envelope and on the other hand energy-efficient building system technologies amended by an on-site renewable energy production.

IEA HPT Annex 40 is to investigate heat pumps for the application in nearly zero energy buildings. Due to the unique features of the heat pump, the application in nearly zero energy buildings can be particularly beneficial. Besides the high performance of the heat pump in combination with adapted systems of low supply temperatures, which can be installed in buildings with high performance envelope due to the low space heating loads, also the integration options of heat pumps with other building technologies can be an advantage of the heat pump in these buildings.

In Task 4 of the IEA HPT Annex 40, field monitoring projects of heat pumps in high performance buildings as well as in nearly or net zero energy buildings have been accomplished. Results of the field testing are evaluated regarding:

- Performance of the heat pump operation in nearly or Net Zero Energy Buildings
- Verification of the nearly zero energy balance
- Optimisation potentials for the heat pump operation in low or nearly zero energy buildings
- Performance of the heat pump in multifunctional operation for different building services
- Controller settings in order to improve heat pump operation

In some of the projects, also evaluations of the self-consumption were accomplished, both for residential and for office use. Moreover, tests were made to shift the heat pump operation to times with on-site PV generation. It was found that in residential multi-family use, the self-consumption can be increased by 10-15% to values of more than 30%, which is a high value compared to other evaluations for residential use. Furthermore, it was found that with office use, even values around 40 % self-consumption were reached without particular load shift due to better load match of the on-site generation with office use.

This report on Task 4 covers the results of the different field monitoring projects performed in Annex 40, which are:

- Grid integration of nZEB in Canada
- Long term monitoring of low energy office buildings in Germany
- Demonstration project of an Eco city with demand response in Japan
- Field monitoring in the frame of the “Energiesprong” project to retrofit buildings by the “net zero on the meter” concept in the Netherlands
- Field monitoring results of the first pilot and demonstration nZEB in Norway
- Field monitoring of two nZEB buildings according to the MINERGIE-A® standard with residential and mixed residential and office use in Switzerland





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# 1 Integration of nZEB into the grid in Canada

## 1.1 Integration of nZEB to the grid

Heat pumps have been recognised as a key component in future low energy buildings (IEA Heat Pump Centre, 2012). However, in addition to efficiently integrating renewable energy into the built environment, heat pumps also play a crucial role in the design and optimal operation of buildings within future electrical grids. By linking the thermal and electrical networks of buildings, heat pumps in combination with thermal storage offer significant advantages over more costly and complex electrical storage methods (e.g. batteries). Electricity drawn from the grid or on-site production can be easily converted into thermal energy and stored in the thermal mass of the building or other designated storage devices. This has particularly important implications for buildings with on-site electricity generation, where off-peak generated electricity can be converted to thermal energy and stored for use at a more opportune time.

### 1.1.1 Study framework for building/grid interactions

Research has to date been focused on high performance housing in two Canadian cities: Toronto and Vancouver. The shell of each home was then modified to develop separate high performance housing models for each city. The energy target of each high performance home was an ERS-86 rating on the EnerGuide rating scale (OEE, 2005), which can also be defined as Net Zero Ready (Parekh, 2010). Key building parameters for each region are provided in Tab. 1.

Tab. 1: Key housing characteristics

	Toronto	Vancouver
Roof RSI	8.93 m <sup>2</sup> K/W (R51)	8.93 m <sup>2</sup> K/W (R51)
Wall RSI	5.46 m <sup>2</sup> K/W (R31)	4.48 m <sup>2</sup> K/W (R25)
Basement Wall RSI	4.95 m <sup>2</sup> K/W (R28)	4.95 m <sup>2</sup> K/W (R28)
Basement Slab RSI	2.58 m <sup>2</sup> K/W (R15)	1.86 m <sup>2</sup> K/W (R11)
Window U-Value	1.35 W/(m <sup>2</sup> K)	1.35 W/(m <sup>2</sup> K)
Infiltration (air changes/hour @ 50Pa)	0.60 ACH	1.0 ACH
Electricity Generation	4 kW Photovoltaic	4 kW Photovoltaic

For both homes, the DHW draw was assumed to be 233 l/day. Lighting loads were set at 0.7 kWh/day based on the use of CFL fixtures, while appliances were assumed to use 14 kWh/day based on EnerGuide energy consumption values (OEE, 2005).

All homes were modelled as “grid-tied” systems, in which any generation exceeding the load of the house was exported to the grid. If building loads exceeded generation, any deficit was drawn from the local electrical grid.

#### System Definition

Four distinct HVAC systems were modelled to examine the impact that heat pump and thermal storage technologies can have on the building/grid interaction:

- Base case (electrically heated) with air-conditioning (AC) unit
- Air-source heat pump with auxiliary electric heating (ASHP)
- Ground-source heat pump in water-air configuration (GSHP-WA)
- Ground-source heat pump with radiant floor distribution (GSHP-WW)

For all cases, the above ground floors were maintained at 21 °C in heating, and 23 °C in cooling operation, while the basement was maintained at a minimum temperature of 16 °C.

Tab. 2 summarises key components and rated Coefficients of Performance (COP) for each mechanical system (Daikin 2015, Carrier 2011a, Carrier 2011b, Daikin-McQuay 2012, McQuay 2011). Rated COP values are provided at AHRI standard conditions for air-source and ground-loop heat pumps.

Tab. 2: HVAC system summary

	Base	ASHP	GSHP-WA	GSHP-WW
Heating	Electric Baseboards	HP (COP 3.0)	HP (COP 3.5)	HP* (COP 3.5)
		Electric Baseboard Auxiliary		
Cooling	AC (COP 3.5)	HP (COP 3.4)	HP (COP 5.1)	AC (COP 3.5)
Notes	Split System AC	Split System HP	Split System HP	Radiant floor (Basement, 1 <sup>st</sup> , 2 <sup>nd</sup> )
	On/Off control	On/Off control	Capacity control	Buffer tank (1.5 m <sup>3</sup> )
				Capacity control (HP only)

\*The GSHP-WW HP is equipped with a smaller HP (1.0 ton vs. 2.0 ton) because of the additional thermal storage used in the system

### 1.1.2 Impact of heat pumps on building/grid interactions

Tab. 3 summarises the performance of each system on an annual basis. As expected each heat pump system offers a substantial reduction in the energy use for space heating in comparison to the base case. What is more interesting from a grid interaction perspective, is the relationship between PV generation, consumption, and export to the grid. An analysis of these results shows, that although PV only generates a small fraction of the energy needs of the house (23-34 %), most of the PV generated electricity is exported to the grid (55-65 %). This is because times of peak PV generation (mid-day, summer months) do not coincide with the periods of intensive energy use in the house. Load mismatch is particularly pronounced in the winter months, where thermal demands on the HVAC system peak during the evening and nighttime when PV generation is at a minimum.

Tab. 3: Total system energy use & PV generation

	Toronto				Vancouver			
	Base	ASHP	GSHP-WA	GSHP-WW	Base	ASHP	GSHP-WA	GSHP-WW
Heat [kWh]	6,930	4,340	2,243	1,675	6,679	2,516	1,675	1,464
Cool [kWh]	1,073	1,015	306	1,139	818	804	290	902
Fans + Pumps [kWh]	1,029	1,082	1,350	1,562	1,016	1,072	1,284	1,754
DHW [kWh]	4,652	4,652	4,652	4,659	4,379	4,374	4,374	4,383
Light + Appliances [kWh]	4,514	4,514	4,514	4,514	4,514	4,514	4,514	4,514
Total Use [kWh]	18,198	15,603	13,064	13,549	17,406	13,279	12,136	13,017
PV Generation [kWh]	4,267	4,267	4,267	4,267	4,081	4,081	4,081	4,081
PV Generation / Total Use [%]	23.4 %	27.3 %	32.7 %	31.5 %	23.4 %	30.7 %	33.6 %	31.4 %
PV Export to Grid [kWh]	2,364	2,443	2,679	2,352	2,350	2,468	2,654	2,317
PV Consumed Locally[kWh]	1,903	1,825	1,588	1,915	1,731	1,614	1,427	1,765
Percentage PV Exported [%]	55.4 %	57.2 %	62.8 %	55.1 %	57.6 %	60.5 %	65.0 %	56.8 %

### 1.1.3 Seasonal system performance

In order to more closely assess and compare each system, an analysis was performed on HVAC system power (heat pumps, pumps, fans, auxiliary heaters) over the core heating months (December 1<sup>st</sup> to February 28<sup>th</sup>).

One of the most interesting aspects of the comparisons in Fig. 1 is the presentation of the data spread inherent in each system.

Using the Toronto data as an example, there is a substantial decrease in the data spread (25<sup>th</sup> -75<sup>th</sup> percentile) with the integration of each heat pump system, which can be attributed to the fact that system power use values are significantly reduced by the high efficiencies offered with the heat pump systems.

In both cities, the two GSHP systems offer relatively narrow data ranges, both overall and between the 25<sup>th</sup> and 75<sup>th</sup> percentiles. This represents an ideal trait when examining the system from a grid perspective, as it suggests a minimum of demand fluctuation for the grid.

An analysis of the median value of each heat pump system also reveals an interesting trend. While both GSHP systems offer the greatest peak demand reductions because of their high efficiencies and variable capacity compressors, the median power draw is actually slightly higher than for the ASHP. The use of capacity control in both units results in these systems operating at lower power for a longer period of time, increasing the median electricity imports. This is supported by an analysis of the operating hours of each heat pump during the heating season, which shows that, for instance, the GSHP-WA system operates for 1,521 hours in Toronto (compared to 546 hours for the ASHP) and 1,317 hours in Vancouver (compared to 613 hours for the ASHP). Future work will examine variable capacity air-source heat pumps, as well as the potential of staged baseboard heating.

An additional point that is evident is that the impact of heat pumps appears somewhat smaller when considering the complete performance of the building. In fact, heating and cooling (the primary end uses served by the heat pumps in this study) accounts for only 30 % of total energy use in the studied building. As such, in order for heat pumps to further improve the grid interaction characteristics of buildings, it may be fruitful to consider additional thermal loads, especially domestic hot water draws.

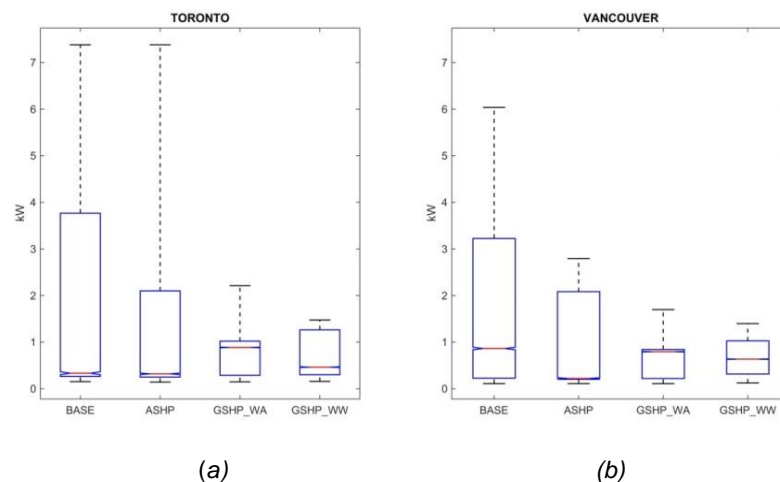


Fig. 1: Box plots of HVAC system power during heating season for (a) Toronto (b) Vancouver



## 2 Long term monitoring of nZEB offices in Germany

### 2.1 Outline

Geothermal heat pumps have reached a high stage of development in residential buildings (single/double family houses and multi-family residencies) and, for applications in new buildings, the market penetration is already large and it is currently developing. The situation for heat pump applications in non-residential buildings is different: they only represent a small share in currently sold heat pumps. If knowledge and confidence in these systems grows, applications could be increased in the future.

In the frame of a long term monitoring of low energy office buildings, which could be transformed into nZEB by adding a further renewable production on-site, were monitored continuously in several projects, namely: EnOB:Monitor, LowEX:Monitor and ModQs as part of the research program “Energy Optimised Buildings (EnOB)”, funded by the German Federal Ministry for Economic Affairs and Energy. Fig. 2 gives an overview on the building sites and types and Fig. 3 left shows the energy consumption and the way to transform the current building performance to NZEB. The evaluation is based on high-quality measurement data collected by universities and research institutes during long term monitoring campaigns.



Fig. 2: Overview of building sites of long term monitored nZEB offices

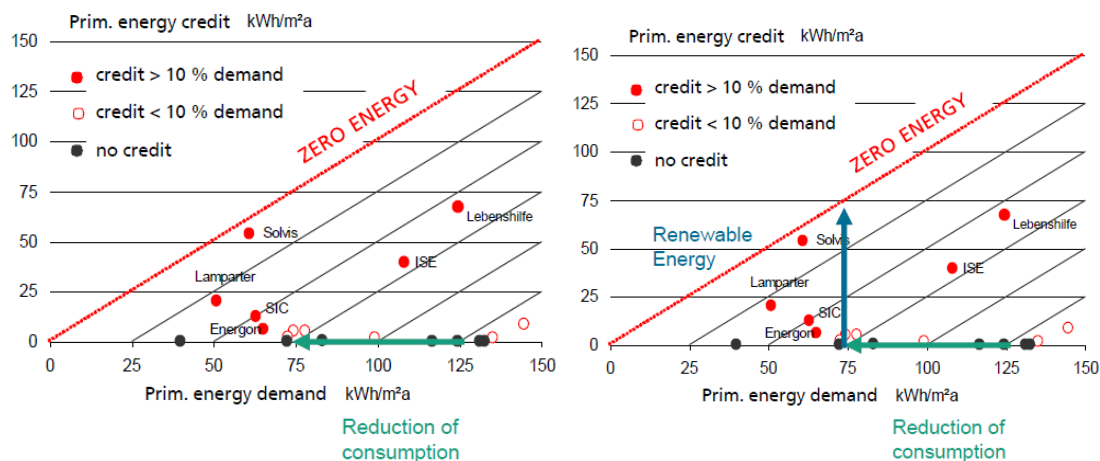


Fig. 3: Energy consumption of some of the long term monitored low energy office (left) and transformation to NZEB (right)

## 2.2 Evaluation methodology

Four balance boundaries were defined as presented in Fig. 4, both, for the system layout on the left and the concept layout on the right. For every balance boundary, the seasonal performance factors are evaluated by relating the thermal energy to the applied end energy for the heat pump and circulating pumps.

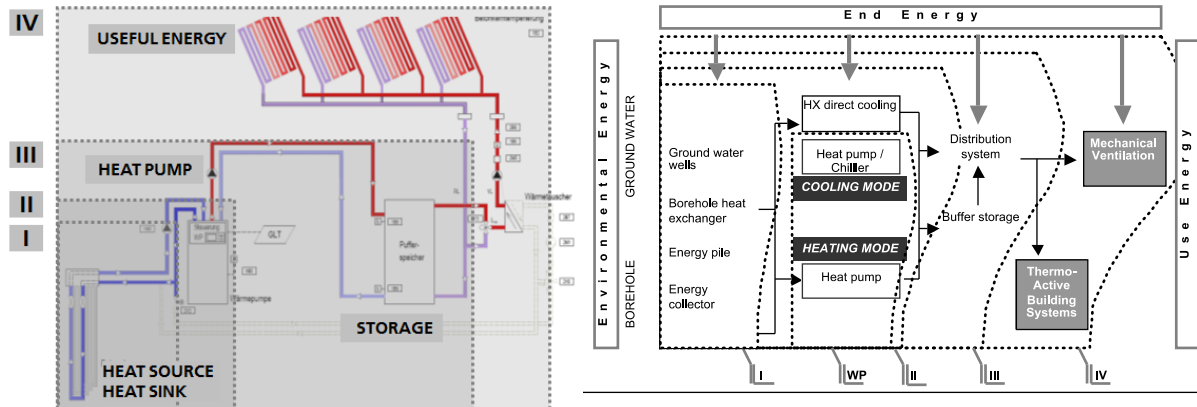


Fig. 4: Definition of balance boundaries for characteristic numbers (left: system-, right: concept layout)

The single boundaries include the following systems. Installed systems in the monitored buildings are summarised in Fig. 5.

- Boundary I considers the thermal energy of the environmental heat source/sink and circulating pumps in the primary circuit (borehole, ground water).
- Boundary HP considers the end energy for the heat transformation without taking the end energy for the circulating pump in the primary circuit into account.
- Boundary II considers additionally to Boundary HP the electrical energy for the primary circulating pump of the heat source/sink.
- Boundary III considers additionally buffer storages (heat storage losses) and the circulating pump for the storage loading.
- Boundary IV considers the whole system also including the circulating pumps in the secondary circuit (heat/cold distribution system on the building side) and thermal energy transferred by the radiant heating and cooling systems (TABS, underfloor heating, etc.) as well as the mechanical ventilation system.

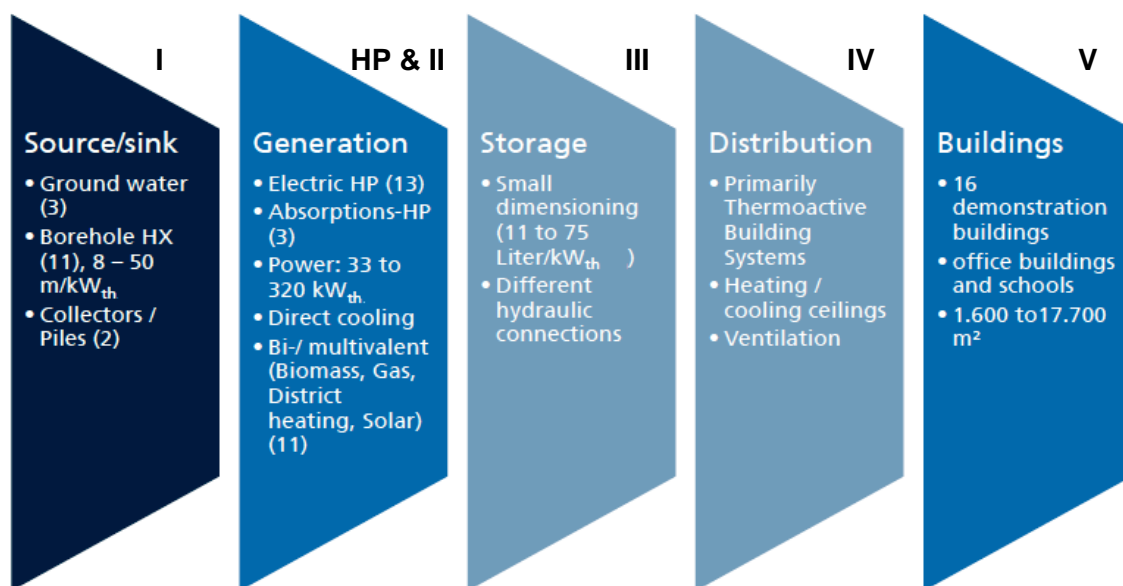


Fig. 5: Overview of installed systems according to the evaluation boundaries

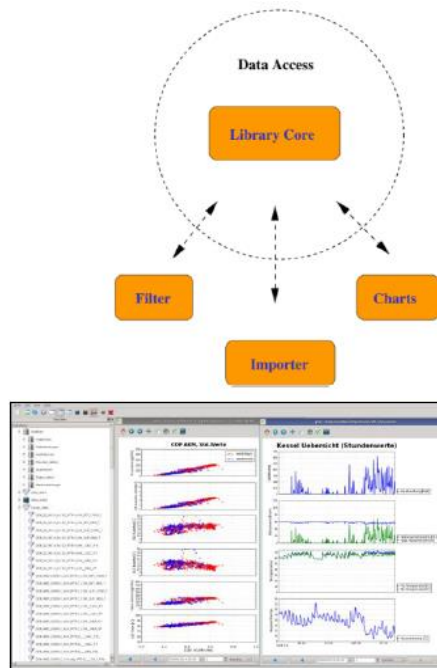


Furthermore, it is distinguished between three operational modes:

- **Heating mode:** Heating energy supply by the heat pump
- **Active cooling:** Cooling energy supply by the heat pump in reverse operation by re-cooling to the environmental heat sink.
- **Direct cooling:** Direct re-cooling to the environmental heat sink without heat transformation in a heat pump in reverse operation or a chiller

If multiple operating modes occur at the same time (e.g. free cooling for the server and heating of the building), the electrical energies are accounted to the respective application according to the ratio of the thermal energies supplied for each operation mode.

## 2.2.1 Measurement concept and data processing



In each building, extensive monitoring-systems have been recording detailed performance data of the heat pump systems. System temperatures, volume flows, supplied heating and cooling energy, electrical consumption of the heat pump, auxiliary energy demand of the pumps, operating times and operation modes of the heat pumps have been monitored with a typical time resolution of 60 seconds to 10 minutes. The various hydraulic layouts and the differences in the exact positioning of the monitoring sensors of each building were taken into account at the first step of the data processing, before all heat pump systems were analysed in a standardised way. The data storage tool has been developed at Fraunhofer ISE and is storing and processing time series data in a database using the HDF5-fileformat. It is based on Python Numpy and PyTables and offers comfortable evaluation of large data of buildings and plants data acquisition systems including import, filtering and visualisation.

Fig. 6: Visualisation data storage tool

## 2.3 Details on monitored buildings

More details on the monitored buildings and installed building system technologies are given in Tab. 4.

### 2.3.1 Buildings and generators

Currently, 16 offices and schools are evaluated, which comprise 15 new and one retrofit buildings, of which three are schools. Floor areas are between 1,000-17,400 m<sup>2</sup>. Five further buildings are to follow.

Heat sources or sinks, respectively, use ground water (W) in three cases, borehole heat exchanger in 11 buildings and ground collectors or piles in two applications (G). Design of the borehole heat exchanger fields show a wide range of 5-50 m/kW<sub>th</sub> of the heat pumps.

The heat pumps have nominal heating capacities from 7-291 kW<sub>th</sub> with one to four compressor stages. 13 buildings are equipped with electrical heat pumps, and three buildings have thermal heat pumps (T), two of them gas-driven. All heat pump systems are used for heating and all include the possibility of direct cooling. Six buildings also use active cooling by the heat pump in reverse operation.

Five systems are designed monovalently, 11 bi-/multivalently in combination with biomass, gas, district heating and solar. Six buildings benefit of waste heat recovery, e.g. from a server room or decoupled from cooling.

Tab. 4: Key facts of the analysed buildings and their energy concepts

	W01	W02	W03	G01	G02	G03	G04	G05	G06	G07	G08	G09	G10	G11	G12	T01	T02	T03
Occupancy	School	Pro-duction	Office												School	Mu-seum	School	Sports hall
Total conditioned area in m <sup>2</sup>	10,700	4,600	1,600	2,100	5,000	100	1,000	4,100	4,900	900	17,400	3,300	2,000	1,800	1,700	3,200	4,440	1,600
HP nominal heat. power in kW	2x135	54	75	57	-	-	33	122	2x112	3x7	291	75	68	64	40	54	75	37
Heat source/sink	Ground Water			Borehole heat exchanger					Energy Piles	Earth Coll.	Borehole heat exchanger							
Heating																Th. HP	Gas-HP	Gas-HP
Direct cooling																		
Active Cooling																		
Waste heat use																		
Storage Heating (l/kW <sub>HP,nom</sub> )	11	0	11	16	0	0	121*	23	7	24	4*	13	29	23	0 / 13	150*	20	65*
Storage Cooling (l/kW <sub>HP,nom</sub> )			15					26	17			15		17		74*		
Multiple heat/cold generators																		

\* shared storage

### 2.3.2 Storage, distribution and emission systems

Installed emission systems sorted by typical temperature levels and type of building (new, retrofit) are depicted in Fig. 7.

The cold supply uses primarily direct cooling. Heat storages are available for all plants, but with very small design of 11-25 l/kW<sub>th,HP</sub>. Hydraulic connections are different, while combined storages connected to multiple heat generators are installed in four plants. Additional cold storages are installed in five plants, with one combined heat/cold storage. The design of the cold storage ranges from 15-75 l/kW<sub>th,HP</sub>.

The prevalent emission systems are thermally-activated building systems (TABS) in form of concrete-core activation and heating-/cooling ceilings with supply temperatures of 23-30 °C. Additionally, ventilation and trench heaters of supply temperatures between 35-48 °C are installed.

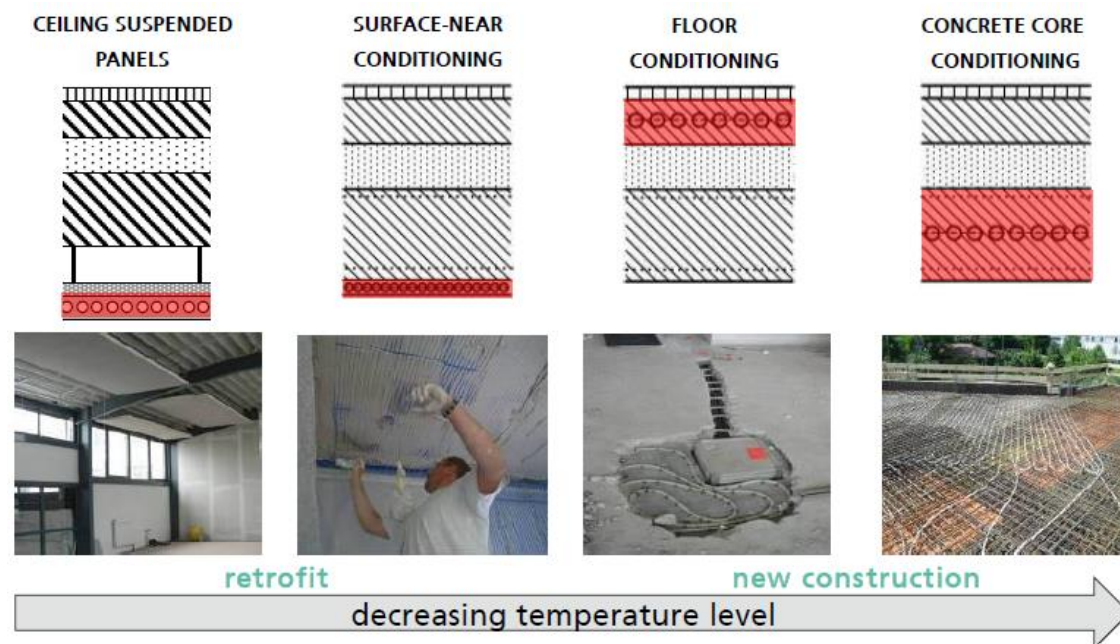


Fig. 7: Distribution systems installed in the office buildings sorted by decreasing temperature level

## 2.4 Monitoring results for space heating operation

The heat pump systems have been monitored in high temporal resolution over several years of operation. The comprehensive and comparative results of the field monitoring projects are presented in the following.

### 2.4.1 Boundary I: heat source/sink and primary pump



In boundary I (only heat source/sink and primary pump), the systems reach seasonal performance factors (SPF) between 2.9 to 61.7  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$  in heating mode, see Fig. 8. Reasons for low efficiencies are long operation periods or even constant operation of the primary pumps, unmatched volume flows of the individual boreholes, as well as unfavourable hydraulic layouts and oversized pumps (up to 230  $\text{W}_{\text{el}}/\text{kW}_{\text{th}}$ ). High efficiencies in boundary I can be reached with well-designed hydraulics and correctly designed high-efficiency pumps (see buildings G09 to G12 in Fig. 8).

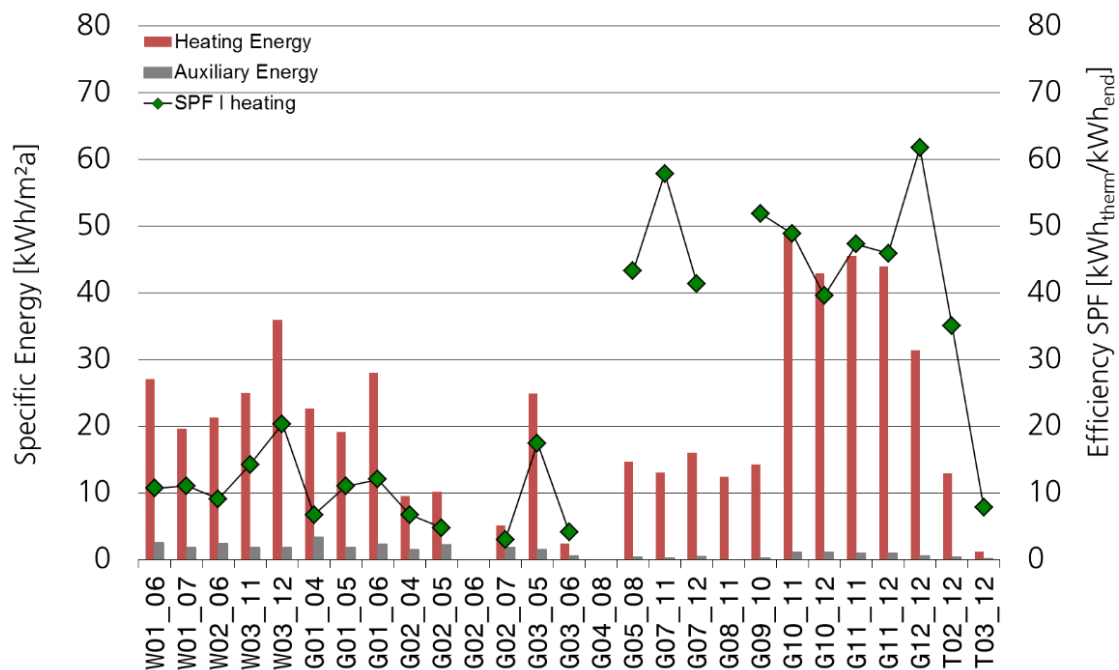


Fig. 8: Specific energies and SPF for boundary I in heating mode. Abbreviations: ground water (W), ground (G), thermal (T). The number after the building name represents the operation year.

### 2.4.2 Boundary HP: heat pump without primary pump



The heat pumps themselves (without accounting the primary pump) reach seasonal performance factors between 3.2 and 6.7  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$  for electrical heat pumps and 1.1 to 1.3  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$  for gas driven heat pumps (green diamonds in Fig. 9). The significant differences in efficiency of the individual systems are mainly due to the different temperature differences between primary and secondary side, which are given on the secondary side by the type of heating distribution systems and by the hydraulic layout. The use and optimised operation of low-temperature distribution systems result in a high energy efficiency of the heat pump of 4.8 to 6.7  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$  (Fig. 9: Buildings G01, G05, G09). On the contrary, for example at the building G10, the heat storage both supplies the concrete core conditioning system (required set point temperature of 27 to 30 °C) and the air handling unit (required set point temperature of 40 to 45 °C). Consequently, the heat pump only reached an SPF of 4.0  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$ . In building G12, the different distribution systems are separated hydraulically with respect to their temperature levels, i.e. the concrete core conditioning is connected by switching valves directly to the heat pump, and the air handling unit to the heat storage. This system achieved a SPF of 5.2  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$ .

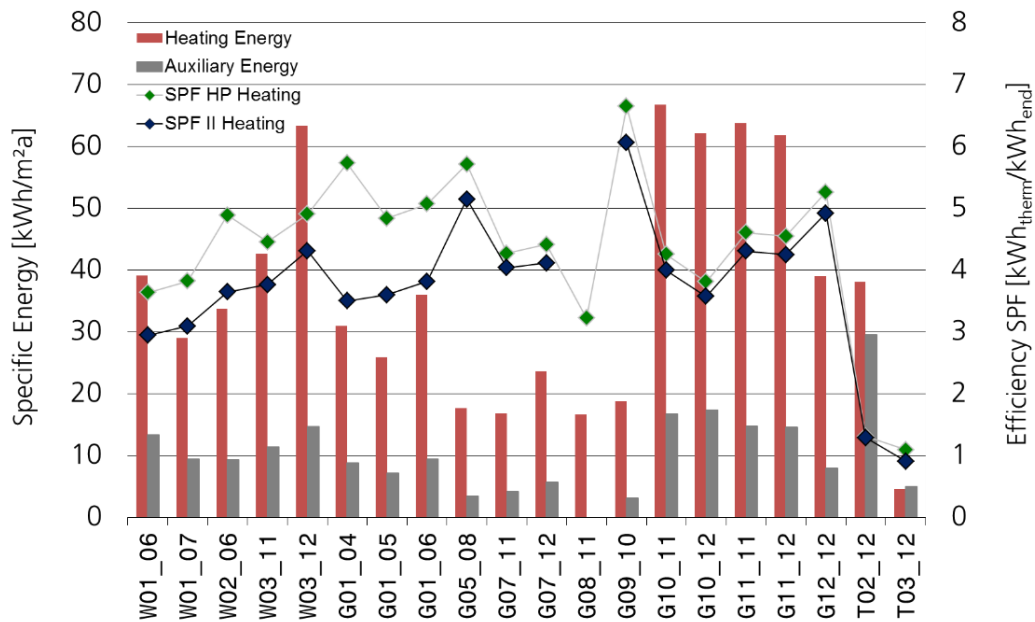


Fig. 9: Specific energy values for boundary II, heating mode. Seasonal Performance Factors (SPF) are displayed for the boundary HP (green markers) and for boundary II (blue markers).

### 2.4.3 Boundary II: heat pump with primary pump



The seasonal performance factor of heat pump system and primary pump (boundary II) range from 2.6-6.1  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$  for electrical heat pumps (blue diamonds in Fig. 9) and 0.9-1.3  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{end}}$  for gas driven heat pumps (blue diamonds in Fig. 9). The electrical energy demand of the primary pump accounts for 6-25 % of the total electrical energy demand in balance boundary II for the heating mode. Thus, depending on the system, it has a significant impact on the overall efficiency. The operation of high-efficiency systems requires a good and careful hydraulic and thermal design of the heat sources. Improper planning (e.g. undisturbed soil temperature, extraction capacity for geothermal probes, possible delivery rates for ground-water) and sizing lead to insufficient heating/cooling capacities and low energy efficiencies, which can hardly be compensated or corrected during system operation.

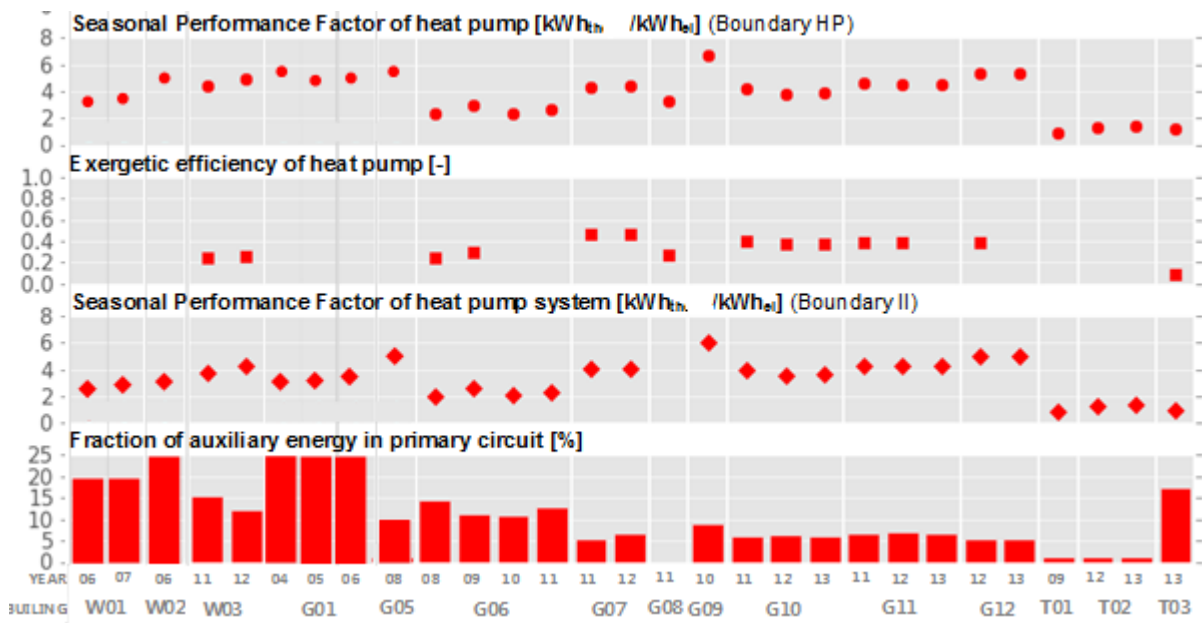


Fig. 10: Analysis of heat pump systems in heating mode: (1) seasonal performance factor of heat pump, (2) exergetic efficiency of heat pump, (3) seasonal performance factor of heat pump system in balance boundary II, (4) fraction of auxiliary energy in primary circuit.



For example, in the buildings W03, G05 and G09, the entire system (heat pump, borehole heat exchangers, storage and pumps) is a complete package in which the individual components are already well matched by the manufacturer. The thus achieved quality assurance in planning, design and installation allows a significant increase of efficiency to 3.8 kWh<sub>th</sub>/kWh<sub>el</sub> (groundwater) and 5.1- 6.1 kWh<sub>th</sub>/kWh<sub>el</sub> (soil). In addition, this complete system also allows for a dual operation mode, in which the heat pump can provide heating and cooling energy simultaneously. For primary energy analysis, the cumulative primary energy consumption (CEC) was used, as this factor includes the whole upstream conversion chain, including e.g. also the energy needed to construct the power plants. This analysis shows that the electric heat pumps (1.3-2.8 kWh<sub>th</sub>/kWh<sub>prim</sub>) even at today's electricity mix in Germany are significantly more efficient than gas heat pumps (0.9-1.1 kWh<sub>th</sub>/kWh<sub>prim</sub>) (CEC: electricity 2.19, natural gas 1.12 kWh<sub>prim</sub>/kWh<sub>end</sub>).

Fig. 11 shows an analysis of the heat pumps G09 with an SPF of 6.1 and G06 with an SPF of 2.6 regarding temperature differences in the primary and secondary circuit and the temperature lift as temperature differences in the primary and secondary circuit. While the G06 system has smaller temperature difference in the primary circuit, the system G09 shows a stable temperature difference in the range of 4 K. The temperature lift also shows a clear difference: The system G09 has a stable temperature lift in the range of 20 K between the primary and secondary circuit, while the poor performance correlates to a temperature lift of around 40 K, so nearly twice.

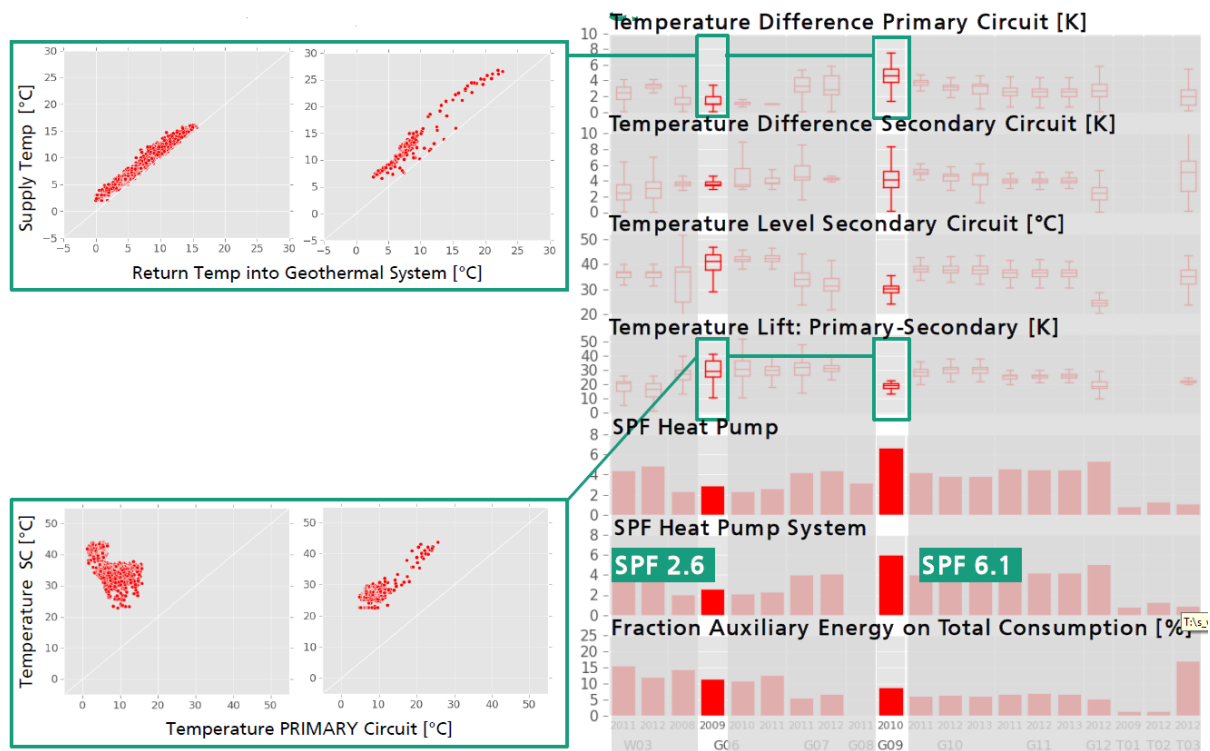


Fig. 11: Comparison of temperature conditions for two heat pumps with poor and excellent performance values

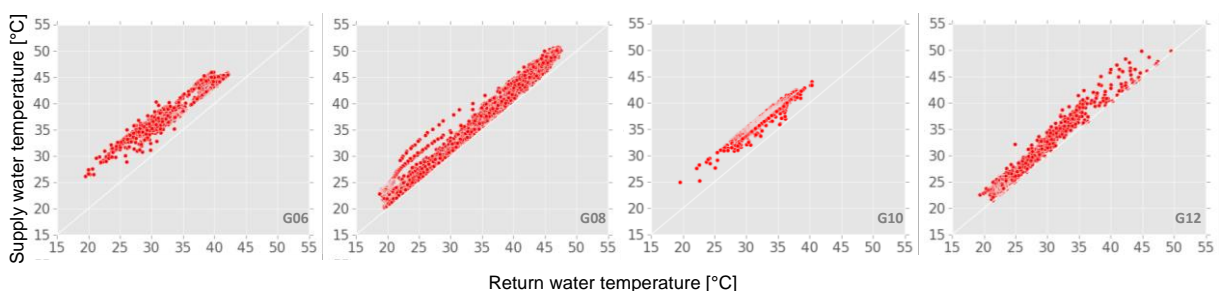


Fig. 12: Analysis of temperatures in the secondary circuit in the heating mode: supply vs. return temperature. Results are presented for four ground-coupled heat pump systems.

## 2.5 Monitoring results for space cooling operation

### 2.5.1 Boundary I: heat source/sink and primary pump



In boundary I (only heat source/sink and primary pump), which corresponds to a direct cooling operation in cooling mode, the systems reach seasonal performance factors (SPF) between 3.5 and 42.1  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$  in direct cooling mode, see Fig. 13.

Reasons for low efficiencies are long operation periods or even constant operation of the primary pumps, unmatched volume flows of the individual boreholes, as well as unfavourable hydraulic layouts and oversized pumps (up to 230  $\text{W}_{\text{el}}/\text{kW}_{\text{th}}$ ). High efficiencies in boundary I can be reached with well-designed hydraulics and correctly designed high-efficiency pumps (see buildings G09 to G12 in Fig. 13). The target value of 20, however, is only reached by three systems. For the building G10, for instance, an optimised control of the primary volume flow rate according to the temperature difference leads to a decrease of the electrical energy consumption of more than 50 % and an improvement of the depicted SPF of 14  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$  to 30  $\text{kWh}_{\text{th}}/\text{kWh}_{\text{el}}$ .

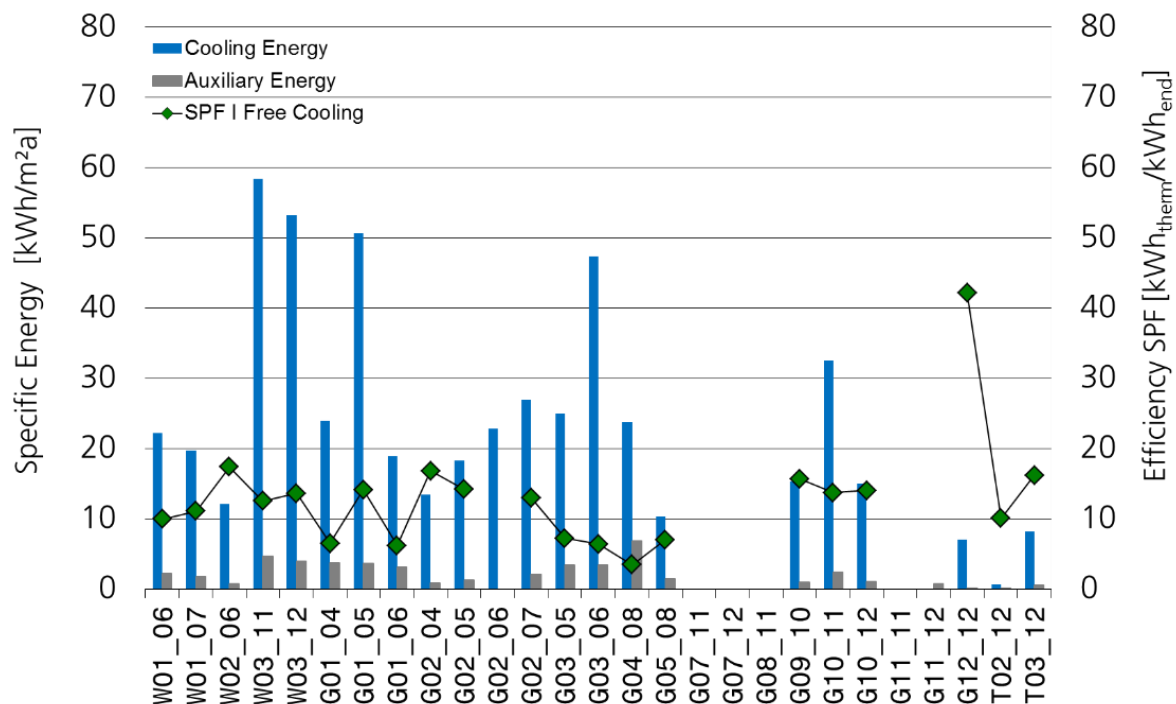


Fig. 13: Specific energies and SPF for Boundary I in free cooling mode. For the buildings G07, G08 and G11 no monitoring data is available for the free cooling system.

Fig. 14 return temperature to the ground heat exchanger for the space cooling operation of four buildings.

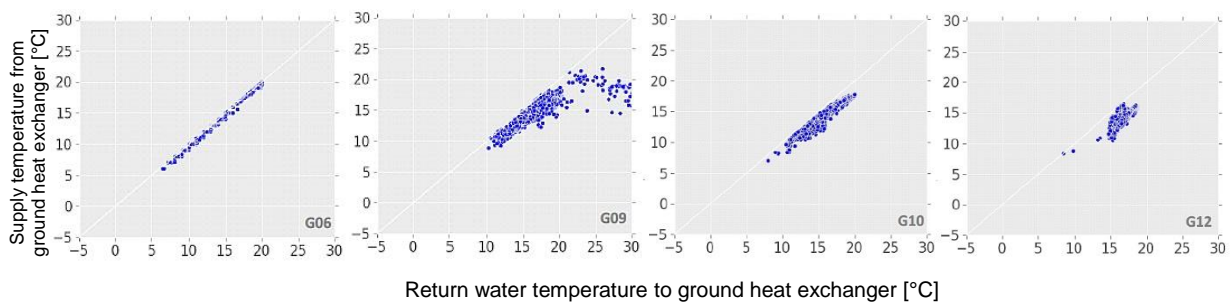


Fig. 14: Supply water temperature vs. return water temperature of the ground heat exchanger for four ground-coupled systems in cooling mode.

## 2.5.2 Boundary II: Heat Pump with Primary Pump



Fig. 15 gives an overview of the results for the cooling mode according to the different boundaries. The fraction of active cooling with the heat pump in reverse operation are between 16-56 %, depending on necessary supply water temperature level. The SPF in the boundary HP in active cooling mode is in the range of 2.5 – 6. If the boundary is enlarged to the boundary II of the heat pump system, i.e. including the primary pump, the SPF in active cooling mode decreases to 2.1 - 5.0 kWh<sub>th</sub>/kWh<sub>el</sub>.



Fig. 15: Evaluation of cooling energy and fraction of active cooling as well as SPF according to boundary I, HP and II for the analysed systems

In the investigated buildings, a low-ex approach is applied, since temperatures range from 16-20 °C and are therefore quite high for the cooling modes. In buildings with an SPF < 4, though, the temperatures in the secondary circuit are quite low with 10-15 °C, so the performance is limited. In buildings with an SPF > 5 the temperatures in the secondary circuit are between 15-19 °C.

In building W03, for instance, the supply temperature of the secondary circuit is 12 °C, and 57 % of cooling energy is produced by active cooling, while in buildings G09, the supply temperature in secondary circuit is 15-19 °C, and the fraction of active cooling by the heat pump is only 16 %. The overall SPF of direct cooling and active cooling operation of the systems is in the range of 3.4 – 12 kWh<sub>th</sub>/kWh<sub>el</sub>.

## 2.5.3 Control of the heat pump operation

Most of the analysed heat pumps have the possibility to operate at different power levels, e.g. by activating only one or two of several compressors. But, the measurement data show that this possibility is often not used in its full potential: The heat pumps switch to the maximum power level too quickly and too often, and thus turn off after a short running time. At one building, the control of the heat pump allows multiple power stages, but this setting just was not activated by the user.

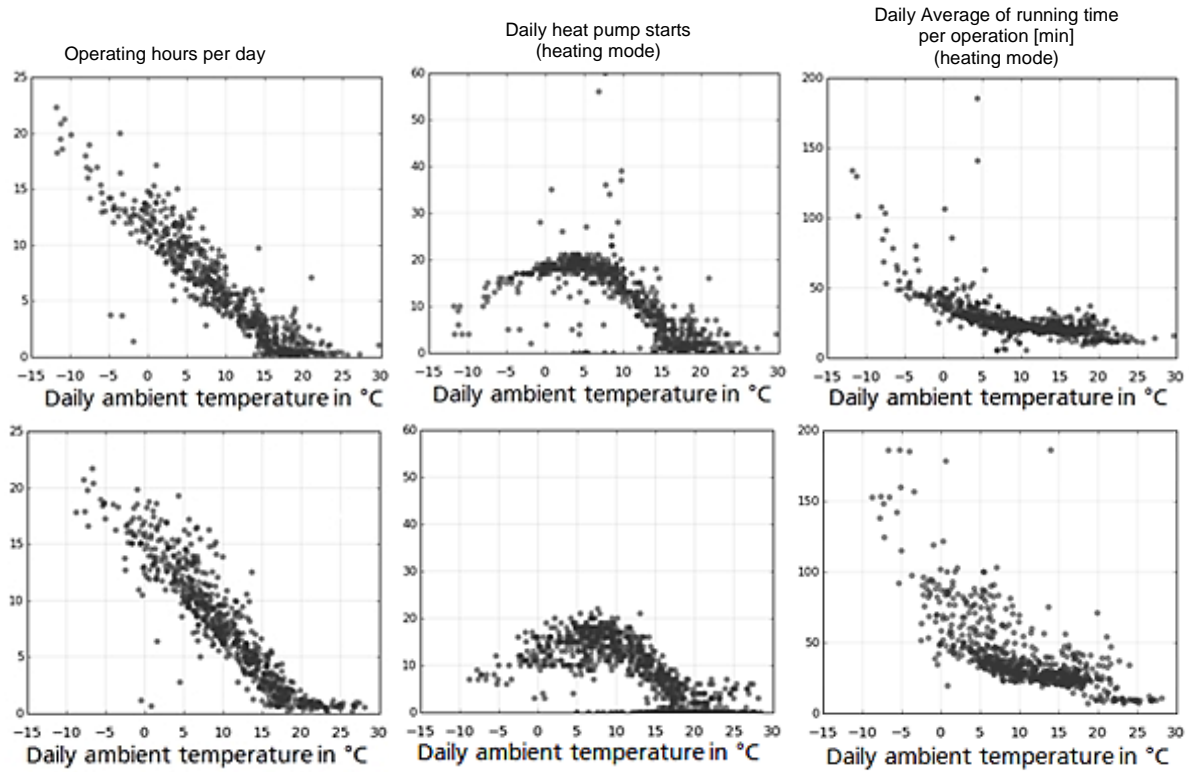


Fig. 16: Operational analysis of two selected buildings (heating): Daily operating hours, number of daily heat pump starts and daily average of the timespans the compressor is running per operation.

Fig. 16 shows the operation analysis of two selected buildings. As both their heat pumps operate only at one power level, their daily running time of up to 23 hours indicates that they are well designed for the heating demand of the building. It can be observed, that the heat pumps typically turn on 10 to 20 times per day in the transitional period (daily average ambient temperature 0–15 °C), operating for typically 20 to 80 minutes. Furthermore, the following faulty or inefficient operations were frequently observed in the buildings while analysing the monitoring data of the buildings:

- Heating mode operation in summer (Reasons: keeping the hot storage on its temperature level or actual heating of the building).
- Heating and cooling at the same day.
- Distribution systems get the wrong fluid (e.g. in cooling mode, hot water is supplied).
- Circulation pumps are switched on (sometimes 24/7), but none or almost no thermal energy is transported.
- If multiple compressor levels are possible, they are not used in their full potential, or even not activated at all.

## 2.6 Conclusions

The heat pump systems of 16 non-residential buildings have been analysed regarding specific energies and efficiencies using long-term monitoring data with high temporal resolution. Their seasonal performance factors vary between 2.9 and 6.1 kWh<sub>th</sub>/kWh<sub>el</sub> (heating mode, heat pump with compressor and primary pump). This shows the efficiency potential of ground-coupled heat pumps, but also that they are very sensitive to incorrect planning and/or operation. So, to realise the full potential of heat pump systems, several aspects have to be taken into account: Single components (e.g. pipe diameters) have to be dimensioned correctly, target values for the maximum installed power of pumps have to be set during planning phase and distribution systems which permit supply temperatures near room temperature (16 to 20 °C in cooling mode, 28 to 33 °C in heating mode) have to be installed. Further areas of the detailed cross-section analysis of ground-coupled heat pumps in non-residential buildings will be published in the near future.



## 3 nZEB buildings and projects in Japan

### 3.1 ZEB Project at the University of Tokyo

The building was constructed in Komaba campus, one of the three major campuses of the University of Tokyo. The building is called “The building for innovative education”. It has five floors and one underground floor level. The total floor area of the building is 4477 m<sup>2</sup>. It includes several studios and convention rooms such as halls and meeting rooms.

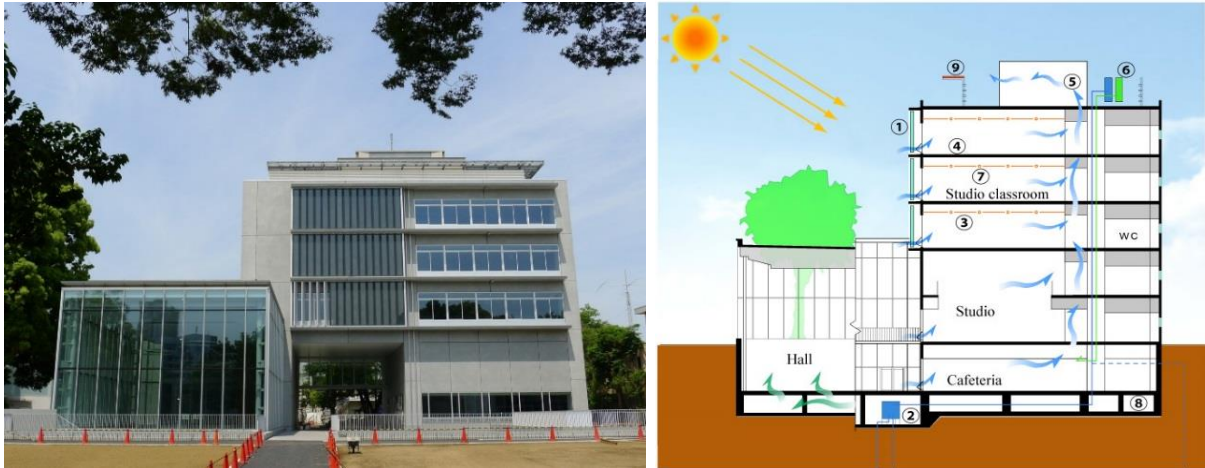


Fig. 17: The building's exterior view (left) and the applied technologies (right)

#### 3.1.1 Heat source system

The heat source system comprises three heat pumps: two ASHP and one GSHP (ground heat and ground water). 10 Boreholes with 100 m depth deliver a heating capacity of estimated 50 kW. A well, which lifts water at a rate of about 100 l/min is installed for the ground water source, the heating power of the ground water source is around 70 kW at a temperature difference of 5 °C.

Cooling energy from the ground water can directly be used for radiant cooling panels without using a heat pump. Tab. 5 shows the properties of the heat pumps.

Tab. 5: Properties of the heat pumps

Heat Pump	Location	Heating ability (rated value)	COP (rated value)
GSHP	Basement floor	121 kW	4.4
ASHP-1A	Rooftop	99 kW	3.0
ASHP-1B	Rooftop	132 kW	3.0

#### 3.1.2 Double skin cladding system

In order to solve the contradicting requirements on selective control of light, heat and airflows, the design team invented and developed a smart double skin cladding system with adaptively movable louvers. Also, there is a distinction between fixed and openable windows.

The unit for openable windows consists of double layered slat panels and a double glazed panel. It can be rolled around the vertical axis. Consequently, both slat panels and glazed panel can face outside/inside selectively depending on outside conditions. In addition, a white coloured side of slat and a black coloured side of slat are also turned around, thus, both sides of slat can face outside selectively, as well.

#### 3.1.3 Radiant cooling/heating panel system

Heating and cooling by radiant panels is a method to heat or cool the occupant directly. It does not need the energy for bringing air and for activating fans. It also avoids needless draft and upgrades comfort. The installed ceiling panels have the function of radiant panels.

However, it is expected that the ability of these radiant panels become short at the peak load or at the start-up. Thus, the system designers combined fan coil units with the radiant panels.

### **3.1.4 LED lighting system and integrated system**

The building embodies integrated control system that maximizes use of natural light and facilitates complementary use of artificial light by LED with dimmer function.

### **3.1.5 PV system**

A photovoltaic system of 300 m<sup>2</sup> of thin-type multi-crystalline Si solar modules is installed on the roof of the building. The maximum capacity of generation reaches 30 kW<sub>p</sub> which is about 10% of anticipated maximum peak load demand of electricity in summer. Annual total electric power generated by installed PV is estimated as 300 GJ on primary energy basis. Generated electricity is designed to be used in the building (i.e. PV here is separated from network). The building also embodies a continuous monitoring system to measure site based real efficiency of the PV.

### **3.1.6 Integrated building operation system**

The building embodies an energy monitoring system based on the idea of an information embedded building; the monitoring system consists of sensors of energy use, temperature, humidity, indoor air quality, illumination intensity etc. The real time basis data is transferred from sensors as digital data to a server which is located off-site.

Furthermore, building, lighting, and air-conditioning are totally integrated and controlled through artificial intelligence (AI).

The previously mentioned louvers in the double skin cladding system moves based on evaluation of the data from a pyranometer; In case the pyranometer would suggest that it is raining or cloudy, louvers moves to introduce maximum quantity of day light to inside. In case it would suggest bright and no direct sun beams, louvers also settle to the direction to introduce natural day light as much as possible. In case of sunny day with direct sun beams that could increase cooling load for instance in summer, the louvers are settled to prevent inclusion of sun beams to the inside of the building. In case that the indoor space is heated artificially, louvers are settled to proactively introduce heat gains. Together and harmonized with the adaptively controlled louver system, the artificial light by LED is controlled. Motion sensors works to switch-off and turn on LED lighting which is controlled to assure sufficient illumination intensity based on illuminometer.

### **3.1.7 Energy performance**

While averaged energy consumption of buildings in the University of Tokyo except for buildings for experiment is 1,830 MJ/m<sup>2</sup>/a (508 kWh/m<sup>2</sup>/a), the measured energy consumption of this building is 666 MJ/m<sup>2</sup>/a (185 kWh/m<sup>2</sup>/a), which corresponds to 37% of the averaged value. With considering the energy production of PV power, the net energy consumption is 612 MJ/m<sup>2</sup>/a (170 kWh/m<sup>2</sup>/a), which corresponds to 34% of the averaged value. Although this is still not a net zero energy in the strict sense, it becomes clear that energy performance of this building is very high.

Brand new technologies and methods were developed that would enhance the prospect of fructifying the idea of a real ZEB. Although we conceived these specific to the current building context, it is strongly believe that these could be successfully extended productively, to any other ZEB oriented project. In addition, the design integration method we adopted can be a valuable forerunning prototype for all the subsequent projects of this genre.

The building was fully completed in May 2011. An actual energy performance evaluation of the building against the pre-design ZEB targets is fully completed. Operation and maintainance of the building is committed to cut-down the energy levels. The research on this building is ongoing. Every opportunity to report and disseminate the knowledge obtained from this prototype will be used to propagate the message of ZEB.

### 3.2 Other evaluated buildings

Monitorings were also made in other buildings, which are shortly presented regarding building features and available energy balance data.

### 3.2.1 City Hall at Okinawa Prefecture

The building is the City Hall in Okinawa Prefecture and has a site area of 13,944.8 m<sup>2</sup>, with a construction area of 6,143.2 m<sup>2</sup> and a total floor area of 15,434.8 m<sup>2</sup>. The structure is made of reinforced concrete with precast concrete sections and has six floors above ground. The building was completed in March 2002.



*Fig. 18: The building's exterior view (left), Amahaji style eaves (middle) and perforated PC paneling on western face (right)*

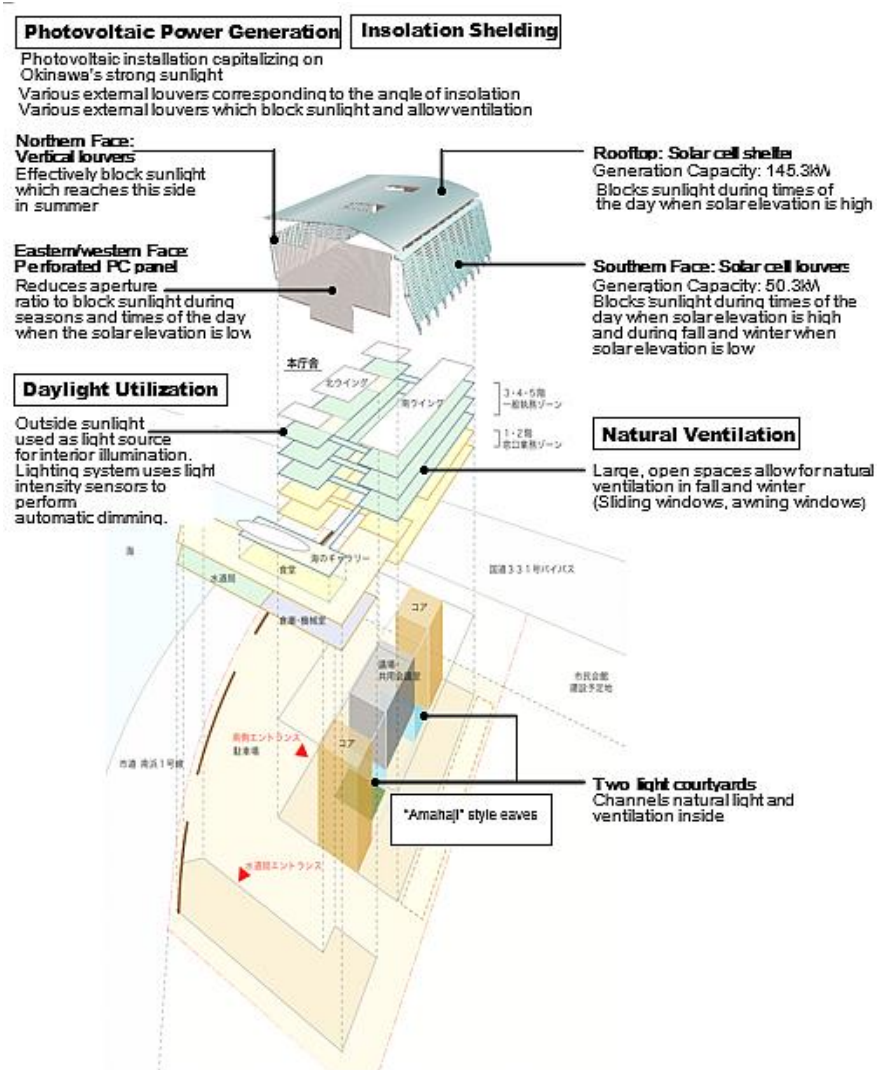


Fig. 19: Environmental friendly technologies in the building concepts

Primary energy consumption was reduced by 22% from 1,477 MJ/(m<sup>2</sup>a) to 1,152 MJ/(m<sup>2</sup>a). This breaks down to 67.8 MJ/(m<sup>2</sup>a) from natural ventilation, 109.7 MJ/(m<sup>2</sup>a) from insolation shielding and control and 138.9 MJ/(m<sup>2</sup>a) from photovoltaic power generation.

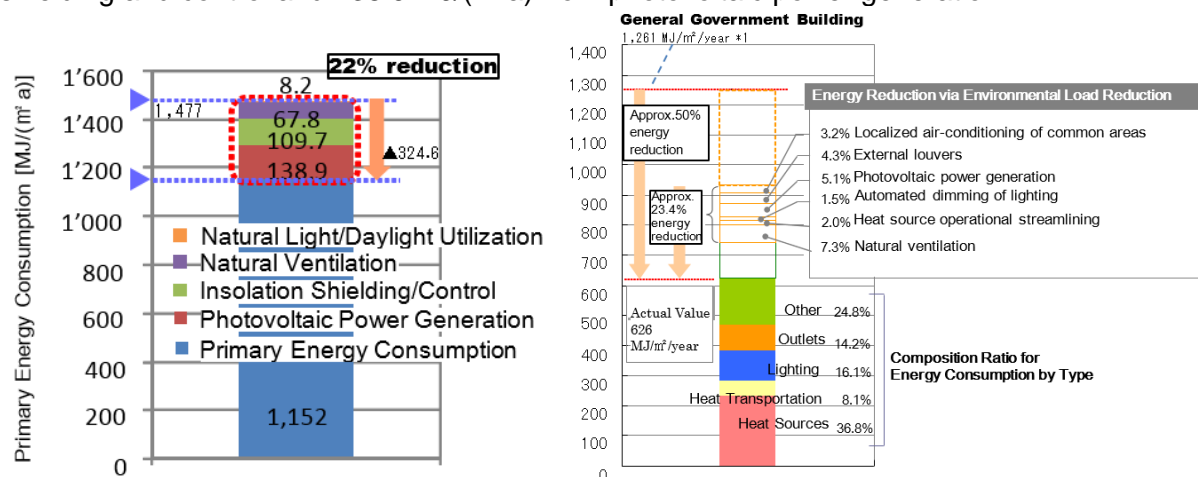


Fig. 20: Primary energy consumption of the Okinawa City Hall (left) and Government building (right)

### 3.2.2 K Government Building at Mie Prefecture



Fig. 21: View of K Government Building

The Building is called K Government building and is located in Mie Prefecture. The total floor area is 9,534 m<sup>2</sup> with four floors above the ground. The building consists of reinforced concrete and pre-cast concrete. It has been completed in 2007.

Fig. 21 show the view of the K Government Building and Fig. 22 the environmental friendly technologies integrated in the building concept. Features of the building are insolation controlled by the use of grating and recycled wood louvers, insolation shielding and diffused light introduced by the use of grating

louvers, insolation shielding and sunlight introduction the use of recycled wood louvers. The office space which is built with precast concrete, and the directly-affixed ceiling enables floor-mounted air outlets to provide air-conditioning. The construction incorporates a wireless control system and an environmental design has been applied, which takes full advantage of natural wind and light.

The construction incorporates an observation tower to facilitate natural ventilation, and by adoption of skylights natural lighting and ventilation is facilitated. Localized air-conditioning of areas with open ceiling space is emitted into the rooms by the use of radiative cooling and heating panels. Additionally, a localized air-conditioning of only reservoir space for open ceiling space areas is integrated. The adoption of radiative heating and cooling panels which also provide dehumidification, is made.

Primary energy consumption for the main building is approximately 626 MJ/(m<sup>2</sup>a). When compared with the standard for a general building (1,261 MJ/m<sup>2</sup>a), this is an effective reduction of roughly 50%. In addition, approximately 23.4% of this reduction comes from environmental load-reduction approaches including natural ventilation. The primary energy balance of the building is given in Fig. 20 right.



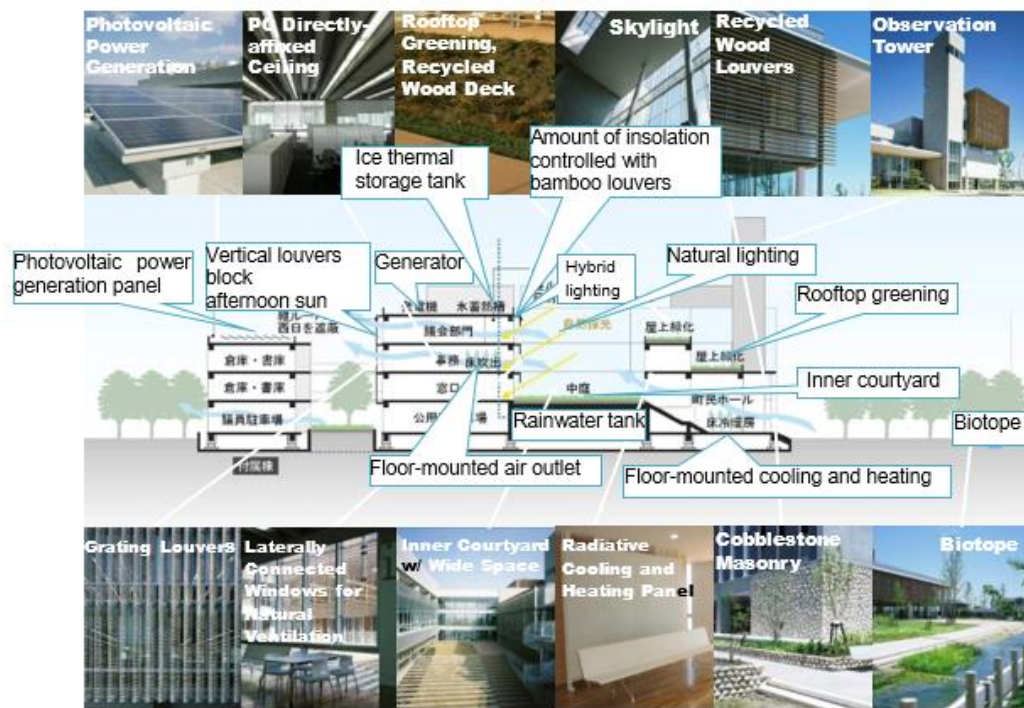


Fig. 22: Environmentally friendly technologies applied in the K Government building

### 3.2.3 Technical Research Institute at Tobitakyu, Chofu City, Tokyo



Fig. 23: View of the Technical Research Institute in Tobitakyu, Chofu City, Tokyo

The Technical Research Institute is located in Tobitakyu, Chofu City in Tokyo. It has a target site area of 5,256.7 m<sup>2</sup>, the total floor area is 8,812.2 m<sup>2</sup> and the construction area 2202.4 m<sup>2</sup>. The building has five floors above ground, one floor below the ground and the rooftop level. The total height is 18.14 m. The structure is made of reinforced concrete, and the building has been constructed in the period of April 2010 - October 2011.

The building is equipped with ductless air-conditioning utilizing flat slab construction. A streamlined interior planning integrating construction, facilities and building structure (floor-less and ceiling-less office area) has been applied. It is further equipped with a task/ambient air-conditioning.

Annual CO<sub>2</sub> emissions for this building (for twelve months from November 2011) are 38.2 kg-CO<sub>2</sub>/(m<sup>2</sup>a). Compared with the average for Tokyo, which sums up to 100 kg-CO<sub>2</sub>/(m<sup>2</sup>a), this is a reduction of 61.8%. This is, it is even lower than the 50 kg-CO<sub>2</sub>/(m<sup>2</sup>a) target set during the building design phase. Fig. 23 shows the front view and the side view of the building and Fig. 24 shows the different technology implemented in the energy concept of the building.

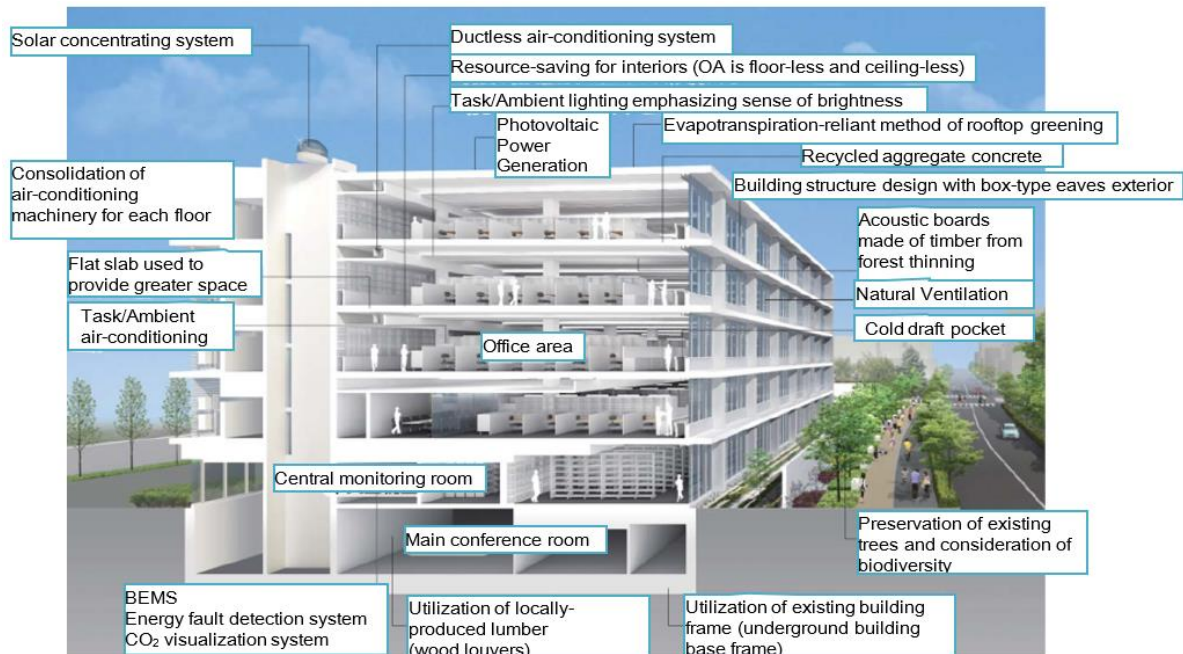


Fig. 24: Environmentally friendly technologies applied in the Technical Research Institute

### 3.2.4 Construction Firm Headquarter at Chuo-ku, Tokyo



The building height is approximately 110 m and located at Chuo-ku, Tokyo. The site area is approx. 3,000 m<sup>2</sup> and the construction area about 2,200 m<sup>2</sup>, while the total floor area is about 51,800 m<sup>2</sup>. The structure is made of reinforced concrete with three floors below ground and twenty-two floors above ground.

The target for building CO<sub>2</sub>-emissions, chosen during building planning in 2009, was to reduce emissions by 50% compared with the 2005 average emissions level for Tokyo office buildings (99 kg-CO<sub>2</sub>/m<sup>2</sup>a). At the time of its completion in 2012, emissions had been reduced by approximately 62%. Furthermore, a goal has been set to reduce emissions by 70% in 2015 which, when combined with CO<sub>2</sub> credits created in-house, will achieve zero carbon status for the building. Fig. 25 shows a front view and the properties of the innovative façade.

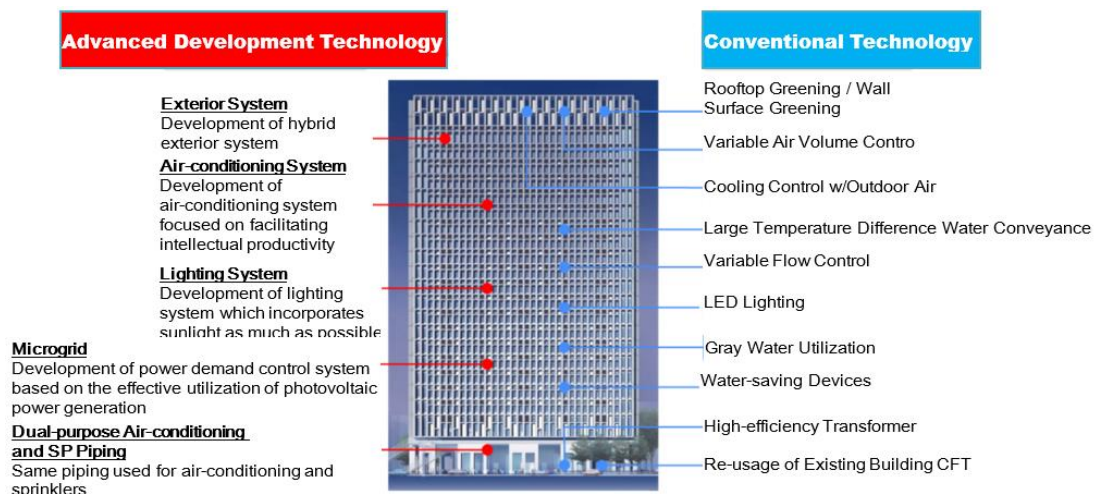


Fig. 25: Innovative façade characteristics of the Construction Firm Headquarter



### 3.2.5 Construction Technology Institute at Kiyose-city, Tokyo



Fig. 26: Construction Technology Institute

The building is located at Kiyose-city in Tokyo and has a construction area of 3,370 m<sup>2</sup> and a total floor area is 5,532 m<sup>2</sup>. It serves as laboratory and has also office spaces. The 3-storey building has a structure which is made of steel frame. The building has been completed in September 2010 and has a CASBEE rating CASBEE-EB Rank-S, BEE7.0 and reached the LEED Platinum (95 points) label. Fig. 27 show the applied passive and active as well as management methods.

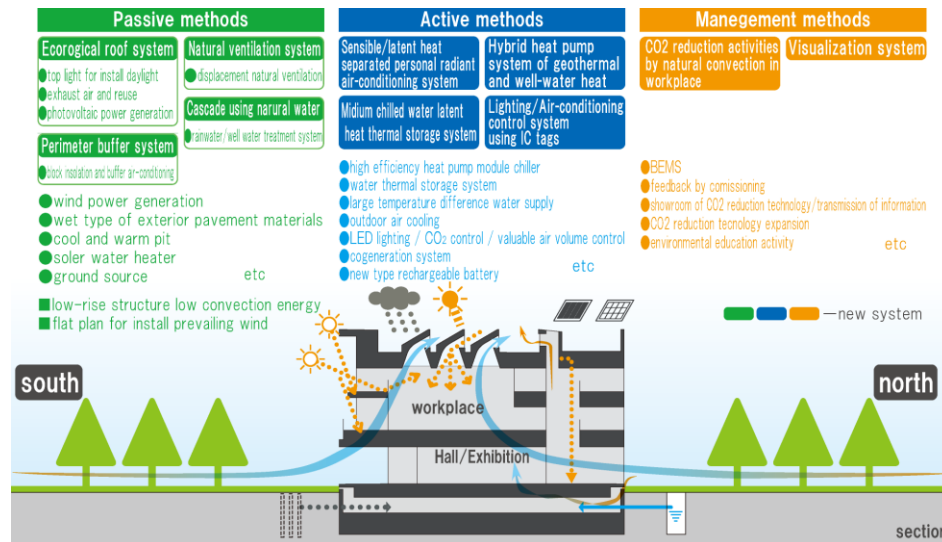


Fig. 27: Efficiency methods in the construction technology institute at Kiyose-city

Compared with a general office building, this building produces roughly 65% less CO<sub>2</sub>. This reduction is achieved through energy reduction methods and technologies (51.8%) and energy generation (12.9%). Primary energy consumption for this building is around 880 MJ/(m<sup>2</sup>a). Through the use of carbon credits, the 189 t-CO<sub>2</sub>/(m<sup>2</sup>a) produced by this building is offset and has enabled it to achieve zero carbon status for three years in a row.

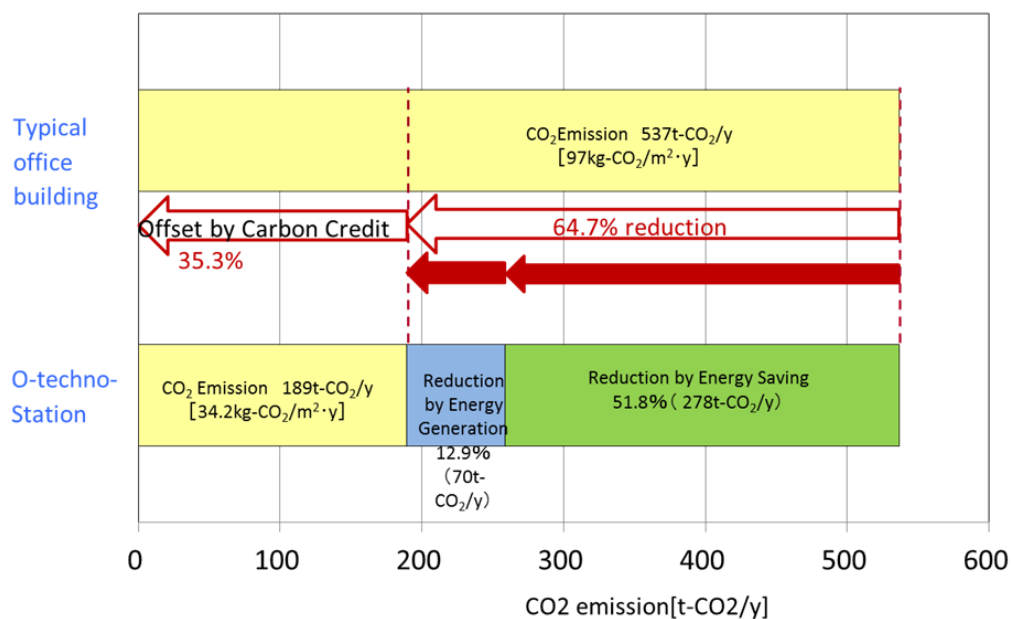


Fig. 28: Carbon savings of the Construction Technology Institute compared to typical office building

### 3.3 Keihanna eco city demonstration project

In the Keihanna region, a demonstration project is accomplished in order to establish energy management technologies such as HEMS, BEMS, EVC, and CEMS. In the demonstration project also demand response (DR) associated with consumer's behaviour is evaluated, which results from electricity rate setting and further measures (power DR).

The demonstration for HEMS, BEMS, EVC, and CEMS had been conducted from an initial stage with the objective of reducing carbon dioxide emissions, energy saving and establishment of power supply-demand management systems for power DR and started in FY2012 after the Great East Japan Earthquake.

#### 3.3.1 Applied techniques and system configuration

Several techniques have been applied to the demonstration households:

- Notification: Issue notification of tight demand and ask for suppression of usage amount in peak hours, in order to understand the resulting extent of usage amount suppression (no price incentive).
- TOU: Set the higher price for peak hours, in order to understand the extent of usage amount suppression resulting from the price incentive (applicable only to weekdays during the demonstration).
- CPP: Set the price 2-4 times higher than TOU for peak hours of high-demand days and issue a notification on the day before, in order to understand the extent of usage amount suppression resulting from the change of price incentive.
- Energy-saving consultation: Prepare and distribute an energy-saving advice sheet and explain the power-saving method by way of door-to-door visits and so on, in order to understand the resulting extent of usage amount suppression (no price incentive).

Smart meters were installed and visualization terminals that enable the understanding of the usage amount for every 30 minutes were distributed.

#### 3.3.2 Results of demonstration

In both the summer and winter of each year, 46 weekdays respectively (excluding weekends, holidays, Obon vacation, year-end and new year holidays) were decided to be the securable period. The previously distributed points, actual number of DR execution and an average temperature and humidity at the peak hours during the period are shown in Tab. 6.

Tab. 6: Demonstration outline in each year

Period	DR time (hour of day)	Distributed points	DR execution counts	Mean air temp. (°C)	Mean air humid. (%)
23.07.12-28.09.12	13-16	7,000	15 times	33.9	49.4
17.12.12-28.02.13	18-21	16,000	24 times	2.3	54.0
08.07.13-18.09.13	13-16	7,000	16 times	34.8	49.4
02.12.13-13.02.14	18-21	16,000	21 times	2.7	52.4

#### Visualization

As for the effect of visualization, by setting the households in Keihanna selected at random and not participating in the demonstration as a reference, and by comparing their electricity usage amount in the peak hours of the day of DR execution of Group A, about a 1–4 percent reducing effect was recognised. The saving-effect of the visualization, depending on season is shown in Tab. 7.

Tab. 7: Saving effect of visualization

	2012 summer	2012 winter	2013 summer	2013 winter
Effectiveness of visualization	3.9%	1.2%	3.7%	3.1%



### Notification

The effect by notification was determined in regard to the power-saving requests issued to Group B in FY2012, by comparing the usage amount during the peak hours (13:00–16:00 h in summer and 18.00–21.00 h in winter) of the DR execution date with Group A. The resulting values were about four percent in summer and about 11 percent in winter.

### CPP (TOU)

CPP (TOU) was applied to Group C throughout the demonstration period, and its effect was determined by comparing the power usage amount in the hours to which CPP (TOU) was applicable with Group A.

The effect of TOU was about 7–8% in summer and about 14–15% in winter. Furthermore, the effect was stable for two years. It is presumed that, by changing the energy source of heating appliances, which was easier in winter, and by putting on warm clothes and restraining the use of air-conditioners, daily power-saving actions have taken place.

It became clear that, in all of the demonstration periods, the effect of CPP became significant when the price was increased by 40–80 points. The rate was about 4–16% in summer and about 2–7% in winter. Since the peak hours in summer are more suitable to going out than in winter, it is presumed to have been easier to restrain the usage amount by going out on the DR execution dates. In addition, the dominant method of restraint in winter was to shift the energy source of heating appliances to other sources than electricity; it is presumed that there were less available power-saving menus to be additionally carried out at the time of CPP than in summer.

### Energy-saving consultations

Energy-saving consultations were provided for Groups B and D in the second year, and their effect was verified by comparing their usage amount to Group A, excluding the night hours when electric water heaters were operating. By only providing consultations to Group B and also CPP (TOU) to Group D, their synergy effect was examined. The effects can be seen in Tab. 8. As seen, the restraining effect was greater in winter for both cases.

*Tab. 8: Saving effect of consultation for energy savings*

Measure	Season	Mitigating rate (7am-11pm at weekday)	Reference		
			~30C	30C~34C	34C~
			~1C	1~4C	4C~
Executive energy-saving consults alone (Group B)	Summer	2.9%	3.9%	3.1%	1.1%
	Winter	13.1%	13.0%	13.1%	13.1%
Executive energy-saving consults with group conducting TOU & CPP (Group D)	Summer	12.7%	14.3%	12.8%	11.9%
	Winter	15.9%	16.7%	16.2%	15.3%

In winter, in addition to the fact that there are more power-saving menus available as basic actions such as shifting the heat source of electric appliances, wearing warm clothes indoors and so on, it is presumed that, having experienced the consultations in summer, the second consultation attained more interest, which led the participants to extend their actions to various power-saving activities and even to the replacement of energy saving appliances.

### **3.3.3 Conclusion**

Large-scale demonstrations of power demand response were implemented in four seasons in FY2012–FY2013. As a result, it was established that CPP (TOU), which is a price-induced-type DR, has a certain effect, and that magnitude of the effect changes depending on the price. In addition, the effect of visualization, notification (request for power-saving) and energy-saving consultation was established.

In addition, by means of various questionnaire surveys, it also became clear what type of power-saving activity is chosen by the demonstration households in response to different techniques.

On the other hand, as for CPP, it is believed that the data obtained in the demonstration must be analyzed in a more multilateral manner, in the reliability and continuity point of view and taking future development into consideration, since the demonstration households cannot be regarded as a proper sample of general households in the whole Kansai area, and also since its effect altered in summer and winter during the two years.

Furthermore, in this demonstration scheme, incentives such as points were given to the demonstration households as well as system construction being performed by distributing visualization terminals and so on; however, there will be many agenda items such as the way to raise the cost at the time of general implementation.

Based on the evaluation obtained from the demonstration, and from the consumer's point of view, the possibility of general implementation will be continuously considered.

### **3.4 Condition of tight power supply-demand balance**

The Toyota City Low-carbon Society Verification Project is experimenting with various systems for efficient energy use in the whole region, enhancing the convenience of daily life and aiming at the realization of a low-carbon society. This project is assisted by the national government and 50 entities including Toyota City and a number of private enterprises participated. In this report, the demand response demonstration project conducted as a part of this project by Chubu Electric Power Company is presented.

#### **3.4.1 System configuration and price menu design**

Data transmitting equipment to transmit the power usage amount (every 30 minutes) was installed in 160 households participating in the demonstration, and the data was sent via a mobile phone network.

By installing specialized tablet terminals presenting (visualizing) the power demand data of the day before of each consumer as well as the time-of-use rate of the next day and the notification of DR execution (rate change) in the households subject to DR test (80 households), it was arranged to encourage power-saving and peak shift of electricity consumption.

Apart from the price menu set by the contract between each consumer and Chubu Electric Company, a 'Mock Electricity Rate Menu' was set for the DR demonstration test. Specifically, it was the rate menu in which a higher rate was set for the peak hours of the 'DR execution date' when a tight supply-demand balance was expected, and a lower rate was set for the other time zone. As a consequence, a lower electricity rate was to be applied by shifting power-saving activities and electricity use within the DR execution hours, which gave an incentive for power-saving to the customers participating in the demonstration. As for the level of the mock electricity rate, taking the estimated number of DR execution hours per year into consideration, the rate of 'the other hours' was set so that the total value would be the same as the regular rate in a normal situation of electricity usage.

#### **3.4.2 Results of demand response demonstration test**

The time zone of DR execution in this demonstration was set as 13:00–16:00 h in summer, 09:00–12:00 h in winter, and 13:00–16:00 h in spring and autumn, when the demand of the entire system increased (see Tab. 9).

The effect of the demand response was estimated by comparing the object households of DR (80 households) and reference households (80 households).

As a result of the demonstration, the effect of DR on the consumers without a photovoltaic power generator (about 50 households) in the peak demand period (summer and winter) was estimated at around 10–15%. In addition, a decrease of the effect was observed over time after the start of the demonstration.

Tab. 9: Implementation status of DR

	Unit price	Counts for issuing DR	Issuing period
2012 winter	50/70/90/110	10	9:00-12:00
2013 spring	80	8	13:00-16:00
2013 summer	50/80/110*	16(5*)	13:00-16:00
2013 fall	80*	4(4*)	13:00-16:00
2013 winter	50/80/110*	13(4*)	9:00-12:00

\*DR without change of price was also issued, and the issue counts were shown in parenthesis

On the other hand, in the intermediate seasons (spring and winter), hardly any DR effect was observed. Also, as the number of customers equipped with photovoltaic power generators (about 30 households) whose base power amount (average usage amount of system power) was small, hardly any DR effect was observed. However, an increase of redundant power through photovoltaic generation was not evaluated in this demonstration.

From the results of the questionnaire, it can be presumed that the consumers equipped with photovoltaic power generators were always conscious about selling electricity and working on power-saving, therefore, they had few possibilities for additional power-saving. Besides, by statistical analysis of the sensitivity of the effect of DR to the unit price of electricity in peak hours applying multiple linear regression analysis to the data in summer and winter, it was revealed that even the DR without a price change (power-saving request only) has a certain effect and that a slight correlation between the unit price of electricity in peak hours and the effect of DR is observed.

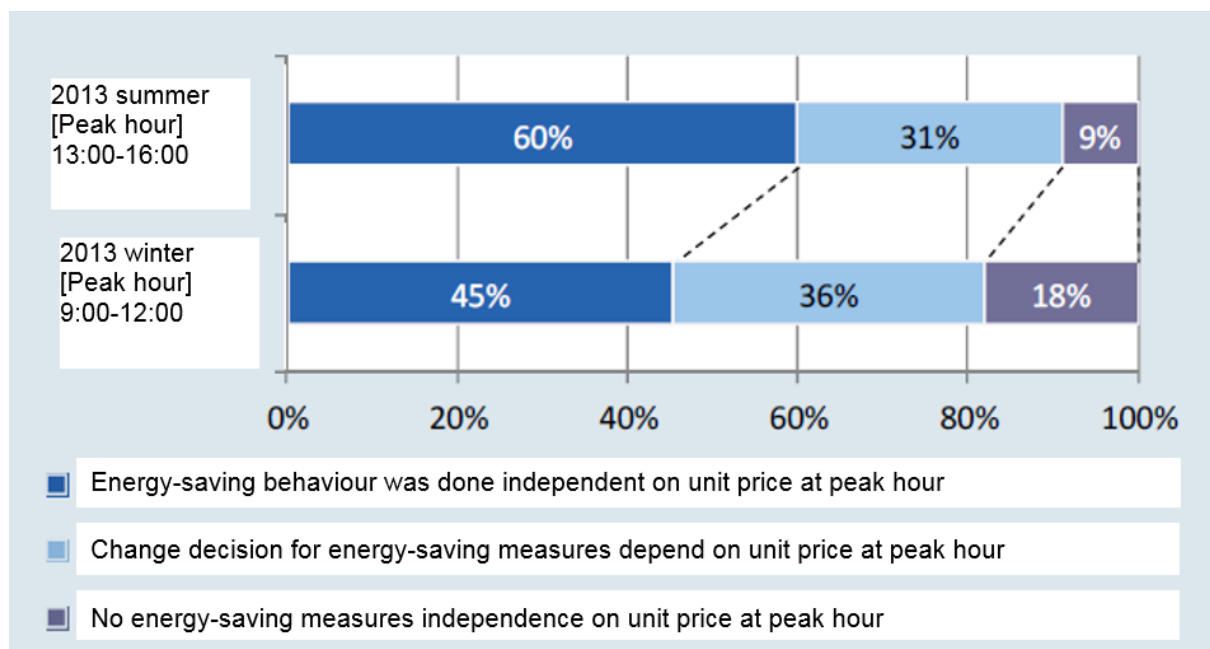


Fig. 29: Participants behaviour regarding electric power price at peak time

In order to confirm the attention level to the DR demonstration, the frequency of checking the visualization terminal during the demonstration was investigated. The result indicates that the frequency was reduced with the progress of the demonstration and that the attention to the DR demonstration had an inclination to wane.

Consequently, the power-saving actions dependent on the electricity unit price were investigated. As a result, it was revealed that about one-third had changed power-saving actions depending on the unit price in the peak hours both in summer and in winter and, in winter, more households did not take any power-saving actions than in summer (see Fig. 29).

### **3.4.3 Conclusions**

In this demonstration, in spite of the diversified features such as specific area, new residential area, and so on, a certain extent of information about the suppression amount and power-saving action at the time of DR execution in each season was obtained.

On the other hand, in regard to the price-based DR implemented in this demonstration, the evaluation of effectiveness, for example, the possibility that consumer's interest will decrease over time, the possibility that the expected demand suppression amount cannot be achieved in a period of abnormal high temperature and so on has not been thoroughly conducted.

In the future, in addition to the results of this demonstration, DR demonstration cases, both in the home country and abroad, conducted with various conditions and with a large number of participants will be analysed and a more appropriate evaluation and effective application method of DR will be examined.

## 4 Energy leap nZEB projects in the Netherlands

### 4.1 Approach of net Zero refurbishment: TRANSITION ZERO

The project “TRANSITION ZERO” (Platform31, 2015a) in the frame of the monitoring project “Energiesprong” (energy leap) is coordinated by Platform31, which already brokered a deal between housing associations and builders to refurbish 111,000 houses to net Zero Energy ( $E=0$ ) levels in the Netherlands. The goal of the project is to make Net Zero Energy refurbishments a market reality not only in the Netherlands, but also in the UK and in France. TRANSITION ZERO will organize massive demand for a currently non-existing  $E=0$  refurbishment proposition from social housing organizations, facilitates financiers and governments to tune their financing products and regulations towards this non-existing product and challenges the building sector to start an ambitious innovation process to deliver the proposition (Platform31, 2015b).

A mass demand for the refurbishment shall be organized with several ideas:

- Energy performance guarantee: The refurbishments will come with an energy performance warranty on the house for 30 years.
- One-week delivery: The refurbishments shall be executed within one week, while the tenants can stay in their homes.
- Affordability: The price target is the present value of the energy cost savings over the lifetime of the package.
- Attractiveness: It is the goal to improve quality of living and the appearance of the house.



Fig. 30: Evaluation of Net Zero energy refurbishment (left) and overview of monitoring projects (right)

#### 4.1.1 Field monitoring of refurbishment-projects in Kerkrade



Fig. 31: Apartment in Kerkrade after renovation

The project in Kerkrade consists of a renovation of 153 apartments according to  $E=0$  and has been accomplished within 10 days. Completely new prefabricated façades with triple glazing and inbuilt ventilation ducts were installed. Furthermore, prefabricated roof elements with inbuilt photovoltaic panels with a capacity of  $3.15 \text{ kW}_p$  were applied. The  $R_c$  of the different parts is between  $5\text{-}10 \text{ m}^2\text{K/W}$ . The main renovation concept is a high degree of insulation and a high efficiency boiler. A passive cooling by overhang and night ventilation have been applied for the buildings.

Analysed data shows an energy consumption which is lower than expected, but so is the solar electricity yield, as depicted in Fig. 32 left. The specific energy use for the space heating on the opposite is higher than expected.

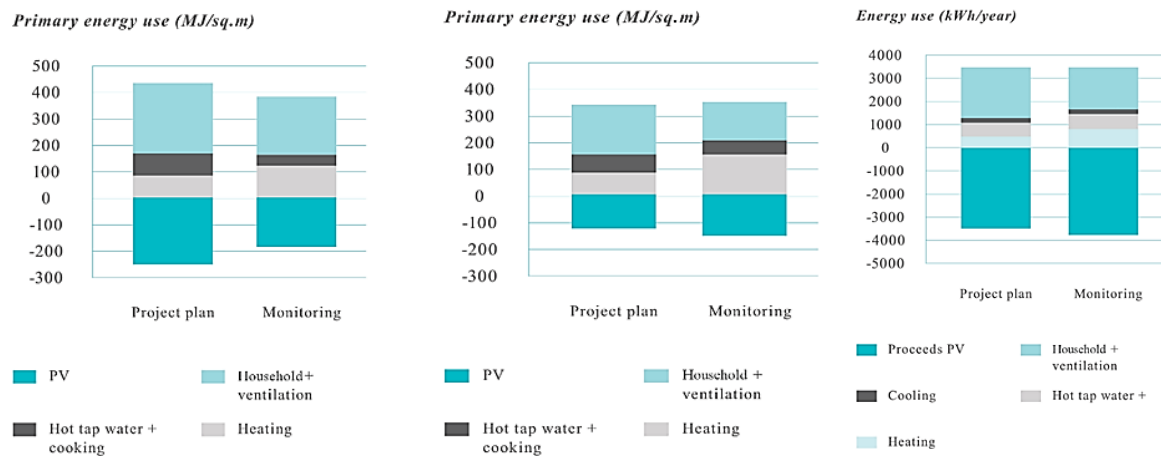


Fig. 32: Comparison of monitored energy use to project planning values for Kerkrade (left), Montferland (middle) and Rijswijk Buiten (right)

#### 4.1.2 Montferland



Fig. 33: Apartments in Montferland

In Montferland, a refurbishment of 61 apartments has been made as a part of the Energiesprong program. It involved the demolition and new building of 61 homes. During the re-building an air heat pump was installed which is supported by a central heating boiler that provides DHW and is switched-on at low temperatures. To save DHW, there are inbuilt heat exchangers in the shower, which will recover some heat of the waste water for preheating. In combination with the air-source heat pump, a high efficiency gas boiler is installed to cover the space heating demand.

The boiler feeds the underfloor heating, which is heated in winter and allows cooling during summer. The possibility of cooling during summer time is important, since due to a very high insulation degree, overheating gets a problem in summer. In the new built homes, 25 % of residents considered the indoor environmental conditions as too hot in summer. It can be seen on the monitoring that the percentage of properties with temperatures exceeding over 100 hours in the bedrooms as well as in the living rooms is with 7% and 13% very low.

To gain electricity, PV is installed on the roof of the buildings. The PV yield is higher than expected, but also the primary energy consumption is higher. The specific energy use for space heating is significantly higher than expected, while the usage for DHW, household appliances and ventilation is lower.



### 4.1.3 Rijswijk Buiten



Fig. 34: Apartments in Rijswijk Buiten

In Rijswijk Buiten, a new construction of five properties has been built. For the Net Zero Energy properties in Rijswijk Buiten, PV-generators and ventilation systems were installed in combination with a well-insulated and completely sealed outer layer ( $R_C = 4.1 \text{ m}^2\text{K/W}$ ). It also has been tried to animate the residents to buy energy-efficient LED lighting, a heat pump dryer and at least two A+++ household appliances from the categories washing machine, fridge/freezer and dishwasher. In addition to this, the consortium put 10 stand-by killers and an energy-efficient doorbell at disposal. This kind of measures led

to a low household electricity use as seen in the field monitoring results.

Between the properties, differences in the net energy consumption could be seen as shown in Fig. 35. These differences are partly explainable by the thermostat settings in the properties. Moreover, the same monitoring demonstrate differences in household electricity use between the properties. Besides consumer behaviour this is probably caused by compositions of households as well as the degree of presence of the residents. The averaged monitoring proves a reached Net Zero Energy balance, moreover a slightly plus balance.

To keep the temperatures low in summer and comfortable in winter, it was opted for a free cooling with a ground source with the underfloor heating. This results in an average daily temperature of below  $25^\circ\text{C}$ . It could be seen that lower temperature settings on the thermostat can lead to increased cooling energy use. This can be overcome by making agreements about the temperature settings in summer (almost 70% of the days in summer the temperature is between  $21\text{--}23^\circ\text{C}$ ).

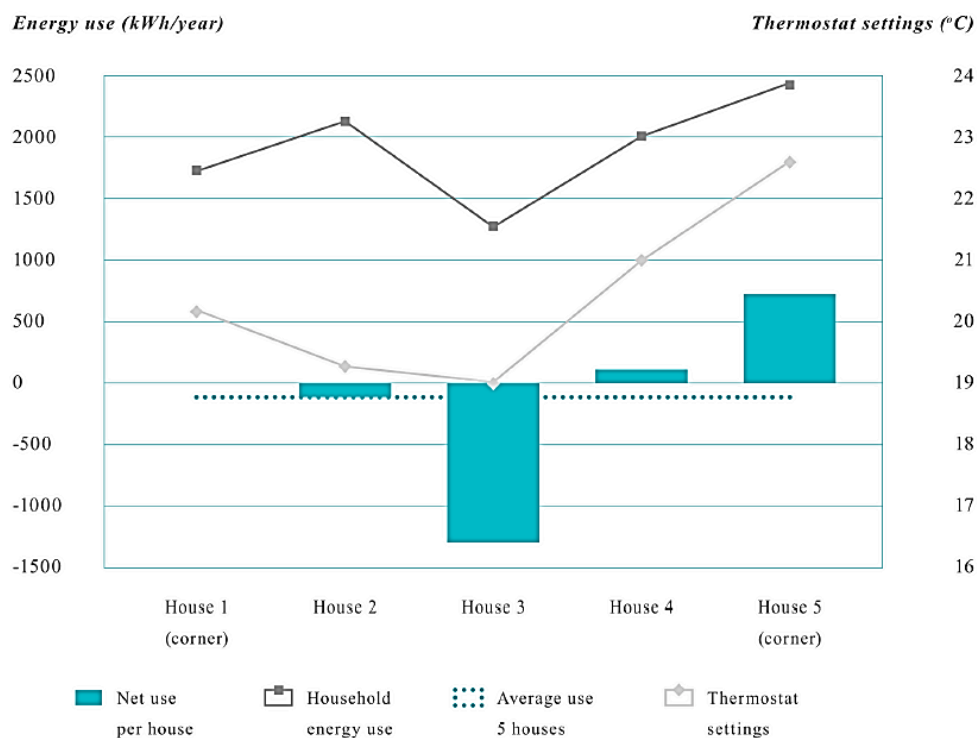


Fig. 35: Comparison of monitored energy use in the five new buildings in Rijswijk Buiten

## 4.2 Showcase Projects

Kennishuis Energie Gebouwde Omgeving has commissioned moBius consult to examine 30 projects, in order to fill a database with relevant information.

### 4.2.1 Energy concepts

These 30 projects use a wide variety of possible solutions. There is no defined concept in order to achieve energy neutrality, which is a positive aspect. Different preferences seem to lead to the desired result. Some measures are applied more frequently than others and can be considered logical elements to achieve a net-zero energy home. The most common measures are described below (Netherlands Enterprise Agency, 2015).

#### Thermal building envelope

In all projects attention is paid to the quality of the thermal shell. Insulation values (R- values) are better than the legal requirement of 3.5 m<sup>2</sup>K/W. In about 50% of the projects, the R-value of the solid facade sections is at least twice as high as defined in the legal requirement. In four projects even an insulation value of 10 m<sup>2</sup>K/W has been applied. The roof usually has a similar insulation value as the facade. The ground floor has a slightly lower insulation value. In about half the homes triple glazed windows were installed.

In over half of the projects extra attention was paid to air tightness. Achieving the right level of air tightness is largely dependent on the quality (control) of the implementation. Therefore, in a third of the projects a test was performed to control the air tightness. About a quarter of all projects meet the high Passief Bouwen air tightness standard ( $q_{v10} < 0.15$ ).

#### Ventilation heat recovery

Using balanced ventilation is a relatively easy and efficient way to recover heat from the exhaust air. Therefore, in almost 75% of the projects balanced ventilation was applied.

Further prevention of heat loss through ventilation can be achieved by ventilation based on what is available (e.g. carbon dioxide). In the case of balanced ventilation, however, this is a relatively expensive solution as additional engineering elements are needed in each space or zone. Combining balanced ventilation and CO<sub>2</sub> control has therefore been applied in only four projects. In most projects, heat is also recovered from shower water.

#### Heat generation

In almost 75% of the projects a heat pump system has been installed. Usually, this is done in combination with a closed heat and cold storage system. In two cases a collective open system was installed. Using thermal storage and a heat pump, buildings can be heated and cooled in a very efficient manner. Consequently, room temperature is often very comfortable.

All houses using a heat pump are all-electric. Electricity is the sole energy carrier, therefore the house no longer needs to be connected to the gas network. One of the disadvantages of electricity is that it is relatively expensive if compared to natural gas, and therefore savings in primary energy do not lead to corresponding lower energy bills. The system should be well monitored in order to make sure that it is functioning properly in practice.

In some projects, a heat pump has been applied without thermal storage. In these cases, (exhaust) air is used as a heat source. In these situations there is no cooling in summer.

#### Solar energy

In most projects, solar energy is passively and actively used in the energetic concept. In just two projects solar energy is not used.

#### Solar orientation

The easiest way to use the sun's energy is by taking into account the orientation of the house. In winter, valuable heat can be obtained by using glass panels on the sunny side of the house. It is important that in summertime heat is well reflected in order to prevent overheating. Optimal solar orientation can be achieved at no extra cost and it is therefore used in most projects. For a number of projects, solar orientation could not be included in the design as the urban layout plan was already established.



### Solar water heaters

In 80 % of the projects solar water heaters are installed to heat water. The size of the collector surface varies from 1.5 m<sup>2</sup> to 16 m<sup>2</sup>. When large solar water heaters are applied, the hot water generated can also be used for the heating system. On average, in these projects approximately 6 m<sup>2</sup> solar water heaters are used. In general, regular flat plate solar water heater systems were installed. In two projects vacuum tubes were used.

### Solar PV cells

Every home consumes energy. In order to become a net-zero energy home it is necessary that energy is generated locally. In 80 % of the projects solar panels are used in order to achieve this goal. The amount and type of solar cells as well as the power generated vary significantly. On average, the EPC in these projects has been reduced by over 0.3 because of the use of solar cells.

## **4.2.2 Examples of homes**

From these projects, several successful concepts can be derived in order to achieve an energy-neutral home. Following are some of these concepts:

### The average net-zero energy home

Based on the common denominator in these projects, an energy concept resulting in an energy efficient home is taking shape. This energy concept consists of the following proven measures:

- Orientation of the house, using glass panels on the sunny side and appropriate sun shading.
- Well insulated structural shell, with facade and roof having an R-value of 6 m<sup>2</sup>K/W to 7 m<sup>2</sup>K/W and 5 m<sup>2</sup>K/W floor R-value.
- Use of three-layer glazing.
- Attention to detail for better air tightness.
- Balanced HRV ventilation.
- Heat recovery from shower water.
- Heat and cold generation using a heat pump connected to an individual sealed source.
- A solar water heater with an average area of 5 to 6 m<sup>2</sup>.
- An average of 25 m<sup>2</sup> of multi-crystalline silicon solar cells.

One of the projects carried out with the measures mentioned above is the Schoonoord project, which achieved a -0.05 EPC rating. The Schoonoord project is monitored by having two families exchange homes after one year. This way, the real effect the energy-efficient home has on energy consumption can be determined.

### Passive home

Out of all 30 projects, about 10 were built according to the design principles of Passive Construction (Passief Bouwen). Five of them also have actually applied for a Passive Construction certificate. In general, these homes also achieve a low EPC rating if home-specific generation of electricity (solar cells and wind turbines) is not taken into account. These homes generate, on average, less electricity than the other homes.

Other than the average net-zero energy home, the Passive Homes have the following characteristics:

- The structural shell has been extremely well insulated with an average facade and roof R-value of 8.5 m<sup>2</sup>K/W; the floor R-value is 6 m<sup>2</sup>K/W.
- Highly insulating window frames were applied.
- Excellent air tightness, monitored using a blower door test.
- In order to cool the house in summer (summer night cooling), in about half of the projects special provisions were made to ventilate the house in a natural and burglar-proof manner.
- The method of heat generation highly varies. As the demand for heat is very low, in about 50% of the projects a regular HR107 water heater is selected.
- Less PV panels were applied, about 20 m<sup>2</sup> on average.

The homes in Borne are a good example of a Passive Home project. The facade and the roof have an insulation value of  $R=9 \text{ m}^2\text{K/W}$  and the floor has an R-value of  $7 \text{ m}^2\text{K/W}$ . Other measures applied in this project are:

- Special parts that can be opened to cool the house in summer.
- Hotfill connections to avoid unnecessary use of electricity for washing machine and dishwasher.
- $16 \text{ m}^2$  PV panels.

Even though fewer measures were taken than in the average home, the ones implemented here were sufficient in order to achieve (exactly) zero EPC. In the  $\text{CO}_2$  neutral street II in Heinkenszand, passive building is combined with a large amount of PV panels. As a result, an EPC of -0.28 has been achieved in this project.

#### Natural home

According to some experts, natural flow of ventilation air is preferred over balanced ventilation. In various projects this vision has been combined with ecological or bio-construction. Some believe that this view contradicts with energy-efficient construction. These projects, however, demonstrate that building in both ecological and energy-efficient ways is indeed possible. As compared to the average energy-neutral home, natural homes have the following characteristics:

- Natural supply of ventilation air. Note: As there is already a natural supply of air available, air tightness is of less importance.
- $\text{CO}_2$  control is often used in order to reduce energy loss by ventilation.
- Significantly more PV panels are used: On average more than  $40 \text{ m}^2$ .

The Brabantwoningen in St. Oedenrode are a prime example of building in a natural, ecological and net-zero energy way. Here, heat loss through ventilation is reduced by applying a hybrid heat pump, which captures its heat from the exhaust air. In this project there has also been a lot of attention for the application of ecological materials. The use of many PV panels has reduced the EPC to -0.29.

#### Innovations in these homes

In these projects many proven techniques have been used. This is reflected in the average energy-neutral house achieving very good energy efficiency results. In addition to these proven elements, many different innovations for the Dutch construction market are applied.

The following innovations have been applied in the projects:

- Earth tubes: In two projects, ventilation air is supplied through an earth tube. In summer, the air in the tube is slightly cooled, while in winter it is slightly heated.
- PCMs: Phase Change Material is installed on a low thermal capacity structure. This is material in which heat is stored by phase transition of the material. In summer, overheating can be reduced using a combination of PCM and night ventilation.
- Vacuum tubes: This is very effective for capturing heat from sunlight. Because this process also works during cold periods, vacuum tubes contribute effectively to spatial heating.
- Wind turbines: In two projects, wind turbines attached to buildings have been used. If installed in optimal position they are able to generate a significant amount of electricity. In practice, yields from wind turbines may be considerably less than the theoretical maximum.
- Pellet burner: Burning sustainably grown wood pellets is a virtually carbon neutral method for domestic heating. There are some projects in the Netherlands in which this technology has been used. The database contains a system installed in an individual property as well as a common system setup in an apartment building.
- Compact storage: Besides seasonal underground storage, heat and cold can also be stored inside for one season. The basis of this compact storage process is a chemical or physical process. In two projects an experiment is being conducted with these processes. The technology is not commercially available yet.
- Monitoring: The energy consumption of residents can be influenced by visually representing their energy consumption. This has been developed in several different projects.

- Now it is also possible to have direct access to energy consumption data through the internet or iPad. In order to compare the house with other houses in the area a benchmark is also used.

The Nulwoning in Groenlo is one example of a house using many innovative measures. Besides the application of proven technologies this home is used as a site to experiment for many other kinds of studies. In the basic concept the following innovations were used:

- An earth tube applied with greater efficiency using an additional control: the air is only sucked in through the earth tube when outside air temperatures are very high or very low.
- Vacuum tubes for hot tap water and heating have been installed.
- There is an innovative compact chemical heat storage system using saline.
- The house is being extensively monitored and constantly optimised.
- In this home an experimental smart grid with electricity stored in batteries is also installed, which reduces peak demand for electricity.

The calculated EPC in this Nulwoning (Zero energy home) is extremely low: -0.21. However, the innovative measures (except for the vacuum tubes) cannot be included in the EPC calculation. Therefore, the actual EPC is even (significantly) lower.

#### **4.2.3 Process and stakeholders**

The projects examined are all very ambitious, and in order to realize them they have usually been preceded by a lengthy preparatory process. The projects were initiated by several different parties. These are market players such as developers, contractors and architects, but also (semi-) public parties, such as provincial governments, municipalities, housing corporations and individuals. About 60% of the projects has been developed by some kind of construction team. One private person built a house himself. About 80% of the projects have been developed as an example or trial pilot project for net-zero energy construction. For some of parties the construction of sustainable housing is their core business. These parties continue to take initiatives in order to develop more projects.

#### **4.2.4 NEN 7120 Calculations**

The EPC for all projects has been recalculated with the latest calculation method described in NEN 7120 (2014). The evaluation of the projects is largely based on these calculations. In NEN 7120 and the corresponding certified software, measures have been included that were not present in the former NEN 5128 (2009) standard. In NEN 7120, for example, many more ventilation systems were defined. This way presence detection ventilation systems can be included, without the need for an attestation of equivalence. The amount of energy saved as a consequence of a measure according to the (former) attestation of equivalence is generally higher than the degree of energy saving according to NEN 7120.

Some additional measures regarding the generation of energy have been included in NEN 7120. This is true for the generation of heat using wooden pellets and for generation of energy that is neighbourhood-specific. Also for electricity generation using PV cells and solar water heaters many more configurations are possible. Also large surface areas of solar water heaters can be factored in, for example for heating purposes. Electricity generation using wind turbines cannot be calculated. For this, a manual adjusting calculation needs to be made.

A major part of the measures as described in section 3.4; "Innovation in homes" cannot be included as a standard in the new calculation method. In the Netherlands, these measures are not being applied at a large scale, yet. In that sense the projects described may be considered as field experiments. In principle the measures mentioned can be included in the calculation with an attestation of equivalence. However, such a declaration is not available due to the fact that these measures are very innovative. The declaration is also not needed (for obtaining an environmental permit) as the EPC produced is well below the legal requirement.

The practical results have been discussed with the stakeholders. However, no structural comparative research has been done in this case. Research into the relationship between the EPC value and actual energy consumption on the one hand and between specific measures and actual energy consumption on the other is being performed by AgentschapNL at this time.



## 5 Field monitoring of nZEB in Norway

In the framework of Task 4, field monitoring results of heat pumps in larger residential or office buildings have been contributed. Among these some of the first nearly Zero Energy buildings in Norway, and even a retrofitted plus energy building, which was qualified as most energy-efficient building.

### 5.1 CO<sub>2</sub> heat pump water heaters in block of flats

Tveita Borettslag (housing cooperative) in Oslo, Norway comprises three blocks of flats with each 273 flats. The buildings, which were erected 1967-69, were heavily renovated in 2011 in order to improve the thermal comfort for the residents and save energy. Among other things, the oil-fired boilers for each block were replaced with two independent heat pump systems – one heat pump that supplies heat to low-temperature radiators (space heating heat pump) and one heat pump for hot water heating (heat pump water heater).



*Fig. 36: Three block of flats at Tveita Borettslag (housing cooperative) in Oslo with totally 819 flats equipped with CO<sub>2</sub> Heat Pump Water Heater (HPWH)*

The three heat pump water heaters (HPWH) use carbon dioxide (CO<sub>2</sub>, R744) as working fluid. This technology has a number of advantages. The global warming potential (GWP) is 1 and CO<sub>2</sub> heat pump cycle is a very efficient for high temperatures heating which is required for water heating.

The CO<sub>2</sub> heat pump system at Tveita Borettslag was the first large-capacity CO<sub>2</sub> heat pump water heater (HPWH) system to be installed in Norway.

#### 5.1.1 Technical concept

Tveita Borettslag comprise three identical block of flats with 273 apartments each. A CO<sub>2</sub> heat pump water heater system covers the entire hot water demand for each of the buildings. The energy and power demands for heating of domestic hot water (DHW) for each block of flats are as follows (measured values):

- Annual heating demand: 600,000 kWh/a, approx. 2,200 kWh/a for each flat
- Average power demand: 100 kW, approx. 360 W for each flat

The existing exhaust air ventilation systems has not been replaced with balanced ventilation systems. The exhaust air at a nearly constant temperature of 22 °C has therefore been considered to be the most cost-efficient heat source for the heat pump.

The heat source system for each block comprises two brine-to-air heat exchangers for heat recovery from exhaust air and a secondary (closed loop) system with pumps, expansion system, brine treatment system, deaerator and various valves – charged with anti-freeze fluid (ethylene glycol).

The secondary system is connected to the evaporator for the CO<sub>2</sub> heat pump water heater unit. At design conditions, the inlet/outlet brine temperatures for the brine-to-air heat exchangers are 12/9 °C.





The hot water system for each block of flats comprises 18 x 400 litres hot water storage tanks connected in series, electric heaters for reheating of DHW in the recirculation pipeline, expansion system and various valves as depicted in Fig. 39

A 400 litres tank has a smaller diameter and cross sectional area than 650 and 1000 litres tanks, resulting in less heat conduction between hot and cold water during tapping and charging of the tanks. Heat conduction will increase the average inlet water temperature to the gas cooler and consequently reduce the COP for the CO<sub>2</sub> heat pump water heater.

The storage tanks have a relatively small tube diameter on inlet/outlet (OD 32 mm), and diffusers have not been installed in order to reduce the water velocity. At maximum water flow rate during tapping mode the water velocity through the tanks becomes quite high, resulting in mixing of water at different temperature levels. This in turn increases the average inlet water temperature to the gas cooler and reduces the COP of the CO<sub>2</sub> heat pump.

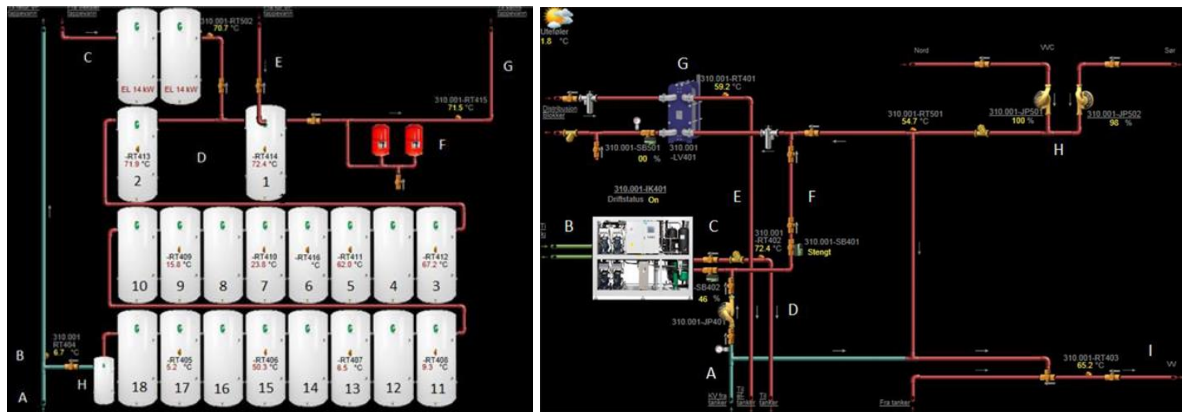


Fig. 39: DHW system configuration

## 5.1.2 Results

### Monitoring

In the monitoring period, water ( $\pm 0.5$ -1.0) and brine temperatures ( $\pm 0.5$  °C), CO<sub>2</sub> temperatures (evaporator, gas cooler,  $\pm 0.5$ -1.0), CO<sub>2</sub> pressures (evaporator ( $\pm 0.5$  bar), gas cooler ( $\pm 1.0$  bar) as well as the heating capacity for the gas cooler were measured. The respective measuring uncertainty is given in the brackets.

The gas cooler pressure of 100 bar could be confirmed by the monitoring at a DHW outlet temperature of 73 °C. The heating capacity was subject to seasonal changes, mainly due to another 280 kW heat pump connected to the same heat source, which caused variations of the source temperature during the heating season. During summer, the HPWH reaches its design heating capacity of 100-110 kW, while the lowest measured value was 85 kW and the average 90-95 kW.

When the CO<sub>2</sub> heat pump supplies heat to the DHW system, the gas coolers pressure is approx. 100 bar, while the outlet water temperature is approx. 73 °C.

### Seasonal performance

Due to limitations in the measuring equipment and the monitoring system, it was not possible to make an exact calculation of the SPF or SCOP for the CO<sub>2</sub> heat pump water heater system. The annual heat supply for DHW heating was estimated at 1,775,000 kWh/a. The annual input energy for the compressor was estimated at 395,000 kWh/a. The estimated annual energy saving was approx. 1,360,000 kWh/a. Out of these, the estimated average COP (SCOP or SPF) for the CO<sub>2</sub> heat pump water heater was approximately 4.4. This corresponds to an annual energy saving of roughly 75 %, compared to a direct electric heating system (electric immersion heaters). A 350 kW system installed in a hospital in Tromsø with similar operation conditions of a source temperature of 5-8°C and hot water system (70-75 °C) an SCOP in the order of 4 can be achieved when including the electric energy input for the pumps for the heat source system and the hot water system.

### 5.1.3 Conclusions and recommendations

CO<sub>2</sub> HPWH represent an energy-efficient and eco-friendly for NZEB with a large DHW demand, i.e. block of flats, apartment buildings, hospitals, nursery homes, sport centres etc. CO<sub>2</sub> HPWH can even be interesting in NZEB office buildings, since the annual DHW demand of a passive office building in Norway is about 20-25 % of the total heat demand.

Optimisation potentials for an improved SPF of the monitored system are following items:

- Gas cooler pressure: Instead of the constant gas cooler pressure of 100 bar, the pressure should be controlled dependent on the operation conditions to optimise the operation.
- Better DHW tank design: Instead of the combination of 18 x 400 l tanks, larger tanks in slim and high dimensions should be used in order to get a good stratification, which will lower the average inlet temperatures for the gas cooler and increase the COP.
- Variable speed pumps instead of constant speed pumps.
- More advanced monitoring systems to facilitate optimised operation.
- Insulation of pipe in the DHW systems.

The following design and optimisation recommendations could be given:

- The heating capacity should equal the average thermal power demand for DHW heating over a 24 hour operating period +25-30 %. The peak load DHW demand is covered by the DHW stored in the accumulation tanks.
- For the gas cooler design, a long thermal length is crucial. The temperature difference between the CO<sub>2</sub> and the inlet city water at the gas cooler inlet, should be 4-6 K in the design point. Counter-flow operation is important for minimum  $\Delta T_A$  (maximum cool down of the CO<sub>2</sub> gas) and maximum COP. The outlet DHW temperature from the gas cooler should be controlled by a variable speed drive pump.
- Optimum gas cooler pressure control is recommended in all systems with variable city water temperature and/or variable heat source temperature. The higher the DHW set-point temperature, the higher the optimum gas cooler pressure. The expansion valve can be replaced by an ejector that increases the suction pressure for the compressor by typically 4 to 8 bar which again increases the COP.
- DHW storage tanks should preferably be tall and slim in order to minimize conductive heat transfer between hot and cold water inside the tanks during DHW tapping and charging. The inlet/outlet water pipelines should have adequate diffusers in order to minimize the water velocity and mixing of hot and cold water. The inlet/outlet tubes should have sufficiently large diameters. A separate storage tank for the DHW recirculation system may be used. The tank should have an electric heater for DHW reheating.

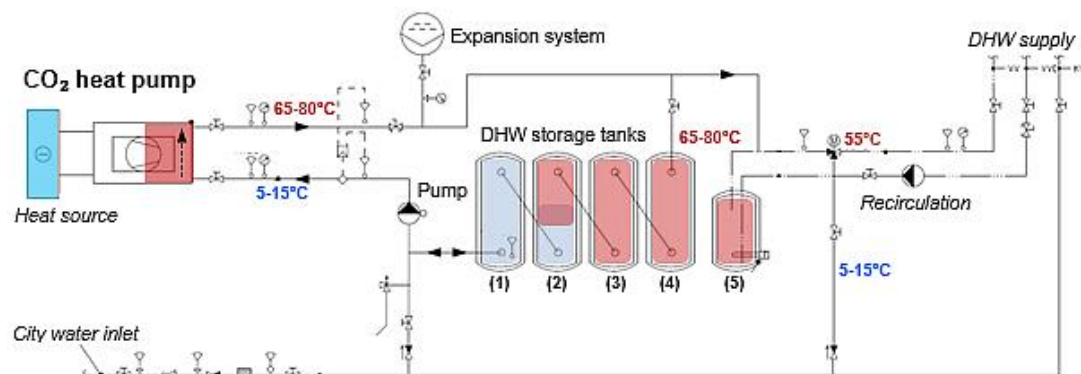


Fig. 40: A CO<sub>2</sub> heat pump water heater (HPWH) installation with a CO<sub>2</sub> heat pump unit, DHW storage tanks and a pump for water circulation through the gas cooler (COWI AS)

During tapping, cold city water at 5-15 °C fills storage 1. The CO<sub>2</sub> heat pump will normally run during tappings. A variable speed pump circulates the cold city water through the counter-flow gas cooler heating the water to the set-point temperature (65-80 °C) before it flows into DHW tank 4. After the tapping, the CO<sub>2</sub> heat pump will run as long as the water temperature at the bottom of DHW tank 1 is lower than the set-point temperature (65-80 °C).

## 5.2 Heat pump system in a new office building

Miljøhuset GK is the headquarters of the contracting company GK Norge AS. The building, which was opened in 2012, is situated in Oslo and has a total heated area of 13,650 m<sup>2</sup> including a repair shop and storage rooms.



Fig. 41: Miljøhuset GK in Oslo (left) and installed air-source heat pump (right)

The building was constructed according to the Norwegian passive house standard NS3701 (Class A), and was certified as "Very good" according to the BREEAM-Nor classification system.

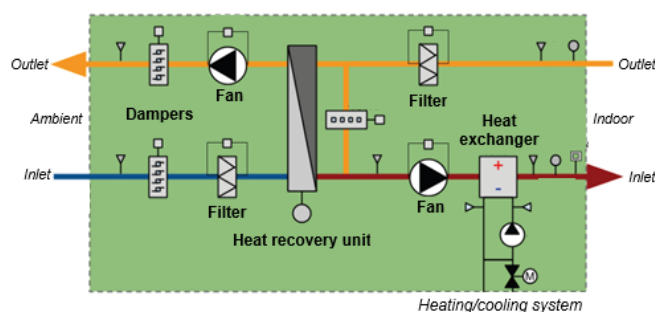


Fig. 42: System concept ventilation

The building has no hydronic heat distribution system, so space heating and cooling are solely provided by the ventilation air. An air-source heat pump system covers the entire space cooling demand and the base load for the space heating. Electric heaters are used for peak load heating. A separate chiller covers the cooling of server stations and telecom equipment.

According to GK Norge AS, the ventilation efficiency and with that the indoor air quality is maintained by using special inlet valves that control the air distribution at varying air flow rates (VAV system) and varying air temperatures.

### 5.2.1 Technical concept

The plant shown in Fig. 43 as schematic of the whole system comprises several sub-systems:

- Reversible heat pump/liquid chiller system – space heating/cooling, snow melting
  - **320 kW** heating cap. (winter mode) – **500 kW** cooling cap. (summer mode)
- Electro boiler (200 kW) – peak load and back-up for space heating and snow melting
- Electric immersion heaters – DHW heating (integrated coils in the storage tanks)
- Electric heaters – 200 W peak load for space heating (located in the rooms)
- Liquid chiller (25 kW) – process cooling (server/telecom equipment), heat recovery
- Dry cooler – rejection of excess heat from the liquid chiller circuit

The standard heat pump/chiller units and the electro boiler are connected to a common closed-loop pipeline system for heating and cooling, supplying warm/chilled liquid to heater/cooling batteries in 6 different ventilation units. The distribution system is charged with 30 % ethylene glycol in order to avoid freezing in the outdoor heat exchangers (evaporators) during winter operation. The distribution temperatures at overall heating and cooling mode are approx. 30 °C and 10 °C, respectively.

The condenser heat from the liquid chiller for process cooling is utilized for preheating of domestic hot water (DHW) and space heating, whenever possible. Two plate heat exchangers (A, B) separate the chiller circuit from the DHW circuit and the space heating circuit. Surplus condenser heat from the chiller is rejected to the ambient by means of a dry cooler system.

The DHW system comprises three storage tanks in serial connection, and electric immersion heaters reheat the preheated water to about 60 °C.

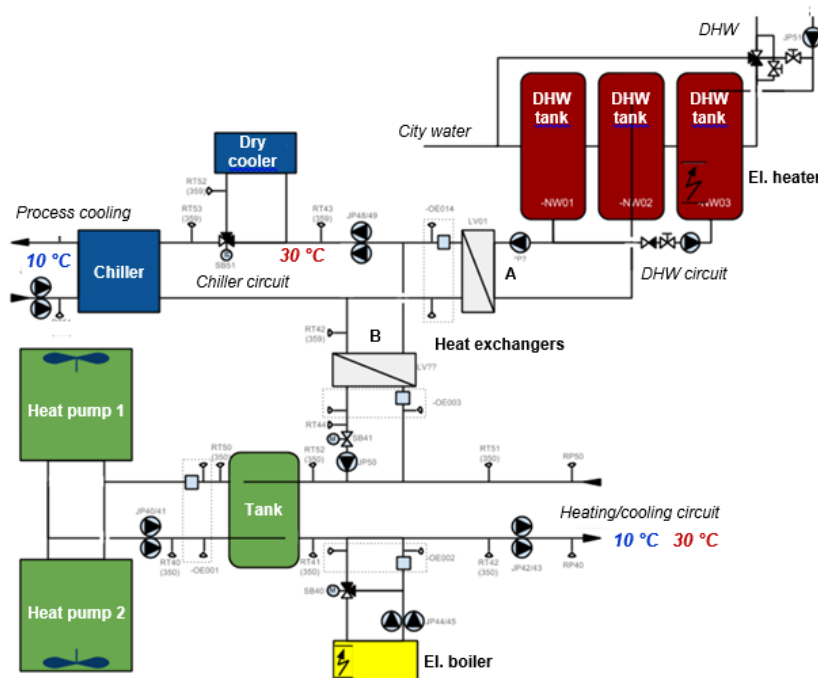


Fig. 43: Simplified sketch of the energy plant for heating/cooling at Miljøhuset GK (Orvik 2014/15)

The heat pump installation as shown in Fig. 41 includes two identical air-source units with reverse operation that either provides heating or cooling to the common distribution system for heating/cooling:

- Type: Standard air-to-brine heat pump/chiller unit
- Heating/cooling capacity: **250 kW** (+7/35 °C), **160 kW** (-15/35 °C)
- Working fluid: R410A – 2 independent circuits per unit
- Compressors: 4 scroll compressors, intermittent operation
- Stop temperature: -12 °C

## 5.2.2 Monitoring results

The theoretical calculations of the maximum heating/cooling demands [kW] and the annual heating/cooling demands [kWh/a] were carried out prior to the building project, and the results were used as a basis for classification of the building according to the Norwegian passive house standard ("Passive house Class A") and according to BREEAM-Nor ("Very Good").

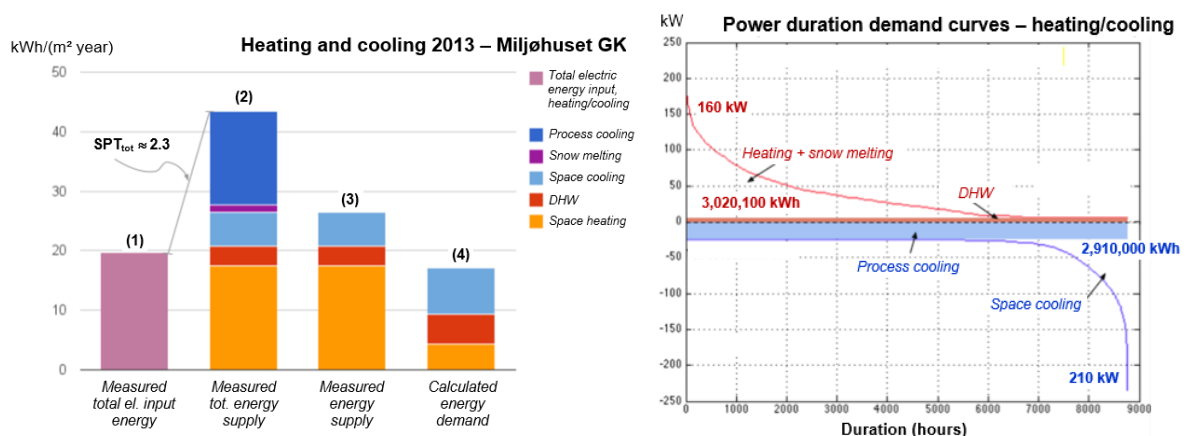


Fig. 44: The measured total electric input energy to the various sub-systems (1), measured thermal energy supply (2, 3) and calculated thermal energy demand, Simien (4). In (3) and (4) process cooling and snow melting are not included (left). The measured power duration demand curves for heating (heating + snow melting) and cooling (process cooling + space cooling) for 2013 are also displayed (Orvik, 2014/15).



The Norwegian building simulation programme "Simien", which is based on the Norwegian standard NS3031, was used for the simulations. The simulations were based on a normal reference year for the climate and standardised values for periods of use for the building incl. ventilation systems during weekdays and weekends, power demand for electrical appliances, presence of people etc. Process cooling and recovery of condenser heat for e.g. space heating and preheating of DHW were not included in the simulations.

Tab. 10 shows the measured thermal energy supply (heating, cooling) for the different sub-systems as well as the average, annual COP (SCOP) for the reversible heat pump/chiller and liquid chiller in 2013 (Orvik, 2014).

Tab. 10: Measured energy balance and SCOPs in 2013

	Heating	%	Cooling	%	SCOP
Heat pump/chiller	125 MWh/a	42	75 MWh/a	26	2.4
Liquid chiller	110 MWh/a	36	216 MWh/a	74	4.0
Electro boiler	15 MWh/a	5			
Electric heater, DHW	52 MWh/a	17			
Total	302 MWh/a	100	291 MWh/a	100	

Fig. 45 (left) shows a breakdown of the heat supply and the cooling energy supply by the different sources. The direct electrical fraction is about 25 %, and mostly used for DHW. About 35 % of the heat is supplied by heat recovery from the process cooling and the heat pump. In cooling operation about 25 % is supplied by the heat pump and 75 % by the chiller.

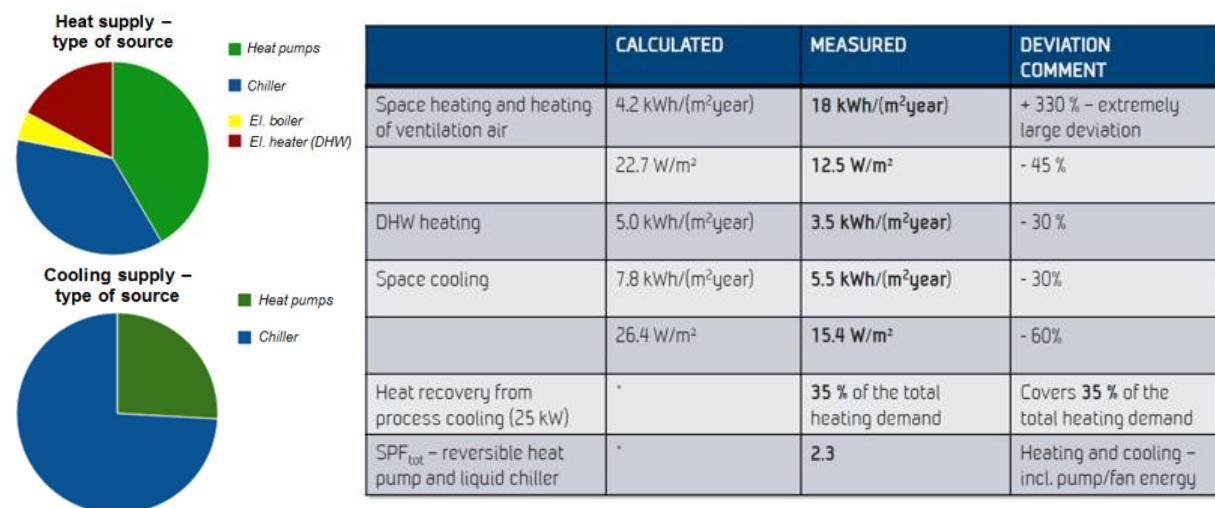


Fig. 45: The measured annual heat supply and cooling supply for 2013 categorised according to type of source (left) and calculated and measured maximum power and annual energy demands for heating and cooling (right). The measured demands for space heating and heating of ventilation air have been corrected according to a "normal" (average) year.

Fig. 45 (right) shows a comparison between measured and calculated energy demands and loads. In particular, in space heating mode, the measured specific heating demand was about four times higher than the calculated value. Reasons are a higher U-values, lower internal loads and less ventilation heat recovery as well as more ventilation operation than calculated. The maximum heat load, though, is about 50 % lower than calculated. More accurate calculations would have led to a considerably lower capacity of the heat pump/chiller, less investment cost and higher performance. The DHW demand is about 15 % of the space heating demand. The cooling demand was about 30 % lower than the calculated value. The deviation may be due to lower internal heat loads. The measured maximum space cooling demand was about 40 % lower than the calculated value. Also for the space cooling, the combined heat pump/chiller system could have been designed for a considerably lower capacity. The measured specific annual process cooling demand accounted for as much as 75 % of the total annual cooling demand for the building. Consequently, the process cooling demand was almost identical to the specific heating demand.

### 5.2.3 Optimisation potentials of the system

The following optimisation potentials of the system were evaluated:

- The combined air-to-brine heat pump and liquid chiller units were designed for a total heating capacity of 500 kW at -7/35 °C and a total cooling capacity of 500 kW at 10/35 °C. The measured maximum heating and cooling capacities in 2013 were with 170 kW and 210 kW, respectively, i.e. considerably lower. The measured Seasonal Performance Factor (SCOP) for the air-to-brine heat pump/liquid chiller units including pumps and fans ranged from 2.2 to 2.4 (2013/2014). The heat pump/chiller units are considerably oversized due to the inaccurate thermal load calculations. If they had been designed for a lower capacity, it would have resulted in lower investment costs (better profitability) and lower annual energy use due to improved SPF. Additionally, the heat pump/chiller units are not optimised for operation in Nordic (cold) climate. A better design with e.g. large fin distance in the evaporator, a more advanced defrosting system and variable speed drive piston or screw compressors would have contributed to a higher SPF.
- The condenser heat from the liquid chiller for process cooling covered about 35 % of the total heating demand in the building (space heating, DHW heating). Heat recovery from process cooling equipment can thus be an important heat source and should always be taken into account when designing the heating and cooling systems for office buildings of passive house or NZEB standard. The cooling capacity of the liquid chiller for process cooling was considerably lower than that of the heat pump/chillers for space cooling, i.e. 25 kW vs. 500 kW, but covered a much larger cooling demand due to very long operating time.
- The electro boiler (peak load) covered about 5 % of the total annual heating demand. The boiler was only used at low ambient air temperatures when the air-source heat pump units were switched off ( $T_{\text{amb}} < -12\text{ °C}$  to  $-15\text{ °C}$ ).
- The measured heat supply from the electric immersion heaters in the DHW system was about 52 MWh/year, which is actually higher than the annual DHW heating demand. There was no net recovery of condenser heat from the liquid process chiller to the DHW system, and about 5 MWh/year heat was actually rejected from the DHW system to the ambient air via the dry cooler. I.e. the electric immersion heaters in the DHW system covered the entire heating demand. The heat recovery system has a serious malfunction and has now been redesigned.
- The measured total annual electricity consumption for pumps, dry cooler system with fans and other auxiliary equipment accounted for about 25 % of the total electricity use for the heating and cooling system. The IE2 pumps should be replaced with IE3 pumps with variable speed drive.

Further aspects to be considered for an optimised system are the following items:

- An air-source heat pump and liquid chiller system were selected due to the low heating demand and the low temperature level in the heat distribution system, and a ground-source system was regarded as unprofitable. However, the measurements showed that the annual heating demand was 4 times higher than the theoretical calculations. Ground-source heat pump and chiller systems have much higher investment costs than air-source systems, but they have the advantages that the heating capacity is independent of the ambient air temperature, and the heat pump supplies heat even at low ambient air temperature, which is especially important for passive house buildings in cold climates. The energy coverage factor will be 20-30 %-points higher than that of air-source systems, the SPF is higher and a large share of the annual cooling demand can be covered by free-cooling from the borehole system. The systems have much less operational problems, lower maintenance costs and no noise from the heat source system. At least 40 years lifetime for the ground-source system (boreholes, BHE etc.). Considerably longer lifetime for the heat pump/chiller units, typically 20-25 years vs. maximum 10 years for air-source systems in Nordic climate.
- Preliminary measurements carried out by SINTEF Building and Infrastructure have demonstrated that the users are very satisfied with the indoor climate (i.e. the air quality and the thermal comfort).



- The project has demonstrated that the entire heating demand in this passive house office building can be covered by heating of ventilation air. This excludes the traditional hydronic heat distribution system with radiators. Due to the elevated air temperature during the heating period, it is essential that the ventilation system is able to maintain adequate ventilation efficiency at varying air flow rates (VAV system) and varying inlet air temperature.
- The maximum supply water temperature in the heat distribution system is as low as 30-35 °C, which is very favourable for an air-source heat pump system since excessive temperature lifts at low ambient air temperatures are avoided. Moderate temperature lifts reduce overall wear and tear and increase the life-time of the compressors and the air-cooled heat exchangers. A measured SPF for heating and cooling of 2.3 is relatively low when taking into account the low distribution temperature. More optimised design and operation will improve the system performance (see below). The supply temperature cannot be lower than 30 °C since the heat pump is also being used for snow melting. The snow melting system has been designed for a supply temperature of 30 °C.
- The twin pump installation between heat pump/chiller units and the accumulation tank is running at constant speed the entire year. This results in a higher annual energy demand for the pump and a reduction in the SCOP for the heat pump/chiller units compared to a system with variable volume flow rate. The existing twin-pumps will be replaced, and separate variable speed drive pumps will be installed in each of the heat pump chillers circuits. The volume flow rate will be controlled according to the heating/cooling capacity of each unit.
- The accumulation tank between the heat pump/chiller units and the heating and cooling system (ref. Figure 15) does not work properly due to mixing of hot and cold brine flows inside the tank (temperature/exergy loss). This results in a lower average COP for the heat pump and chiller units: The accumulation tank will be redesigned/ optimised. By using heat pump/chillers with variable speed compressors the accumulation tank is no longer required.

#### 5.2.4 Conclusions and recommendations

Air-source heat pump and liquid chiller systems represent an interesting alternative in office buildings of passive house or NZEB standard due to moderate investment costs and acceptable operating characteristics. Due to the accomplished project, there are some recommendations to achieve a good operating characteristics:

- Surplus heat from liquid chiller for process cooling (servers, telecom equipment, etc.) should be utilised as much as possible at a moderate temperature level. For DHW heating the application of a desuperheater or an oil cooler (screw compressors) at a sufficiently high temperature level (60-70 °C) increases the efficiency.

Design and operation of air-source heat pump and liquid chillers in Nordic climate:

- Basis of the design is an as far as possible exact load calculation with state-of-the-art computer simulations programs. Low-temperature heat distribution systems with maximum 30-40 °C supply temperature maximises the energy coverage factor and the COP in heating mode, and reduces wear and tear for the compressors. High-temperature cooling systems with minimum 10-12 °C supply temperature maximises the COP in cooling mode. Variable speed drive compressors, e.g. piston, screw or scroll adapts the heating or cooling capacity to the actual demands in the building – no need for accumulation tanks in the distribution system.
- Large heat transfer surface of heat exchanger leads to less frosting due to higher surface temperature, and large fin distance (4-6 mm) leads to lower defrosting frequency, which both consequently leads to less annual energy use for defrosting. Use of an optimised defrosting system with high-quality demand control and use of fans with ultra-low energy consumption, such as fans with energy efficient EC motors can further increase the performance.

### 5.3 Heat pump system in a renovated office building

Powerhouse Kjørbo consists of two office buildings in Sandvika outside Oslo. The buildings from 1985 were refurbished to passive house standard (class A) in 2013-2014, and the total heated area is about 5,200 m<sup>2</sup>. The buildings are planned as plus energy buildings due to the 200,000 kWh/a electricity generation from a large number of PV panels on the roof.

Powerhouse Kjørbo has been certified as "Outstanding" according to the BREEAM-Nor classification system, and is one of the pilot projects supported by the Norwegian Research Centre on Zero Emission Buildings (ZEB – [www.zeb.no](http://www.zeb.no)).



Fig. 46: Powerhouse Kjørbo in Sandvika outside Oslo

Important partners in the project have been the architectural company Snøhetta, the contractor Skanska, the aluminium company Hydro, the real estate firm Entra Eiendom and the Norwegian environmental organization Zero.

Powerhouse Kjørbo has been described as *"the most environmentally friendly office building in the world"*.

In addition to a high-quality air-tight building envelope with low average U-value, VAV ventilation system with low SFP factor and high-efficiency heat recovery, utilisation of daylight, demand controlled lighting systems (LED) and efficient solar shading, the buildings are equipped with an energy efficient heating and cooling system with heat pumps.

#### 5.3.1 System concept

Tab. 11 shows the calculated power and annual energy demands for space heating, heating of ventilation air, domestic hot water (DHW) heating, space cooling and computer cooling.

Tab. 11: Calculated heating and cooling demands at Powerhouse Kjørbo (Nordang, 2014/15)

Demand	Power demand	Specific power demand	Annual energy demand	Specific annual energy demand
Space heating/ ventilation air heating	52.0 kW	10.0 W/m <sup>2</sup>	98,800 kWh/a	19.1 kWh/(m <sup>2</sup> a)
DHW heating	2.8 kW	0.55 W/m <sup>2</sup>	24,800 kWh/a	4.8 kWh/(m <sup>2</sup> a)
<b>Total - heating</b>	<b>54.8 kW</b>	<b>10.6 W/m<sup>2</sup></b>	<b>123,600 kWh/a</b>	<b>23.8 kWh/(m<sup>2</sup>a)</b>
Space cooling	54.0 kW	10.4 W/m <sup>2</sup>	9,500 kWh/a	1.8 kWh/(m <sup>2</sup> a)
Computer cooling	10.0 kW	1.9 W/m <sup>2</sup>	88,000 kWh/a	16.9 kWh/(m <sup>2</sup> a)
<b>Total - cooling</b>	<b>64 kW</b>	<b>12.3 W/m<sup>2</sup></b>	<b>97,500 kWh/a</b>	<b>18.7 kWh/(m<sup>2</sup>a)</b>

The heating and cooling system at Powerhouse Kjørbo comprises a standard ground-coupled brine-to-water heat pump and liquid chiller unit for space heating, heating of ventilation air and space cooling. The heat pump has a heating capacity of 65 kW at 0/45 °C, has 2 scroll compressors with intermittent (on/off) control and electronic expansion valve. It uses the refrigerant R410A and reaches a COP of 4.2 (3.4) at 0/35 °C (0/45 °C), according to manufacturer data. The heat pump has been designed to the full heat load, since extra point for the BREEAM certification can be gained at no NO<sub>x</sub> emissions from of the space heating system. District heating is used as peak load and back-up system. The heat exchanger is connected in series after the condenser for the SH- heat pump unit. The unit is connected to two 900 l storage tanks, which are placed between the heat pump unit and the heat distribution system. 10 225 m boreholes in bedrock (PE 100 turbulence collectors and PE supply/return pipelines charged with 25 % ethanol) is the heat source and heat sink for the heat pump.

Additionally, the boreholes are used for free-cooling operation. The estimated free-cooling from the boreholes was 40-50 kW at 12/17 °C supply/return brine temperature. For DHW operation, a second brine-to-water heat pump of 8.5 kW at 0/45 °C has been installed, which is connected to a 600 l DHW storage tank. The DHW heat pump is a standard R407C brine-to-water heat pump unit. It has a one piston compressor with intermittent control and thermostatic expansion valve. The COP is 4.8 (3.8) at 0/35 °C (0/45 °C), and the heat pump heats the DHW to only 50-60 °C due to the application of a chlorine dioxide (ClO<sub>2</sub>) disinfection system at the city water inlet. Due to the relatively low annual DHW demand, a CO<sub>2</sub> heat pump water heater was considered to be too expensive.

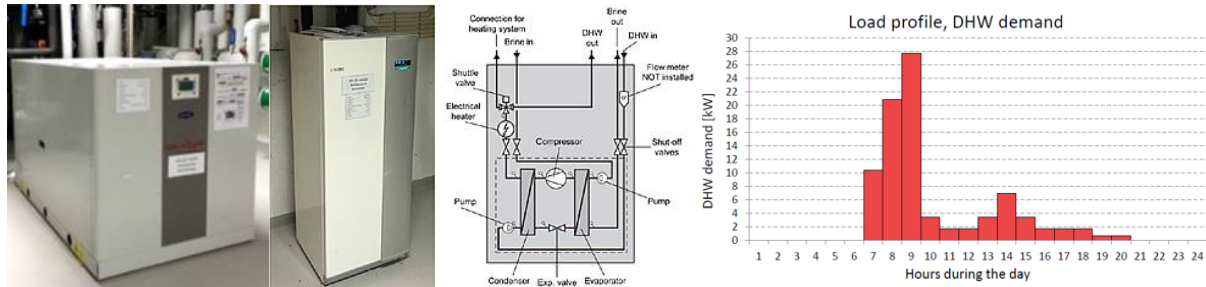


Fig. 47: Space heating heat pump (left), DHW heat pump (middle) and DHW load profile (right) of Powerhouse Kjørbo

A computer and pure water cooling system serves as computer cooling. The centralised heat distribution system is a hydronic closed-loop pipeline system with 2 x 900 litre accumulation tanks connected to radiators and heater batteries in the air-handling/ventilation units and designed to temperatures of 50/40 °C and 50/25 °C, respectively. A separate heat exchanger is installed between the heat distribution system and the ground-source system for rejection of excess heat when the pump is operating in cooling mode. Furthermore, a centralised cooling distribution system – as hydronic closed-loop pipeline system with chilled water connected to cooler batteries in the air-handling (ventilation units) have been installed.

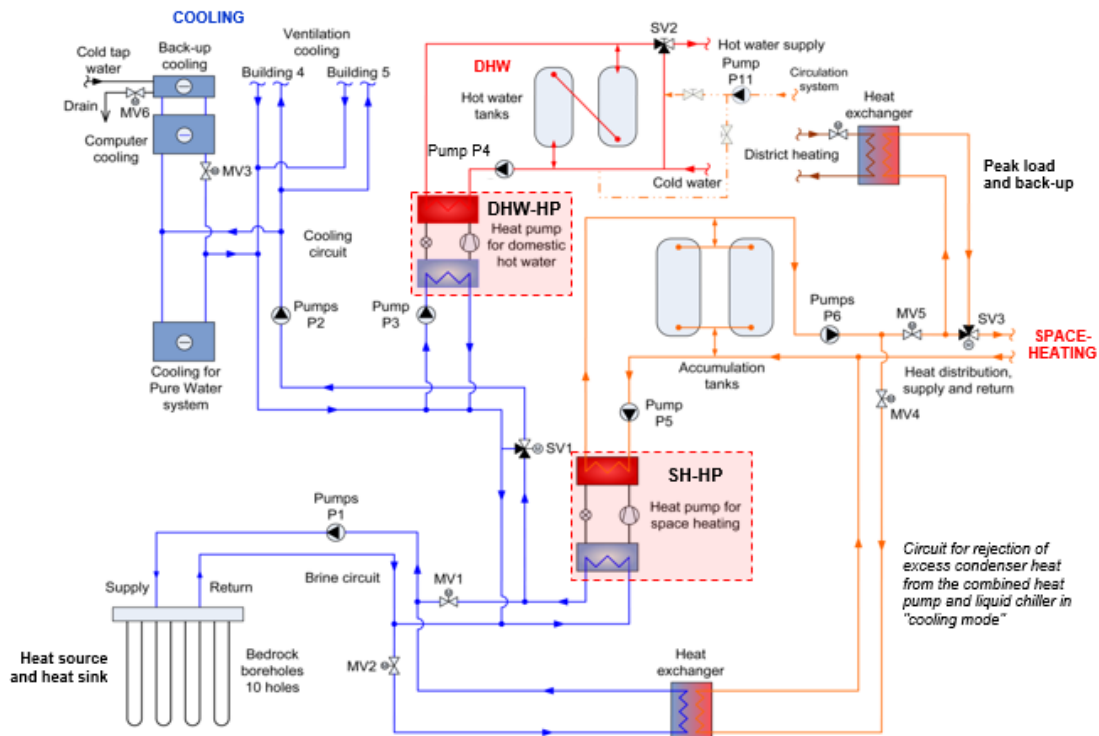


Fig. 48: Simplified sketch of the thermal energy system – heat pump and liquid chiller, DHW heat pump and district heating heat exchanger – for space heating, heating of ventilation air, domestic hot water (DHW) heating, space cooling and process cooling at Powerhouse Kjørbo (Nordang, 2014/15).

Fig. 48 shows a simplified sketch of the thermal energy system at Powerhouse Kjørbo including the ground-source system, the heat pump and liquid chiller unit, the DHW heat pump unit, various plate heat exchangers, accumulation tanks, pumps, valves and pipeline system (Nordang, 2014). The sketch does not include details for the distribution systems.

### 5.3.2 Monitoring results

Fig. 49 shows the instrumentation of the temperature sensors, pressure sensors, electric power/energy meters and thermal power/energy meters which are installed in the borehole (brine) circuit, the DHW system, the space heating system incl. the district heating circuit (back-up) and the circuits for space cooling (cooling of ventilation air) and process cooling. All the sensors are linked to a centralised control and monitoring system.

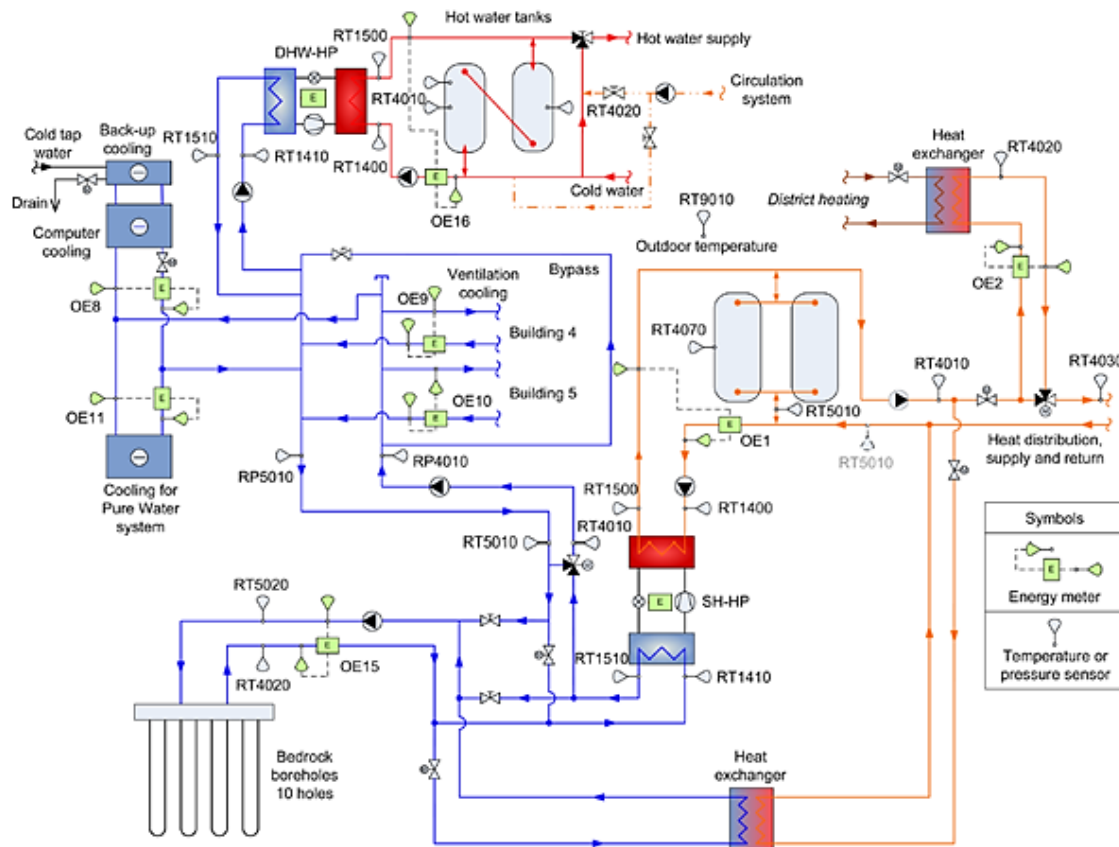


Fig. 49: Instrumentation for the thermal energy plant with temperature sensors, pressure sensors, electrical power/energy meters and thermal power/energy meters (Nordang, 2014/15).

Fig. 50 shows the calculated and measured maximum power demands [kW] and annual specific energy demands [kWh/(m<sup>2</sup>a)] for Powerhouse Kjørbo (Nordang, 2014/15). The duration curves are depicted in Fig. 51 (left). The measured power and energy demands for space heating and ventilation air heating have been subjected to a "normal year correction", since the simulations in Simien were based on average ambient air temperatures over a 30 year period (Nordang, 2014/15). The deviation of the space heating load of about 37 % in the monitoring was mainly due to a lower ventilation heat recovery efficiency. Nevertheless, the entire annual heating demand was covered by the SH heat pump unit despite a 30 % higher consumption. The space cooling power demand for the cooling of ventilation air was 29 % higher mainly owing to the extremely warm summer in Norway in 2014. Consequently, the measured annual energy demand for space cooling was also 11 % higher than the calculated value. The entire cooling demand was covered by the ground source system, i.e. free cooling by the 10 boreholes. The total borehole length is approx. 2,250 m. On the other hand, the DHW energy demand was overestimated by approx. 60 %, i.e. the DHW user pattern for this particular office building departed considerably from the standard (normative) value in the Norwegian building code NS3031.

	CALCULATED	MEASURED	DEVIATION COMMENT
Space heating and heating of ventilation air	19.1 kWh/(m <sup>2</sup> year)	24.6 kWh/(m <sup>2</sup> year)	+ 29 %
	10.0 W/m <sup>2</sup>	14.4 W/m <sup>2</sup>	+ 37 %
DHW heating	4.8 kWh/(m <sup>2</sup> year)	1.9 kWh/(m <sup>2</sup> year)	- 60 %
Space cooling	1.8 kWh/(m <sup>2</sup> year)	2.0 kWh/(m <sup>2</sup> year)	+ 11 %
	10.4 W/m <sup>2</sup>	13.5 W/m <sup>2</sup>	+ 29 %
SPF – heat pump for space and vent. air heating	*	3.9	Incl. pump energy for the borehole system
SPF – heat pump water heater (DHW heating)	*	2.9	Incl. pump energy

Fig. 50: Comparison of calculated and monitoring data (Nordang, 2014/15).

### 5.3.3 The ground-source heat pump system

Two ground-source heat pump units, one for space heating and one for DHW heating are installed at Powerhouse Kjørbo.

#### Seasonal performance factor of the heat pumps

The measured SPF for the heat pump unit for space heating operation was about 3.9 (including the annual input energy to the pumps in the borehole system) and the energy coverage factor was approx. 100 %. Consequently, the net energy saving for the SH heat pump unit was 75 %. The most important factors leading to the high SPF despite the rather high design temperatures of the heat distribution system (50/40 °C) was the oversized ground-source system with a relatively high average brine temperature.

The measured SPF for the DHW heat pump unit was about 2.9 including the annual energy input to the pumps. Since the energy coverage factor was approx. 100 %, this corresponds to a net energy saving of 65 %. The relatively high COP was caused by fluctuations in the outlet temperature from the DHW heat pump between 25 and 60 °C with an average of 45 °C. The standard legionella-safe DHW storage temperature in Norway is 65 to 70 °C. The DHW temperature at Powerhouse Kjørbo is lower since the DHW system has been equipped with a chlorine dioxide cleaning system.

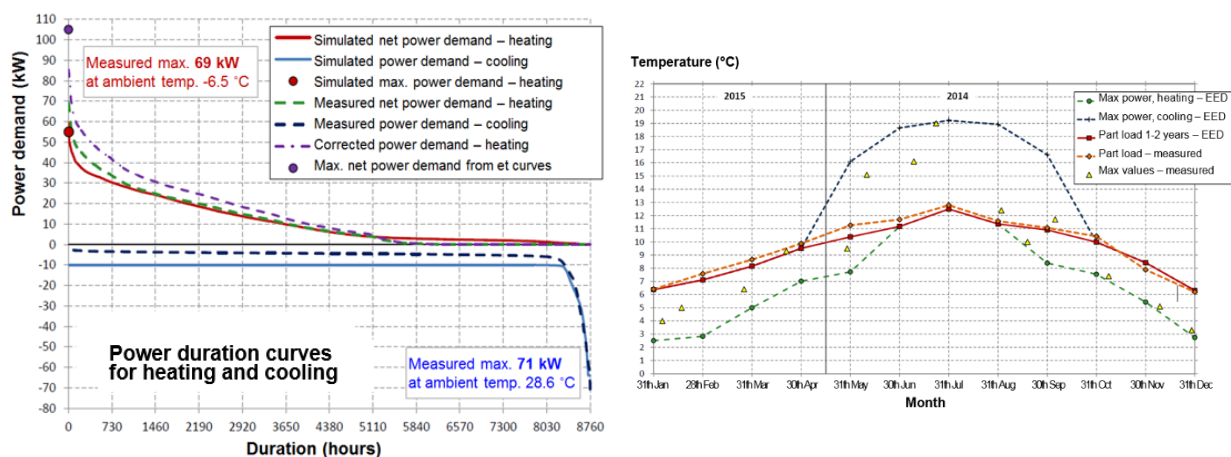


Fig. 51: Simulated (EED) and measured average brine temperatures for the ground-source (borehole) system at max. power and part load in heating and cooling mode (Nordang, 2014).



### Borehole ground heat exchanger system

The borehole system was designed to cover the entire space and process cooling demand in the building (65 kW) by free cooling at 12/17 °C supply/return temperature in the distribution system, i.e the outlet brine temperature from the boreholes cannot exceed the required set-point temperature in the cooling system. In standard ground-source heat pump systems the heat pump is utilised as a liquid chiller that covers the peak load space cooling demand in the building, and the excess condenser heat is rejected to the boreholes at a temperature level between 25-30 °C. The conventional system design requires less boreholes than a system based entirely on free cooling, but the annual energy consumption will be slightly higher due to occasional chiller operation during the summer.

The ground-source simulation programme Earth Energy Designer (EED) was used to calculate the average brine temperatures and thermal energy balance for the borehole system during several years of operation. Fig. 51 (right) shows the simulated and measured mean brine temperatures at max. power (capacity) and part load operation in heating and cooling mode. The measured values correspond rather well with the simulated values, which demonstrates that EED is a suitable tool for borehole simulations as long as the input parameters have sufficient accuracy.

The measured minimum mean temperature during heating mode was as high as 3 °C. The reason for the relatively high minimum temperature in heating mode was that the borehole system was designed to cover the peak load cooling demand with free cooling, since this gives an extra point in the BREEAM evaluation. The measured maximum average brine temperature in cooling mode was approx. 19 °C, which obviously was sufficient to cover the maximum cooling demand since the heat pump unit never has been operated as a chiller.

#### **5.3.4 Improvement of the existing heating and cooling systems**

Based on the operational experience and measurements from the prevailing heating and cooling system at Powerhouse Kjørbo, some recommendations regarding system redesign and alternative operational strategies have been suggested:

- Instead of designing the ground source system to cover the entire cooling demand by free cooling from the boreholes in order to gain extra points at the BREEAM evaluation, the system should have been designed as a conventional ground source system. This would have led to a reduction of boreholes needed from 10 to 5-6, thus reducing the investment costs by approx. 40-50 %.
- In order to improve the eco-friendly profile of the building, the 65 kW heat pump should have used R290 (propane) and the 8.6 kW heat pump should have used CO<sub>2</sub> (R744) as working fluid.
- Due to the intermittent control of the two scroll-compressors of the 65 kW HP, the unit did not operate satisfactorily at low heat loads. Instead of an intermittent control (on/off control), there should have been installed variable speed drive (VSD) compressors.
- The computer cooling system is transferred directly to the boreholes and is not utilised by the heat pump units. The system should have been connected in series before the heat pump evaporators in order to maximise the heat source temperature.

#### **5.3.5 Conclusions and recommendations**

The ground-source heat pump and liquid chiller systems represent an interesting alternative in office buildings of passive house or NZEB standard due to excellent performance and large energy savings, large flexibility with regard to heating and cooling as well as a long lifetime.

Application of sufficiently accurate computer models in order to obtain correct sizing of the heat pump and chiller units as well as the ground source is essential for an energy efficient and economic design. Also, it is important to be aware of the low cooling and heating demands of a NZEB, which is crucial for the cost of the systems.

The following recommendations should be considered to achieve an energy efficient and cost-effective system design:



- Free cooling from the borehole system should be utilised as much as possible. Peak load cooling covered by the heat pump is less energy-efficient than a system with free cooling, but the number of boreholes and thereby the costs for the ground source system can be considerably reduced.
- Since they are 100 % eco-friendly in contrary to the HFCs and HFOs, natural working fluids should be chosen if possible.
- VSD compressors will lead to a very high part load efficiency.
- The building should have a low-temperature hydronic distribution system for heating and a high-temperature distribution system for cooling.
- Surplus heat from separate liquid chillers for process cooling (servers, telecom equipment, etc.) should be utilised as much as possible to cover heating demands of the building.
- Use an optimised instrumentation and monitoring system, since it will help to optimise the operation of the whole system and to detect errors at an early stage.



## 6 Field tests and demand response in Switzerland

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In Switzerland the MINERGIE-A® label is referring to a nearly zero Energy building certification scheme, where the weighted energy for the building technology is balanced on an annual basis by energy production on the building footprint. It has been introduced in March 2011. Moreover, also plus energy buildings which balance the total weighted energy including plug loads exists. In the following, two field tests with extensive measurements of a plus energy multi-family building and one of the first MINERGIE-A® certified buildings with office use are described. As one aspect for the monitoring, also load shift options for demand response and self-consumption fractions are evaluated. Regarding demand response, also a simulation study for storage capability in the thermal mass of the building structure is presented.

### 6.1 Field monitoring of multi-family plus energy buildings in Rupperswil

#### 6.1.1 Motivation

New buildings with an on-site electricity production get more and more common. The balance of energy consumption and the decentralised power supply for the entire system building with grid connection always matches. Energetic target values are specified by architects and planners, but if they match in reality is generally not verified by measurements. Especially sophisticated and innovative building concepts need a competent commissioning and monitoring in the initial phase.

The project deals with a multi-family building with three tenants. The photovoltaic system is designed to produce more electricity than needed for space heating, DHW, mechanical ventilation and all domestic appliances on annual balance. The goal in this project is to use the surplus electricity locally for an electric car. The building is connected to the grid of the local power supplier. The power grid compensates the temporal differences between power production and consumption of the building.

A detailed monitoring allows conclusions on the production of heat and electricity and shows when the energy is used for which application. Based on the monitoring data, further optimisation can be accomplished.

The following questions were to be answered in the project:

- Detailed collection of measurement data concerning thermal and electrical energy flows
- Energy consumption of all characteristic consumers and the PV yield of the building
- Recognise, identify and evaluate characteristic influences on the simultaneity (load match)
- Assessment of the impact of load shifting measures during three heating seasons
- Impact of the use of the electrical car on the energy balance of the building
- Legal impacts/obstacles for rented buildings with local power production
- Impact of user behaviour on the energy balance (installed user information system)

Web based information systems provide information about the power and heating energy consumption of each resident. The interaction between this energy information system and the residents as well as the handling of a bonus/malus system is topic of the investigation based on the feedback of the residents and the data collected by the building owner.

#### 6.1.2 Building specification

The building is a small and heavyweight multi-family building in Rupperswil, Canton Aargau, Switzerland. The building with two floors and a cellar has a heated living space of 320 m<sup>2</sup>. On both the ground floor and the first floor, there is an apartment of 135 m<sup>2</sup> energy reference area each. A studio with 50 m<sup>2</sup> energy reference area is located in the basement. The building is certified according to the Swiss label MINERGIE-P-eco® (AG-005-P-ECO) and has won the Swiss Solar Price 2012 in the category "Plus energy building".



Fig. 52: Multi-family plus energy building in Rupperswil AG, (Source: Setz Architekt, FHNW IEBAU)

#### Building envelope characteristics

- A highly thermally insulated building envelope with a wall thickness of 0.44 m, of which 0.24 m are thermal insulation
- U-value walls: 0.12 W/(m<sup>2</sup>K), U-value floor: 0.11 W/(m<sup>2</sup>K), U-value roof: 0.09 W/(m<sup>2</sup>K)
- Plastic/aluminium windows and doors with a triple glazing, U-value glass: 0.50 W/(m<sup>2</sup>K), U-value window: 0.80 W/(m<sup>2</sup>K)

#### Technical building system

A heat pump with a rated capacity of 8.9 kW (at operating point B0/W35) delivers heat for space heating and domestic hot water. A borehole heat exchanger of 180 m serves as source for the heat pump. A heat storage of 200 l for the space heating and 500 l for the domestic hot water stores the generated heat and hot water, respectively. The emission system for the space heating operation is a low temperature floor heating system. For free cooling operation, the borehole heat exchanger can be directly connected to the floor heating system by a bypass heat exchanger. But, this additional function was not used during the monitoring.

The mechanical ventilation system with heat recovery of cross-counter flow type ( $\eta_{HRV} = 80\%$ ) and a volume flow rate of 120 m<sup>3</sup>/h supplies the apartments with fresh air.

The building has a south-oriented photovoltaic (PV) system which is mounted with a tilt angle of 10°. The total panel area of 102.7 m<sup>2</sup> consists of 63 monocrystalline modules. Three inverters are installed for the DC-AC-conversion of the PV field which has a nominal capacity of 20 kW<sub>p</sub>. The estimated annual energy yield is 18,000 kWh<sub>el</sub>.

#### Heat demand calculations

The total energy reference area adds up to 396 m<sup>2</sup>. The net living area is 285.5 m<sup>2</sup>. The calculated space heating need is 23.7 kWh/(m<sup>2</sup>a), based on the Swiss calculation standard SIA 380/1 (2009). The effective space heating demand including the heat recovery of the mechanical ventilation, which was used for the MINERGIE-P-eco<sup>®</sup> certification, is only 10.8 kWh/(m<sup>2</sup>a). The design heat load according to the Swiss standard SIA 384.201 (2005) is 10.8 kW at a design ambient temperature of -8 °C and a room temperature of 20 °C. The supply temperature of the floor heating system is designed to a flow temperature of 30 °C and a return temperature of 25 °C. The standard DHW energy demand according to SIA 380/1 (2009) is 20.8 kWh/(m<sup>2</sup>a) at a DHW water temperature of 60 °C.

### **6.1.3 Monitoring results**

The evaluated monitoring cover the period of October 2011 until April 2014.

### Energy balance electricity

The cumulated photovoltaic yield exceeds the cumulated energy consumption by 8,383 kWh in the considered project time. This corresponds to 23% of the total electricity consumption.

### PV-yield

In total, 45,492 kWh electrical energy is produced by the PV-plant in the evaluated period. This corresponds to surplus of 5% in comparison to the forecasted yield.

### Total electricity consumption

In the monitoring period, the total consumption of the building added up to 37,000 kWh electricity. The monthly-consumed amount of electrical energy varies between 909 kWh in September 2012 and 1,802 kWh in January 2014. The separation of the total consumption to individual consumer groups shows that the consumption of the household appliances of the three apartments has the largest share in the total consumption, see Fig. 53. The electricity consumption of the brine-to-water heat pump for space heating and domestic hot water represents the second largest share. The third position in the consumer ranking is the mobility e.g. the charging of the battery of the electric car.

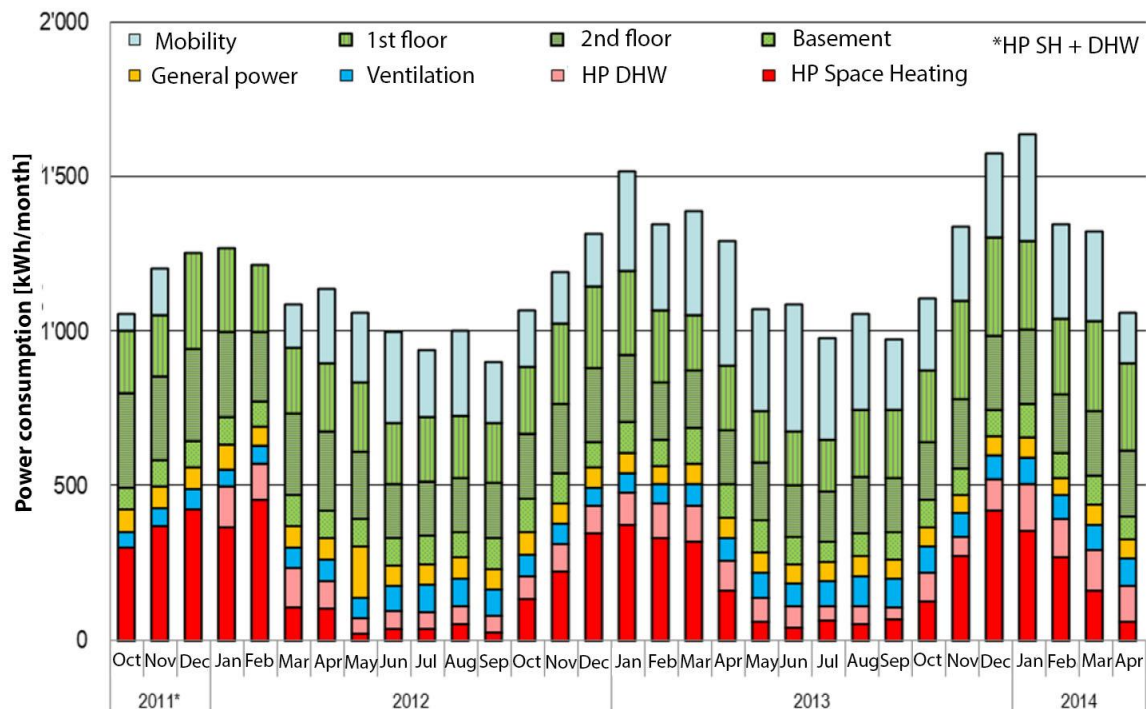


Fig. 53: Monthly electricity consumption divided into different consumer groups for the period from October 2011 to April 2014

### Space heating

In Fig. 54 monthly space heating values for all three tenants is shown in comparison to the calculated space heating demand. Especially in the second half of the heating period (January to April), the measured values are higher than the calculated ones. According to the building owner, the measured higher consumption is attributed to the user behaviour of individual residents.

### Domestic hot water

During the project, the domestic hot water consumption amounts to 234 m<sup>3</sup> or 10,300 kWh, respectively. This corresponds to a specific domestic hot water consumption of 15 kWh/(m<sup>2</sup>a). Fig. 55 shows the measured values for each tenant per month, which corresponds to the standard values for single family houses. However, in multi-family houses, this value is a bit higher. Nevertheless, the consumptions is quite similar to the standard values.

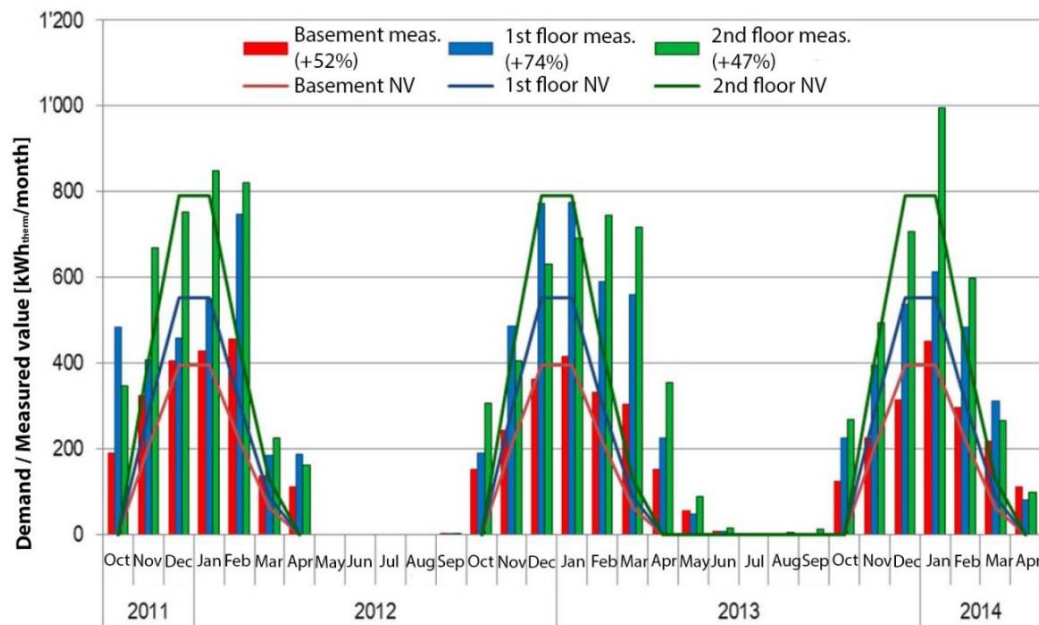


Fig. 54: Space heating demand of the building between October 2011 and April 2014

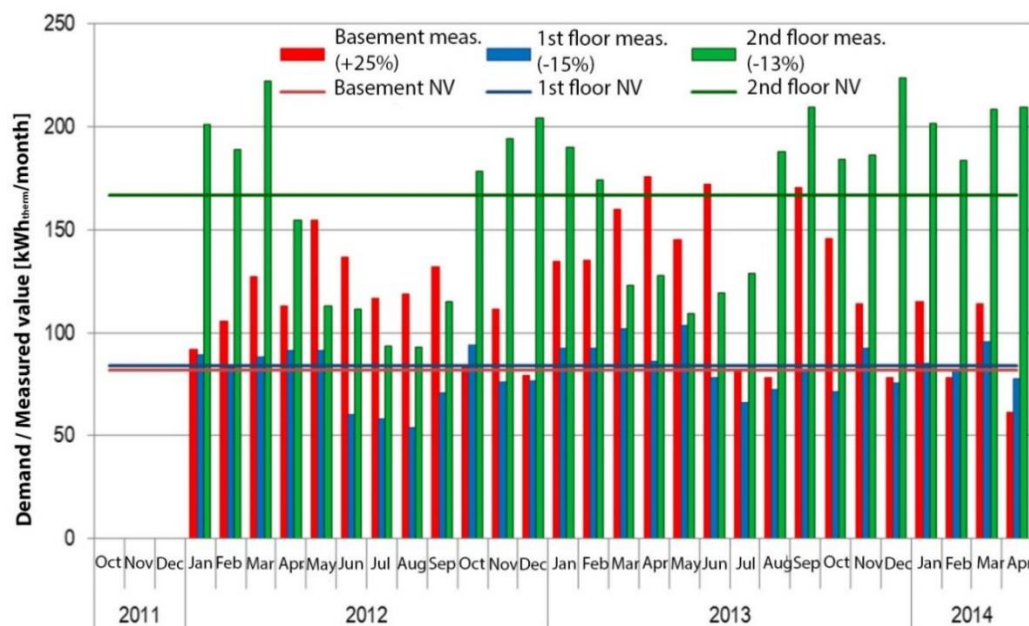


Fig. 55: Domestic hot water demand of the building between October 2011 and April 2014

#### Performance factor of the heat pump

In this project two different operating modes are investigated. The SPF for space heating and domestic hot water according to these operating modes are given in Tab. 12:

- **Driven by demand:** The return flow temperature of the floor heating system or the temperature of the domestic hot water storage define the operating time of the heat pump.
- **Optimised:** To increase the self-consumption of the PV yield, the operating time of the space heating and domestic hot water heat is limited to the day.

The optimisation of the operating time leads to an improved performance factor in comparison to the demand driven operation both for the space heating and the domestic hot water operation, as depicted in Tab. 12. This is due to longer continuous operating time and less compressor starts. Therefore, the electrical consumption of the heat pump decreases.



Tab. 12: Performance factor for space heating and domestic hot water

Operation driven by demand		Optimised operation	
Performance factor space heating	Performance factor domestic hot water	Performance factor space heating	Performance factor domestic hot water
3.8	3.6	4.9	3.9

#### Options load shift - Load shift to noon

The biggest single consumer with separated measuring data is the heat pump (26.5%), the dishwashers (2.2%) and the E-car (2.4%). The energy consumed outside the time period from 10:00 to 16:00 h can be considered as load shifting potential. But in the end, only the heat pump has potential for load shifting because the operation time of the dishwashers and the E-car by the user cannot be fully controlled. An optimal adaption of the operating time of the heat pump to the momentous PV yield leads to a simultaneous rate of up to 58%.

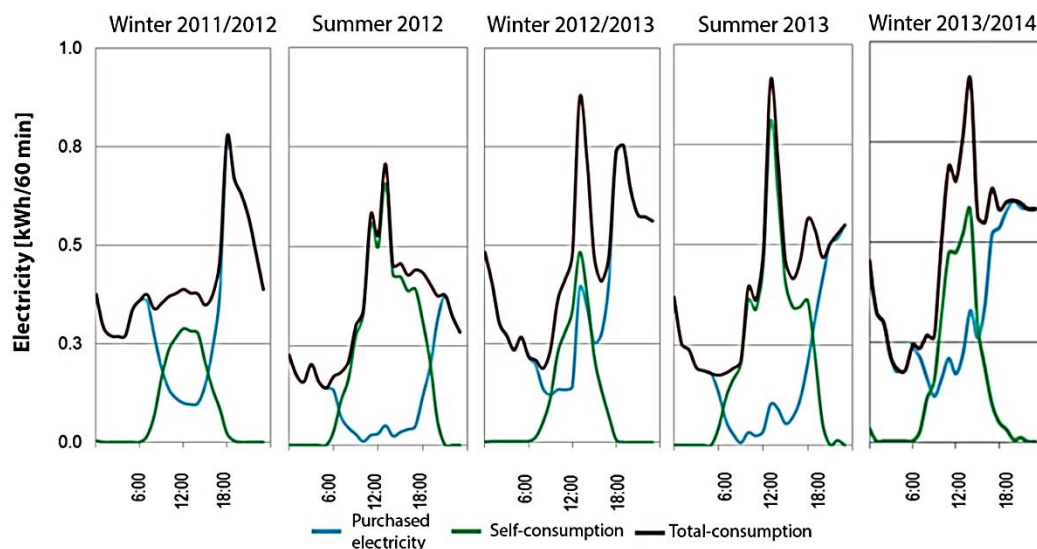


Fig. 56: Load profile of the time-averaged one hour values of the purchased grid electricity, the total electricity and the self-consumption

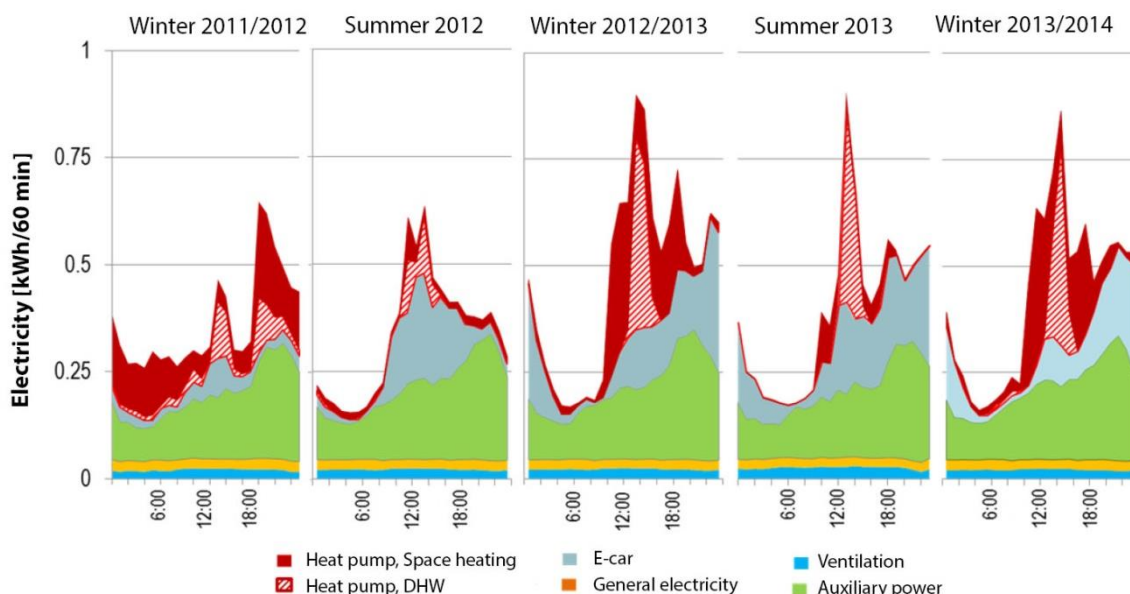


Fig. 57: Averaged one hour values of the energy consumption of each consumer load

During summer 2012, in a first step the operation time of the heat pump for domestic hot water production was limited to the noon hours (Fig. 56 and Fig. 57). In the first half of winter 2012/2013, the heat for space heating was produced during night-time (18:00 - 08:00 h) to benefit from the favourable electricity tariff during the night. This leads to a further load peak in the evening. Already in February 2013, the space heating energy was produced by the heat pump between 10:00-19:00. In winter 2013/2014, the load profile shows a further concentration of the heat pump operation to the noon hours for space heating and domestic hot water.

### Self-coverage and self-consumption rate

Fig. 58 shows the calculated self-coverage rate (also denoted as load or demand cover factor (LCF and DCF, respectively) and the self-consumption rate (also denoted as supply cover factor SCF) based on 15 minutes measured values, including and without considering the electrical car. Including the electric car and neglecting the respective amounts of energy, there are self-coverage rates of 32-34% which are higher than in other zero energy buildings (e.g. Effizienzhaus Plus, Berlin, with self-coverage rates of 15-25%). Thus, it can be assumed that as a result of the load shift to the noon, an enhanced self-consumption has been reached. However, this rate can be further increased by the use of an electric battery.

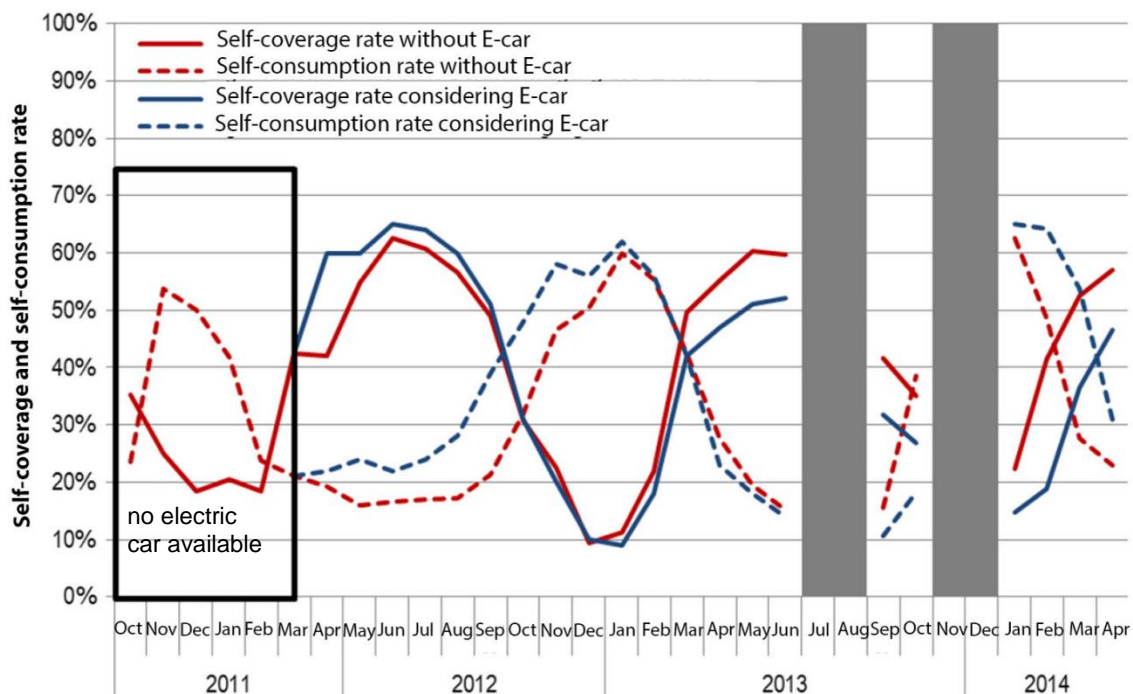


Fig. 58: Self-coverage and self-consumption rate including and without considering the power consumption for the electrical car for the period October 2011 and April 2014 (Periods with missing data are grey)

The self-coverage rate shows in function of the solar radiation a simultaneous course of the year. In wintertime, the PV yield covers only a small amount of the power consumption; therefore, the self-coverage rate is only around 10%. During summer, the self-coverage rate increases to 63% due to the high PV yield.

As expected, the self-coverage and the self-consumption rates are contrary. The large PV plant of the building causes a higher annual yield than the annual consumption. Due to this, in the summer only a part of the PV yield can be consumed directly by the building. This leads to self-consumption rates between 10 and 20%. Even in winter, not the full amount of the generated energy can be used by the building. Therefore, even in the low-radiation period, the self-consumption rate remains below 100%.

## 6.2 Field monitoring of MINERGIE-A® building in Uster

### 6.2.1 Project overview and building concept

In Switzerland, currently, there is no uniform definition of a nearly zero energy building. However, as mentioned above, in March 2011, the MINERGIE-A®-label has been introduced as one implementation of the nZEB concept requiring a net zero energy balance in the balance boundary of the operational energy for the building technology. While initially only applied for the certification of residential buildings, an extension to non-residential buildings like offices and schools has been introduced in May 2014. Therefore, currently not much experience exists and monitoring data for the evaluation of the requirements for office buildings are required. The nZEB for the field-monitoring is a newly constructed building with mixed residential and office use located in the centre of the Swiss town Uster in Eastern Switzerland. It has been commissioned in February 2014 and it is the first MINERGIE-A® certified building in the canton Zurich.

The building is equipped with a ground source heat pump for heating and a 23.7 kW<sub>p</sub> PV-system, as well as 7.1 m<sup>2</sup> PV/T-collector for DHW preheating. The ground-source heat exchanger is used for free-cooling in summer operation. Moreover, a mechanical ventilation system is installed. Fig. 59 summarises the building envelope characteristics, which approaches values of passive house constructions. The calculated specific heating demand of the building is 23.6 kWh/(m<sup>2</sup>a). The nZEB balance according to the Swiss standard MINERGIE-A® has been reached.



Fig. 59: Monitored MINERGIE-A® building in Uster and envelope characteristics (Hässig, 2013)

The building has an energy reference area of 1,206 m<sup>2</sup> which comprises 367 m<sup>2</sup> of office space with 20 workplaces as well as 839 m<sup>2</sup> living space, which is divided into 7 apartments inhabited by 16 persons. Fig. 60 gives an overview of the building system technology.

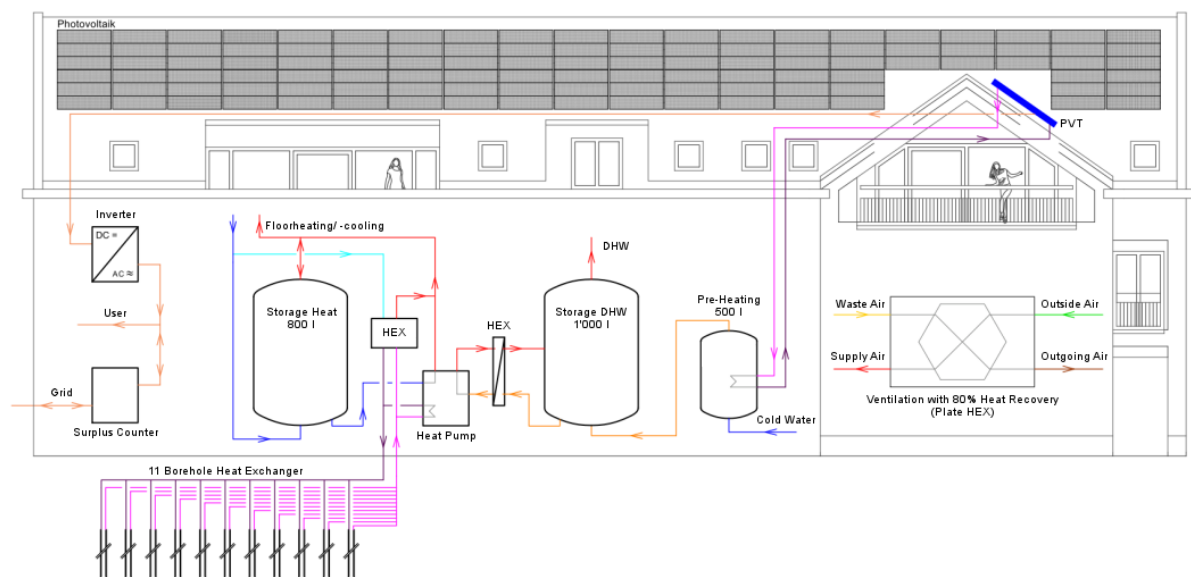


Fig. 60: Building technology of the MINERGIE-A® building in Uster (Hässig, 2013)

The DHW is reheated by the heat pump in a 1,000 l storage, which also contains a direct electrical back-up heating for legionella protection. For the space heating operation, an 800 l buffer storage is integrated in parallel to the floor heating systems. An accompanying direct electrical pipe heating is installed to fulfil the Swiss SIA-standard (SIA385/1, 2011) for DHW comfort. The system has a power of 1 kW and allows supplying tap water at 40 °C in 10 s at any time of the day. As innovative technologies, a PV/T collector for DHW preheating is installed and a publicly rentable electric car is used as local electricity storage of PV-electricity in order to enhance the local use of PV-electricity and reduce grid-interaction. More detailed information about the building technologies are gathered in Tab. 13.

Tab. 13: Data of the installed building technologies

<b>PV generator</b>	
Peak power	23.7 kW <sub>p</sub>
Calculated annual yield	24,000 kWh
103 modules, $\eta = 18.6\%$ ; orientation: SW (52), SE (51); inclination: 35°	total 128 m <sup>2</sup>
<b>PV/T collector</b>	
Total area	7.1 m <sup>2</sup>
Nominal capacity electric / thermal	180 W <sub>p</sub> / 430 W
<b>Ground source heat pump</b>	
Number of boreholes / depth	11 / 70 m
Nominal heating capacity / COP	B0/W35: 33.1 kW / 4.6
	B0/W50: 30.5 kW / 3.0
<b>Storages</b>	
Heating buffer storage	800 l
DHW preheating	500 l
DHW reheating	1000 l
<b>Electrical heating element / electrical tube heating</b>	
Heating element for legionella protection	10 kW
Electrical tube heating	1 kW
<b>Balanced mechanical ventilation with heat recovery</b>	
<u>Office space (20 workplaces)</u>	
On-demand controlled based on CO <sub>2</sub> -concentration	
Nominal volume flow rate	600 m <sup>3</sup> /h
<u>Living space (7 flats)</u>	
Nominal volume flow rate	350 m <sup>3</sup> /h

### 6.2.2 Monitoring system

A detailed measurement concept has been realised to monitor the building. The monitoring system records relevant data of the major components of the building technology, detailed electrical energy consumption of the office space as well as sizes related to comfort conditions. The main objective of the field monitoring was the evaluation of the net zero energy balance according to the requirement of the MINERGIE-A®-label. The monitoring of the PV/T-collector, the PV-generator, the heat pump and electrical energy comprises around 70 measuring points. To ensure precise results, the installed measurement sensors (thermocouple, flowmeter) have been calibrated.

The objectives of the monitoring were:

- To gather experience with the MINERGIE-A® certification in office buildings
- To identify optimisation potentials by the monitoring
- To approve the system design/nearly zero energy balances according to MINERGIE-A® and to investigate load management options for demand response

### 6.2.3 Annual evaluation of field monitoring

#### MINERGIE-A® balance

The MINERGIE-A®-index has been calculated using the following formula:

$$MINERGIE - A^{\circ} - index = \frac{2}{1206 \text{ m}^2} (E_{Ven} + E_{HP} + E_{HR} + E_{Sol} - E_{PVT} - E_{PV}) \quad (\text{Eq. 1})$$

$E_{Ven}$ : Energy consumption ventilation  
 $E_{HP}$ : Energy consumption heat pump  
 $E_{HR}$ : Energy consumption heating element  
 $E_{Sol}$ : Energy consumption circulation pump  
 $E_{PVT}$ : Energy production PV/T-generator  
 $E_{PV}$ : Energy production PV-generator

According to the MINERGIE<sup>®</sup>-guideline, electricity is weighted with the factor 2 based on the interior electricity balance in Switzerland with about 60% hydro power production and about 40% nuclear production. Due to missing monitoring data, simplifications have been made to estimate the electricity consumption of the dwellings ventilation (183 kWh/month, design value) and the consumption of the solar circulation pump of the PV/T collector (consumption of 50 W when turned on).

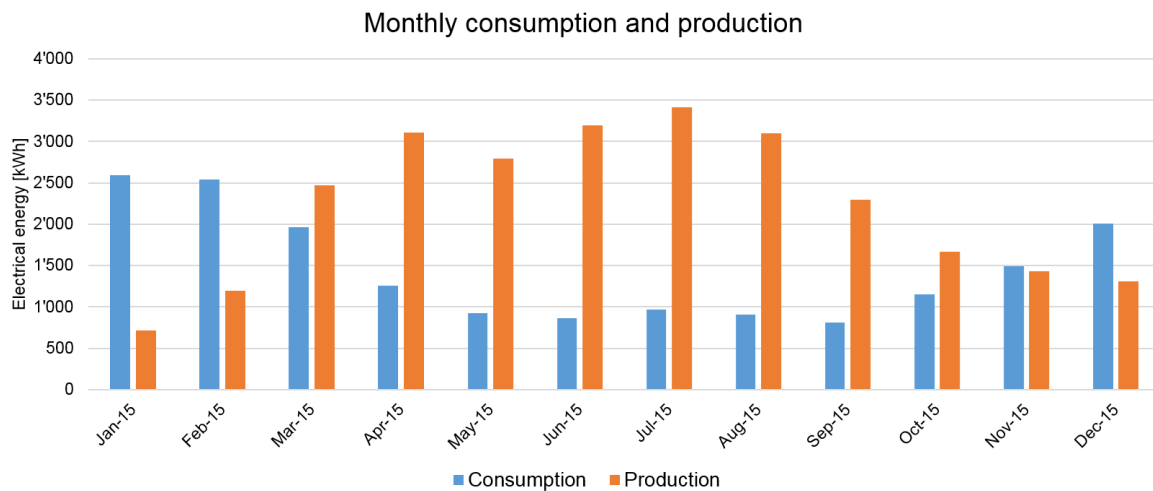


Fig. 61: Electricity production and consumption in 2015 (Büsser, 2016)

For 2015, the MINERGIE-A<sup>®</sup>-index was -16.9 kWh/(m<sup>2</sup>a) which fulfils the requirements and lies considerably below the design value of -5.7 kWh/(m<sup>2</sup>a). Fig. 61 and Tab. 14 show the monitoring data and the MINERGIE-A<sup>®</sup>-index on monthly basis for the year 2015. The main reasons for the difference to the design value of the MINERGIE-A<sup>®</sup>-index is the heat pump with a measured consumption 34% below the design value, which may be due to the warm weather in 2015. Furthermore, there is a surplus in solar yield compared to the calculated values in the design phase.

Tab. 14: Monitoring data for the calculation of the MINERGIE-A<sup>®</sup>-index

Energies [kWh]	E <sub>Vent</sub>	E <sub>HP</sub>	E <sub>HR</sub>	E <sub>Sol</sub>	E <sub>PVT</sub>	E <sub>PV</sub>	MINERGIE-A <sup>®</sup> -index
Jan-15	268	1754	566	3	20	696	3.1
Feb-15	280	1740	517	3	39	1155	1.9
Mar-15	297	1136	524	8	84	2386	-1.1
Apr-15	299	556	394	10	117	2995	-3.4
May-15	297	305	315	12	101	2690	-3.4
Jun-15	285	306	257	14	121	3075	-4.2
Jul-15	284	420	252	14	128	3282	-4.4
Aug-15	283	349	259	13	113	2988	-4.0
Sep-15	294	261	247	9	82	2210	-2.8
Oct-15	296	584	264	6	49	1615	-1.2
Nov-15	326	909	255	5	38	1393	-0.2
Dec-15	331	1414	260	4	29	1277	0.9



In order to give a complete picture, Fig. 62 left shows the electric consumption of the building technology as well as the solar production for 2015. Considering only the building technology, the heat pump is with 56% responsible the largest share of the electrical consumption. DHW production (direct heating and tube heating) and consumption of the ventilation have a fraction of 24% and 20% of the total consumption, respectively, while the share of the solar circulation pump is below 1%. Furthermore, Fig. 62 right shows the distribution of the electric consumption including office plug loads and electronical data processing (EDP) appliances for the evaluation period May 14 until Aug 15.

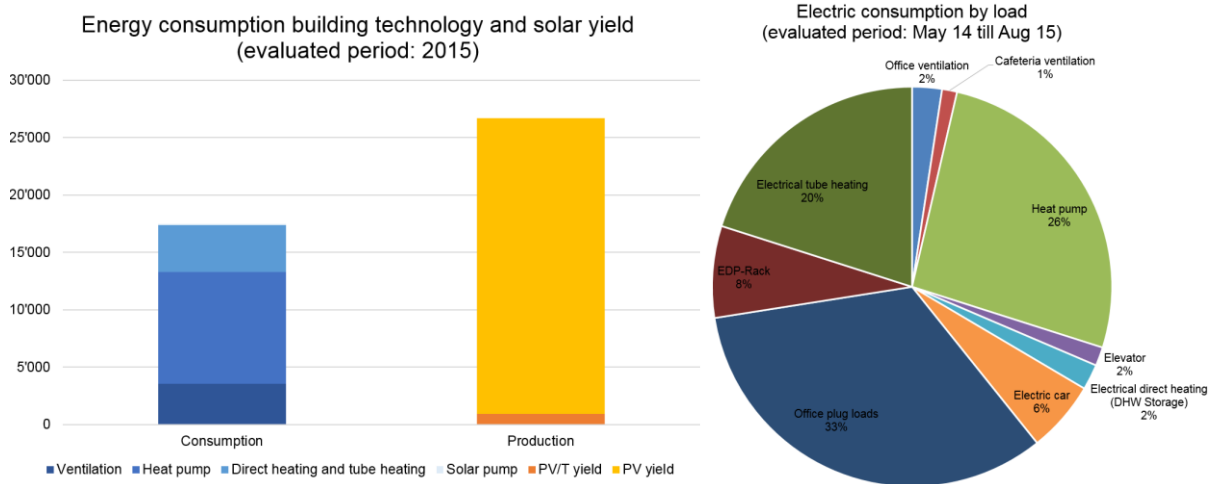


Fig. 62: Electricity consumption and solar yield (left) and consumption by load (right) (Büsser, 2016)

### Heat pump performance

For the period from May 14 until March 15, the seasonal performance factors for heating and DHW operation as well as the overall seasonal performance factor including the entire source pumping energy have been determined. The time period involves only 11 months due to missing data of April 15. The  $SPF_H$  in space heating mode reaches with 4.68 a very high value, and also the  $SPF_{DHW}$  in DHW mode is high for the evaluated period with a values of 3.51. The overall SPF is 4.29 (Fig. 63 right).

The high SPF in the monitored period can be explained by the high source temperature for the heat pump, which allows the heat pump to operate at low temperature lifts and thereby high performance level. Fig. 63 left shows the return flow temperature of the boreholes (2 min before stopping the circulation pump) for the year 2015. The source temperatures are constantly on a high level. Furthermore, in Fig. 63 right, the monthly SPF in space heating and DHW mode as well as overall SPF are shown.

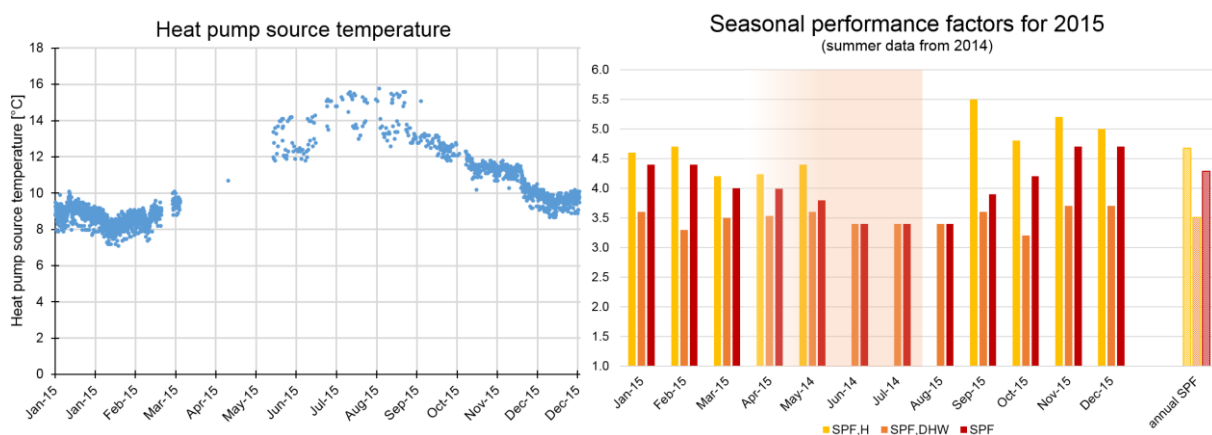


Fig. 63: Heat pump source temperature (left) and SPF (right) (Büsser, 2016)

Due to a measurement interruption, a combined consideration of 2014 and 2015 data has been applied. Annual data from 2015 has been complemented with summer data (May, June and July) from 2014. The data from April has been interpolated from March 15 and May 14.



In September 2015 a very high  $SPF_H$  of 5.5 has been reached. Comparing this value to Fig. 63 left, this high performance number can be linked to the very high source temperatures of the heat pump, which in September were in the range of approximately 13 °C. An explanation for the high source temperatures is the ground-coupled free-cooling operation which takes place in the summer month and regenerates the borehole-field.

#### Cooling operation

In cooling operation, the system efficiency can be described as the ratio of the heat removed from the building and the electricity consumed by the source pump and the floor-heating circuit pumps.

$$SPF_C = \frac{Q_C}{E_C} \quad (\text{Eq. 2})$$

$Q_C$ : Removed heat for cooling

$E_C$ : Energy consumption of the pumps for cooling

The system performance for cooling operation has been evaluated for August 2014 and July 2015 (10.7.-31.7.). Cooling is realised by using the boreholes as heat sink. Therefore, there is no conventional mechanical cooling with a chiller, but electricity is only used for the circulating pumps. This results in a high performance factor of 15.5 in August 2014 and 13.5 in July 2015.

#### Demand cover factor and supply cover factor

As a metric for the grid interaction and demand response capability, the self-consumption of the office use has been evaluated. Characteristic values are defined in the following.

$T$  is the accounting period, for which the balance is calculated. Usually, a period of one year is selected (prEN 15603:2013). The accounting time step  $\tau$  is a discrete time interval in the accounting period  $T$ . If the accounting time step is a multiple of the measuring interval  $\Delta t$ ,  $\tau / \Delta t$  intervals have to be summed up. For the following evaluations, the measuring interval is  $\Delta t = 5 \text{ min}$ .

The self-consumption  $SC$  describes the amount of electricity, which is used by loads inside the building ( $E_{tot}$ ) and can be supplied by the PV-generator ( $E_{PV}$ ) during the accounting time step.

$$SC_\tau = \min \left( \sum_{i=1}^{\frac{\tau}{\Delta t}} E_{PV,i}; \sum_{i=1}^{\frac{\tau}{\Delta t}} E_{tot,i} \right) [kWh] \quad (\text{Eq. 3})$$

The demand cover factor  $DCF$  defines the ratio of the  $SC$  and  $E_{tot}$  for the accounting timestep  $\tau$  (Salom et al., 2011):

$$DCF_\tau = \frac{SC_\tau}{\sum_{i=1}^{\frac{\tau}{\Delta t}} E_{tot,i}} \cdot 100 [\%] \quad (\text{Eq. 4})$$

and for an accounting period  $T$ , respectively:

$$DCF_T = \frac{\tau \cdot \sum_{i=1}^{\frac{T}{\tau}} DCF_{\tau,i}}{T} [\%] \quad (\text{Eq. 5})$$

The supply cover factor  $SCF$  describes the percentile ratio of the  $SC$  and the PV-yield  $E_{PV}$ :

$$SCF = \frac{SC}{E_{PV}} \cdot 100 [\%] \quad (\text{Eq. 6})$$

SCF and DCF for the measured period from May 2014 to August 2015 are given in Fig. 64. Due to the lower PV-yield during wintertime, the self-consumption increases. At the same time, the demand cover factor decreases because of the increasing total electricity consumption.

The supply cover factor is thus higher during winter because the electricity consumption compared to the on-site production is higher than during summer.

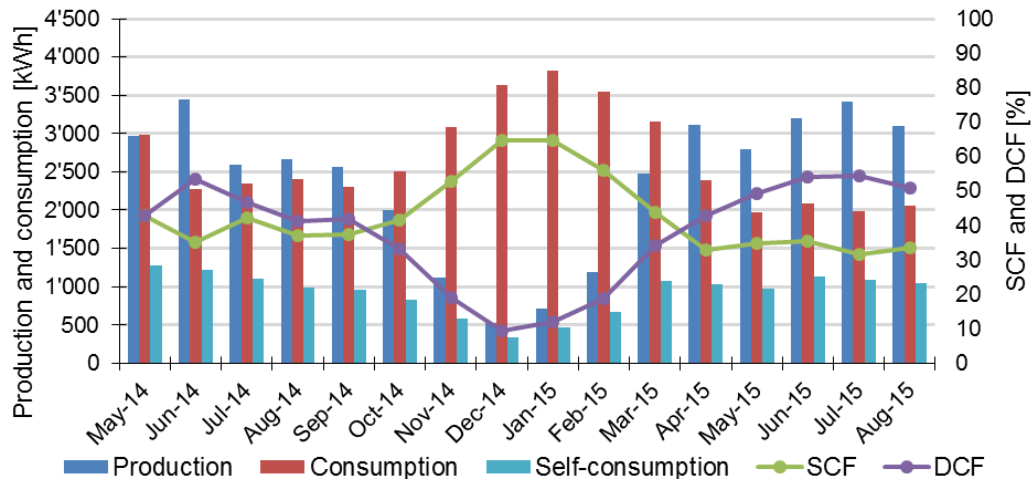


Fig. 64: Production, consumption, self-consumption, SCF and DCF (Hässig et. al, 2015)

In a further evaluation, the potential of increasing the supply cover factor and the demand cover factor by increasing the self-consumption by load shifting of specific building technologies to be covered by 100% of the on-site PV-production has been analysed. This would be the maximum load shift, which can be achieved. Calculations have been made for the following appliances:

- Heat pump (HP)
- Electric car
- Electrical direct heating (Heating element HE)
- Dryer

Tab. 15: Theoretical maximal SCF and DCF at full self-consumption operation (Büsser, 2016)

Unit [kWh]	None	HP	Car	HE	Dryer	All
Production	25,907	25,907	25,907	25,907	25,907	25,907
Consumption	29,291	29,291	29,291	29,291	29,291	29,291
Measured SC	10,018	10,018	10,018	10,018	10,018	10,018
SC without appliance	-	8,862	9,667	9,864	9,882	8,331
Consumption appliance	-	8,878	1,477	354	519	11,228
Theoretical SC	-	17,740	11,144	10,218	1,0401	19,559
SCF	39 %	68 %	43 %	39 %	40 %	75 %
DCF	34 %	61 %	38 %	35 %	36 %	67 %

The calculation in Tab. 15 is based on monitoring data of the period 08.01.2015 - 22.12.2015.

## PV/T

Based on the monitoring of the PV/T collector, the effect of higher efficiency due to lower collector temperatures could be approved. The promised 40 % higher solar gain by the manufacturer, however, has not been reached. In summer, though, the solar fraction of the DHW preheating is 16%, reaching maximum temperatures of 40 °C in the DHW preheating storage. The average efficiency of the collector circuit is 30%.

Currently, a major drawback of the PV/T collectors are the still high investment costs, the low flexibility and the competition of the system with the heat pump for DHW preheating. PV/T collectors may get interesting, when they get more cost-effective and the low-temperature heat can be used advantageous, for example to regenerate a ground borehole heat exchanger field or for big DHW preheating demands. However, DHW preheating by a PV/T may lead to decreasing performance values of the heat pump, since the heat pump tends to have a higher share of higher DHW temperature levels which may limit the performance.

## 6.2.4 Conclusion

### System performance and comfort

The overall system performance in the period from May 2014 till March 2015 is with 4.29 a very good performance. Also the  $SPF_{DHW}$  of 3.51 is a good value, even though solar preheating with the PV/T collector leads to heat pump operation at higher DHW temperature for the storage reheating. In free-cooling, an  $SPF_c$  of around 14 is reached. The solar fraction of the PV/T collector is 16 %, with a thermal efficiency of the collector cycle of 30 % in summer.

The MINERGIE®-A-index for the first year of operation is with -16.9 kWh/(m<sup>2</sup>a) clearly below the requirements and also lower than the design value. Furthermore, comfort and user satisfaction in the offices and for the residential use (flats) were consistently above average.

### Demand cover- and supply cover factor

Demand cover- and supply cover factor of the building vary depending on the accounting period. In this evaluation, the electricity production has been recalculated to solely cover the office use. It is assumed that simultaneity due to the daytime consumption in offices is likely to achieve higher supply cover factors than in residential use, where the needs occur partly in the morning and evening with lower PV-production.

With a supply and demand cover factor in the range of 35-40% according to Tab. 15 without further optimisation of the operation, a higher value than in residential buildings with typically 15-25% is actually reached.

The electric car could be efficiently used to increase the self-consumption of the generated PV-electricity, which was limited by the charging capacity, though. In the installed charging station charging always takes place at maximum capacity of 22 kW, which corresponds to the total PV power at favourable weather conditions. In the future, a smart charging control may be applied, where the charging power and charging time can be adapted within the range of instantaneous PV surplus power and user limitation on the required charging time. Thereby, the self-consumption can be further increased, as shown in Tab. 15.

## 6.3 Storage capability in the building thermal mass

### 6.3.1 Motivation

The saving goals defined in the energy strategy 2050 of the Swiss government require a significant reduction of the CO<sub>2</sub>-eq.-emission to one ton per person. Heat pumps in combination with energy generated by renewables can make a contribution to achieving these goals. In order to use the growing part of electrical power produced by renewables, there is a need for additional storages. On the one hand these storages must be able to store volatile energy for a later use and on the other hand they must contribute to improve grid stability.

Thermal storages are widespread, but the building structure itself is not used as a thermal storage. The storage of energy is important in an energy supply system with a fluctuated energy production and with fluctuated energy consumption. Presently, the question is, where and how the energy can be stored efficiently. The storage of thermal energy in the building structure is thereby a potentially very efficient method.

### Heat pumps in the power grid

Switchable heat pumps in combination with an intelligent power grid (smart grid) can increase the part of actually used renewable energy and contribute to grid stabilisation and optimised power supply using the building structure as energy storage. Several German industry organisations published the policy paper "Smart Grid and Smart Market" (BDH et al., 2012) with the conclusion that heat pumps have a high potential for load management in smart grids. For this purpose, there are different interfaces which allow communication between consumers, power grid operators and energy suppliers.

Since January 1, 2013 the standard "SG-Ready" exists for heat pumps in Germany (BWP et al., 2013). It allows a differentiate ripple control of the heat pump by the grid operator and by the power supplier, respectively. The heat pump controller requires four operation modes ("locked by grid operator", "normal operation", "reinforced operation mode (recommendation)" and "tarnish command for the heat pump or additional electrical heater").

The "VHP-Ready" standard of Vattenfall (Vattenfall, 2012) was created to combine power cogeneration of heat and power with virtual heat pumps in a way that a linked, flexible and centrally controlled energy system is generated. It works bidirectional and has more detailed requirements as the standard "SG-Ready".

#### Situation in the city of Zurich

The urban environment of the city of Zurich and the more and more compact architecture lead to the fact that heat pumps are increasingly used for multi-family and service buildings. The source heat is taken from the ground (mainly borehole heat exchanger), the ground water or lake water. Air as heat source has only a small share.

#### Thermal storage in the building structure

In this project it is investigated in how far the building structure is suitable as a thermal storage. In a first step building clusters in the residential building stock of Zurich are identified which are well suited for thermal storage operation due to its construction and its heating system. For several reference buildings with different insulation standards the operation of these storages with heat pumps as heat producer is investigated. Thereby, the dynamic of the charging and discharging cycles of the reference buildings is investigated based on dynamical building simulations.

### **6.3.2 Analysis of the building stock of Zurich**

The building categories "residential" and "office" are preferred in the investigation due to its large area share and the wide thermal comfort range which allows room temperature fluctuations. Residential buildings (single- and multi-family buildings) have the biggest share in Zurich with an energy reference area of 11.9 Mio. m<sup>2</sup><sub>ERA</sub>, followed by office buildings with an energy reference area of 6.1 Mio. m<sup>2</sup><sub>ERA</sub>.

In order to realise heat storage in the building structure, a big thermal capacity of the building structure and the activation of it are relevant. The best efficiency is reached by a direct thermal activation what means that the heat transfer from the hydronic heat emission system to the buildings structure by the heating pipes takes place directly. Thereby, the heat can be stored directly in the building structure and the influence on the room temperature is delayed what simplifies the compliance with the room comfort requirements. Therefore, for the further investigations heating systems with floor heating systems and thermal activated building system (TABS) are selected. These heat transfer system have an own thermal capacity. Therefore, thermal storage with an included control function is in most cases easy to realise with the given installations. Heating systems with radiators are out of the scope due to their storage activation by the room air, which leads to an increased risk of violating the thermal comfort.

The investigations result in the statement that especially buildings with the following characteristics are well suited for a storage operated in a day cycle:

- Ideally heavyweight buildings, especially with heavy ceilings and walls built in material with a high thermal capacity
- Good thermal insulation of the building envelope
- Heat transfer system which activates the building structure directly (floor heating system, thermal component activation system)

On the other hand, buildings with the following construction properties are not suited for thermal storage:

- Building with wooden ceilings due to missing thermal capacity compared to a massive concrete ceiling
- Interior thermal insulation of the building envelope prevents a management of heat storage in the outer walls
- In commercial and public buildings suspended ceilings with heating and cooling elements prevents problems concerning thermal storage, because thereby the ceiling as capacity is thermally decoupled from the heating system

The knowledge about the used distribution of the energy reference area of the building stock, the thermal storage capability of single construction components and heat transfer systems are synthesized to a quantitative estimation about the total thermal storage capacity. Thereby, the use (residential and commercial/public) was combined with heat transfer system floor heating and thermally activated building system to estimate the respective storage potential for a day cycle. According to the assumptions made, the combination commercial/ public with thermal activated building system has the highest thermal storage potential of 497 MWh/d. The second highest thermal storage potential has the combination residential use with floor heating system of 188 MWh/d.

### 6.3.3 Building simulations

For the dynamical building simulations a building model with 4 thermal zones was implemented in Matlab/Simulink® using the thermal block-set library CARNOT as shown in Fig. 65. Thereby, every thermal zone corresponds to a single room.

The control of the heat pump works with an implemented heating curve with ambient temperature-control of the return temperature. The energy reference area of all 4 rooms is 100 m<sup>2</sup>.

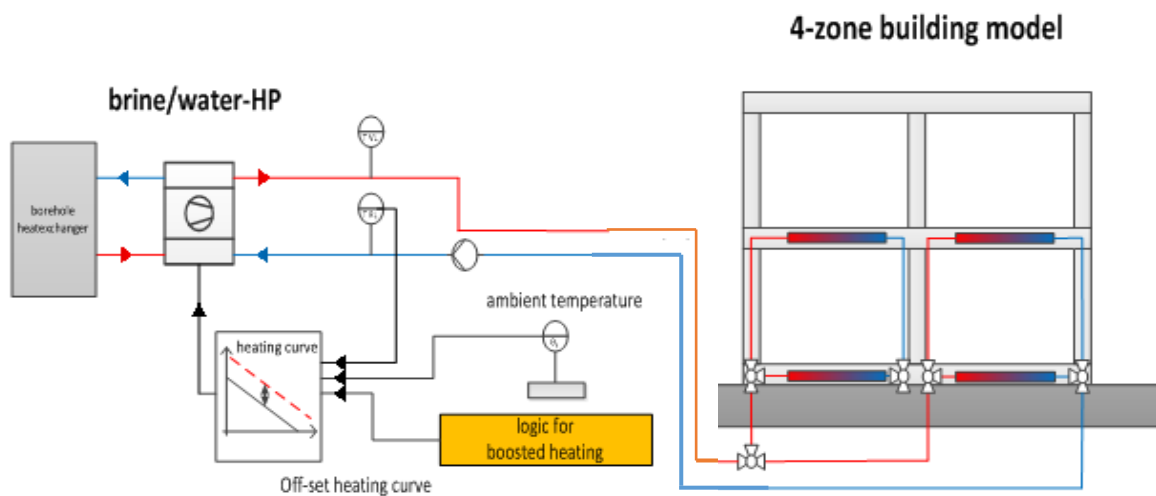


Fig. 65: Implemented heating system with ambient temperature controlled return flow temperature

As example for all building simulations carried out in this project, the results for the reference building "new building" according to building standards of canton Zurich (the Swiss standard SIA 380/1 (2009)) and for the reference building "MINERGIE-P-Eco®" (MINERGIE, 2014) are presented.

Tab. 16 shows the requirements for both buildings.

Tab. 16: Requirements to a new building and a MINERGIE-P-Eco®

	New building (standard SIA 380/1)	MINERGIE-P-Eco®
Max heating needs Q	< 55 kWh/(m <sup>2</sup> a)	< 15 kWh/(m <sup>2</sup> a)
U-value of horizontal outer surfaces	0.20 W/(m <sup>2</sup> K) (25 cm thermal insulation)	0.10 W/(m <sup>2</sup> K) (30-40 cm thermal insulation)
U-value of vertical outer surfaces	0.20 W/(m <sup>2</sup> K) (25 cm thermal insulation)	0.15 - 0.20 W/(m <sup>2</sup> K) (25 cm thermal insulation)
U-value of windows	1.3 W/(m <sup>2</sup> K)	0.8 W/(m <sup>2</sup> K) (triple glazing)

Tab. 17 lists the boundary conditions for the comparative simulations. Thereby, there is always a comparison between an annual simulation with demand-based operation mode and an annual simulation with intermittent-based operation mode.

Tab. 17: Simulation combinations for the reference buildings "new building" and "MINERGIE-P-Eco®"

	Var.	Standard	heat transfer system	HP	control	Operation mode	[10:00-17:00] [17:00-10:00]
Fig. 66	NB3	new building	floor heating system	A/W	return flow	demand	heating curve [35.0 °C/28.0 °C] [35.0 °C/28.0 °C]
	NB4	new building	floor heating system	A/W	return flow	intermittent	heating curve [35.5 °C/28.5 °C] [34.5 °C/27.5 °C]
Fig. 67	ME-P1	MINERGIE-P-Eco®	floor heating system	A/W	return flow	demand	heating curve [30 °C/26 °C] [30 °C/26 °C]
	ME-P2	MINERGIE-P-Eco®	floor heating system	A/W	return flow	intermittent	heating curve [30.5 °C/26.5 °C] [29.5 °C/25.5 °C]

In Fig. 66 the dynamical gradients of the stored heat in the floor/ceiling of the reference building "new" are depicted for the demand-based operation (blue curve) and the intermittent-based operation mode (red curve). In contrast to the refurbished building category, the thermal insulation of the building envelope is improved. But, the activated thermal mass of the floor/ceiling remains constant under the same boundary conditions concerning heat transfer system and operation mode. The stored heat in the floor is 4-6 kWh.

Due to the higher insulation standard, the discharge time gets longer. For the intermittent-based operation mode and in function of ambient temperature and passive solar gains, it takes 7 to 10 hours until the building can be heated again. Interestingly, there are days where with intermittent-based operation due to the previous decrease of the heating curve the building is cooled down so far that it can be heated strongly, while at the demand-based operation mode the passive solar gains are enough to heat the building. Due to this, the heat pump can obtain additional 1.5 kWh<sub>el</sub>.

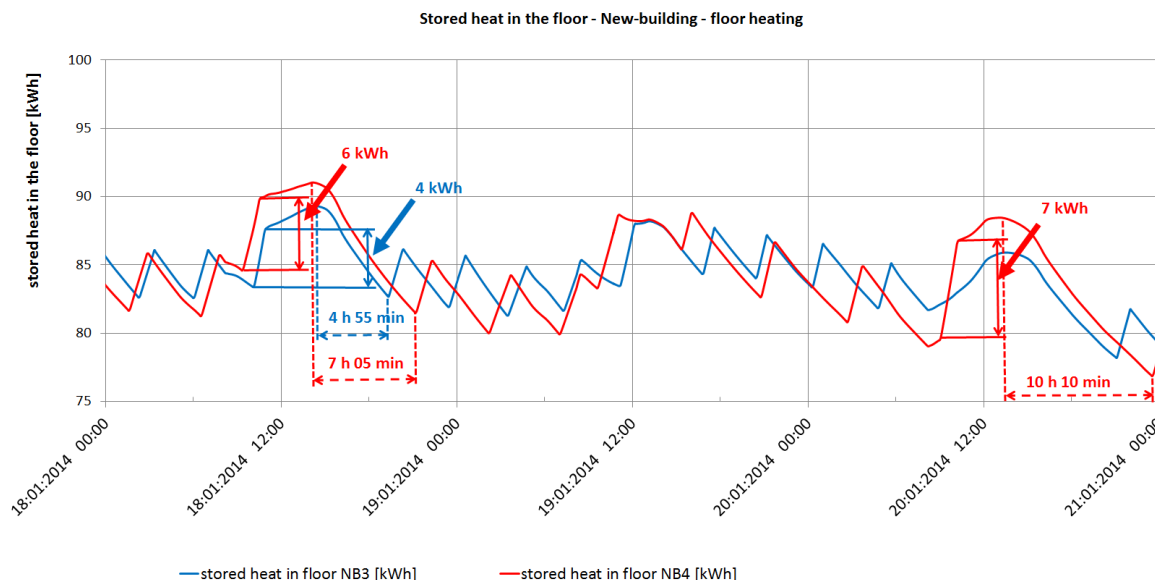


Fig. 66: New building. Stored heat in the floor for demand- (blue) and intermittent-based (red)

Considering the MINERGIE-P-Eco® building with floor heating system and return temperature control (see Fig. 67) the thermal insulation is improved compared to the new building standard. The control parameters concerning the demand-based and intermittent-based operation mode remains constant except for a general decrease of the flow temperature (adapted to the MINERGIE-P-Eco® standard).



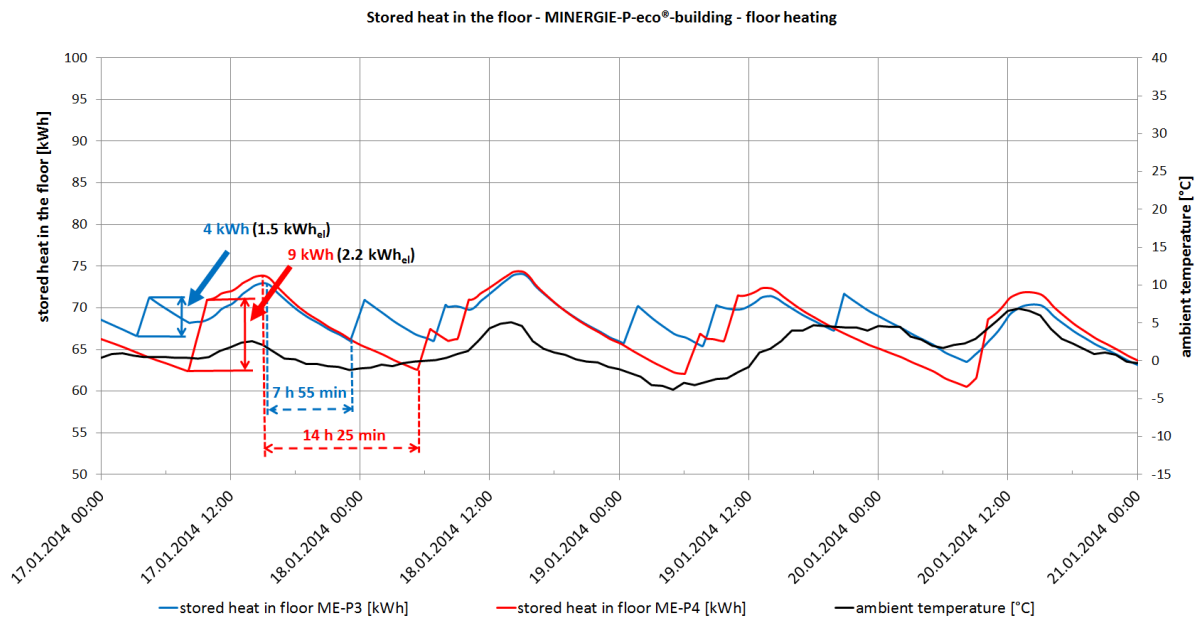


Fig. 67: MINERGIE-P-Eco®. Stored heat in the floor for demand- (blue) and intermittent-based (red)

In the period from 10 a.m. to 5 p.m., in the intermittent-based operation mode on average 4-5 kWh more heat is stored than in the demand-based operation mode. This corresponds to an additional power demand of 0.7 kWh<sub>el</sub>. But, the discharging time of the building gets longer; it takes more than 8 or more than 14 hours for the demand-based and intermittent-based operation mode, respectively, until a heating demand at ambient temperature of 0 °C exists.

### 6.3.4 Conclusion of the building simulations

For both reference buildings dynamical annual simulations were carried out for different operation parameters. Based on the simulation results, following conclusions can be drawn: As a result of the annual simulations for the reference buildings (new building and MINERGIE-P-Eco®) with the two heat transfer systems (floor heating and thermally activated building systems) and the two controlled strategies (return temperature control and room temperature control), it is shown that the requirements for the thermal comfort are fulfilled and that the power demand for the heat pump remains approximately equally for the demand-based and the intermittent-based operation mode.

At the new building, the spectrum of the additional emitted heat is much larger. There are typical situations with a lesser amount of heat compared to the refurbished building, with e.g. an increase of the heat from 4 to 6 kWh<sub>th</sub> and the power demand from 1 to 1.5 kWh<sub>el</sub>. The waiting period after a reinforced charge to the next charge cycle increases by 2 hours from 5 to 7 hours. However, there are also situations where the floor is charged by 7 kWh<sub>th</sub> with an additional power demand of 1.5 kWh<sub>el</sub> in the intermittent-based operation mode and the demand-based operation mode does not need any heat at this time.

A further increase of the thermal insulation as in the MINERGIE-P-Eco® leads to a similar characteristic in the charge cycles as in the new building, but the waiting period after a forced charge increases from 8 to 14 hours.

The new building with thermally activated components shows that the activated thermal inertia is much bigger than for floor heating systems and therefore, also the change of charged heat in the building component is bigger. An increase of the charged load, though, does not automatically correspond to an increase in power demand. A building with thermally activated building systems can be well operated with only one charge cycle per day. Are the charging times distributed stochastic over the day, it can occur that a forced charge needs only a slightly higher power demand than heating during the night. The reason for this is on one hand the passive solar gains during daytime which contributes to charging compared to a higher heat loss during the night at colder ambient temperatures and on the other hand the higher source temperature for the air-to-water heat pump which leads to a higher COP and therefore to a lower power demand.

The impact of a forced single charge depends strongly on the current random conditions. With a room temperature control and an integrated technical storage there is another characteristic observed than with the return temperature control. The regularly charge cycles of the heat pump disappear due to the decoupled heat generation. There is an almost continuous heat delivery with more frequent heat pump operation periods. A forced charge of the floor heating system at defined times (intermittent operation mode) leads to larger individual charge cycles of the floor heating system without mismatching thermal comfort requirements due to a stronger and more accurate cooling of the rooms. Therefore, in these charge cycles the heat generation and the power demand are higher.

## 7 Conclusions

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In Task 4 of the IEA HPT Annex 40, field monitoring of heat pumps in low energy and nearly zero energy buildings has been performed both in residential and in office buildings. Good performance values in the real operation of the heat pump for this application could be confirmed by the measurement. However, also various optimisation potential could be identified based on hydraulic integration, design and control, leading to even better energy performance and cost saving potentials.

In a German long term monitoring in office buildings it was found that auxiliary source energy can make-up large fractions of the electricity consumption. Results are in the range of 6-25 %, which limits the seasonal performance and could be significantly improved with a thorough hydronic layout of the source system. Moreover, control settings for running times of pumps can be optimised and energy-efficient pumps enable better use of the heat source. On the sink side, low temperature emission systems like thermally activated building systems (TABS) should be connected separately in order to benefit from low supply temperatures for the heat pump operation.

Among the field monitoring also the first nZEB P&D buildings in Norway have been evaluated. The nZEB balance has been reached in a retrofitted office building, and despite higher supply temperatures, good performance values have been reached. However, the source system is overdimensioned and system cost could have been significantly reduced with better design. Moreover, improvements were found in the heat recovery from the computer cooling. A CO<sub>2</sub>-heat pump for DHW heating in three retrofitted blocks of flat reached an excellent SPF of more than 4 at DHW temperature of 70 °C.

In the Netherlands strategies for deep retrofitting to nZEB have been evaluated in field monitoring. The objective is to create a large market demand for nZEB retrofitting and reduce the cost by innovation and optimised building processes. A deal with the building associations has been made to refurbish 111,000 buildings to nZEB in the Netherlands, and the concept shall be extended also to France and the UK.

In the frame of Task 4 also first evaluations of self-consumption and load-shift options with the heat pump operation have been accomplished in two MINERGIE-A®-buildings in Switzerland. In a small multi-family plus energy building, self-consumption rate could be increased by 10-15% by shifting the heat pump operation from nighttime to daytime. In a second MINERGIE-A® certified building with mixed residential and office use, the self-consumption of the on-site PV generation for the office use was evaluated to approximately 40 %, which is due to the good load match of PV production and office use during daytime, which is better than in residential buildings. Also in Canada and Japan investigations of demand response have been performed.

Summarising, the field monitoring results confirm that the heat pumps already reach good performance values in the application of nZEB, but performance can even be further increased at decreased cost by system optimisations. Moreover, heat pumps are a candidate for load shifting either to increase the self-consumption of on-site PV generation or as operation reserve for grid-supportive operation. Self-consumption rates of 30 % in residential buildings and 40 % in office buildings could be evaluated.

Thereby, heat pumps are facilitating to reach an nZEB balance by good performance values and demand response capability, which may become an important aspect with the broader introduction of nZEB requirements for new buildings.



## 8 Acknowledgements

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# Abbreviations

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A/W	Air/Water (Heat Pump)
AC	Alternating current
AI	Artificial Intelligence
ASHP	Air-Source Heat Pump
BEMS	Building Energy Management System
BREEAM	Building Research Establishment Environmental Assessment Methodology
CEC	Cumulative primary energy consumption
COP	Coefficient of performance
DC	Direct current
DCF	Demand cover factor
DHW	Domestic Hot Water
DR	Demand Response
e.g.	exempli gratia
EC(M)	Electronically Commutated (Motor)
EED	Earth Energy Designer
EER	Energy efficiency Ratio
EnOB	Energy optimised building
EPC	Energy Performance Certificate
FY	Fiscal year
G	Ground
GSHP	Ground-Source Heat Pump
HC	Hydrocarbons
HEMS	Home Energy Management System
HFC	Hydrofluorocarbons, HydroFlourCarbon
HFO	HydroFlouroOlefine
HP	Heat Pump
HPT	Heat Pumping Technologies
HPWH	Heat Pump Water Heater
HRV	Heat Recovery Ventilation
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
LCF	Load cover factor
LED	Light Emitting Diode, Light-Emitting Diode
LEED	Leadership in Energy-Efficient Design
MFH	Multi-Family House
NRCan	National Research Council Canada
nZEB	nearly Zero Energy Building
NZEB	Net Zero Energy Building
OD	Outer diameter
PE	Poly-Ethylene
PTAC	Packaged Terminal Air Conditioning
PV	Photovoltaics, Photovoltaics
PV/T	Photovoltaic-thermal
RC building	Reinforced Concrete building
SC	Self-consumption
SCF	Supply cover factor
SCOP	Seasonal Coefficient of Performance
SIA	Schweizerischer Ingenieur- und Architektenverein
SPF	Seasonal Performance Factor
T	Thermal
TABS	Thermally activated building systems
VAV	Variable Air Volume

VSD..... Variable speed drive  
W ..... Water

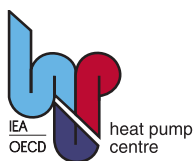
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