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Heat pump integration in Positive Energy Districts – Simulation and monitoring results of IEA HPT Annex 61

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Abstract. IEA HPT Annex 61 investigates heat pump (HP) use in positive energy districts (PED) to derive recommendation for future growing HP application. HP offer unique features for load balancing and waste heat use in district. Five categories from individual building to central district HP integration were derived, which are further detailed by simulation and monitoring of 14 HP installations in PED. Presented results cover strategies for a new built and three retrofit cases. In new built PED, special attention has to be paid to system losses and auxiliaries due to ambitious energy targets. As retrofit strategies, a centralised integration has the advantage to minimize decentral installations in a large number of buildings. If heat source limitations are the major obstacle, source integration is a promising retrofit strategy also offering economic advantages due to synergies among sources. In districts with similar building types a highly reproducible model retrofit strategy can be applied, using control and shared use of on-site PV. Results of all case studies will serve to derive technical documentation, recommendations and best practice systems for mainstreaming HP integration in PED.

1. Introduction

Climate change is rapidly progressing and the 1.5 °C limit of the Paris Agreement may be surpassed in the coming years. 50-60% of the GHG emissions worldwide are due to cities [1]. However, cities exhibit a high complexity, while the individual buildings miss the opportunity of load balancing and waste heat recovery which prevails in districts. Thus, districts seem an adequate scale for integrated energy system planning. Positive Energy Districts (PED) are hence developed as accelerator of the urban energy transition [2]. Heat pumps (HP) can produce different building needs even simultaneously and enable energy flexibility by storage of on-site surplus electricity as heat and cooling energy and are thus key components for integrated energy systems. HP are seen as future heating systems in many scenarios and can cover 50% of the global heat demand by 2045 [3]. For growing HP use the question arises how to best integrate HP in districts. A systematic review of hybrid HP-district heating (DH) shows among other things notable CO_2-reduction of 32.2% [4]. A comparison of 4GDH and 5GDH reveals advantages for a 4GDH [5]. Investigation of different configurations incl. booster HP recommends high temperature DH integration for domestic hot water (DHW) and HP for space heating (SH) for the case study [6].

2. Methodology

In Annex 61 HP concepts for PEDs are investigated by simulation and monitoring. A state-of-the-art analysis of each 50 certified high-performance districts in Germany and Switzerland and the 61 PED

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evaluated in [7] approved that HP are the main building technologies together with photovoltaics (PV), followed by and partly integrated with DH and combined heat and power (CHP) [8]. Based on the results generic system concepts for the HP integration are elaborated and documented. Favorable systems are evaluated in a techno-economic analysis by simulations, which are related to monitoring results of real HP installations in districts. The monitoring offer validation data for system models, while simulation results enable optimization potentials for the monitoring plants.

Integration options have been clustered in five top-level categories depicted in Figure 1, from the individual building level to the entirely central integration in a heating and cooling center providing the building services by a thermal grid. Respective options are also linked to monitoring systems which deliver real world measurements for the evaluation.

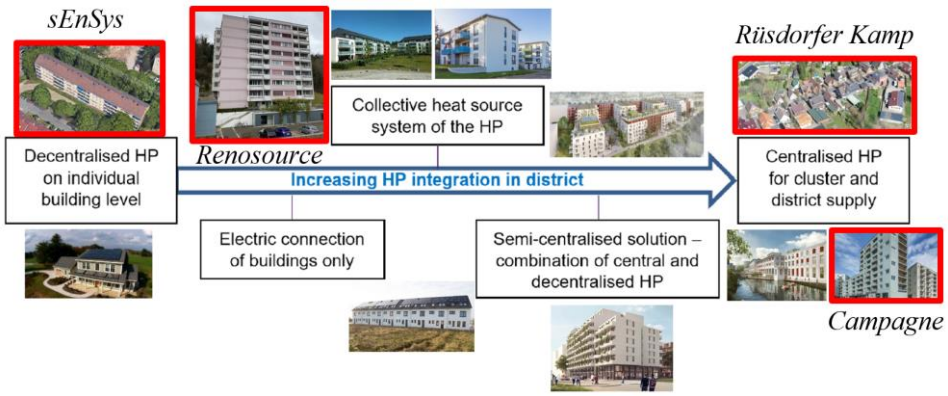


Figure 1. HP integration from individual building to district level: Selected monitoring projects in Annex 61 based on HP integration as well as projects discussed in this paper (framed in red)

3. Results of simulation and monitoring

The scope of the Annex 61 projects comprises both new built and retrofit clusters of buildings and districts in the range up to 25 buildings, which, however, incorporates in some projects in the range of 1000 flats and workplaces or larger areas for commercial use.

3.1. Campagne district Innsbruck, AT – Integration variants of HP in new built blocks of flats

With the urban development project "Campagne Innsbruck", a new district is planned in the east of Innsbruck on an area of approx. 78000 m². The project involves one of the four blocks, which includes 4 multi-apartment buildings for a total of 307 apartments and 2500 m² of commercial space as seen in Figure 2. The buildings were built according to/very close to Passive House standard, i.e. a space heating demand of 15 -20 kWh/(m²yr). The chosen central system combines a groundwater HP for SH, allowing the possibility of free-cooling in summer, and DH for DHW as seen in Figure 3. The distribution system is a 2+2 pipe system with decentral fresh water stations for DHW.



Figure 2. First four buildings of the «Campagne District», Innsbruck

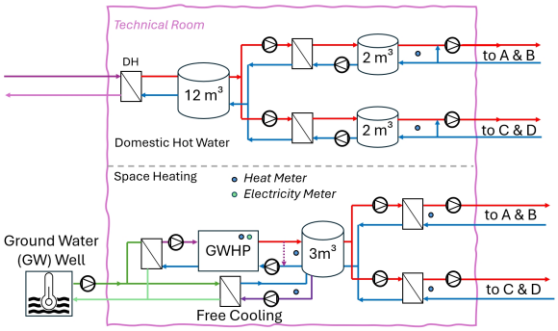


Figure 3. Hydraulic scheme of DHW and SH system of «Campagne District», Innsbruck

As each two of the buildings were realised by different housing companies, a system separation for DHW and SH was implemented. A comprehensive monitoring campaign pays special attention to the central DHW generation and distribution. The placing of heat- and electricity meters at strategical points in the distribution network and technical room allows for comparison with either other HP based or generally different heating systems by the use of (seasonal) performance factors ((S)PF). For a meaningful comparison with other heat generators, it makes sense to also consider the auxiliary energy for their operation. As each distribution system has specific characteristics, an objective comparison is only possible, if all pumps and other auxiliaries as well as system losses are included.

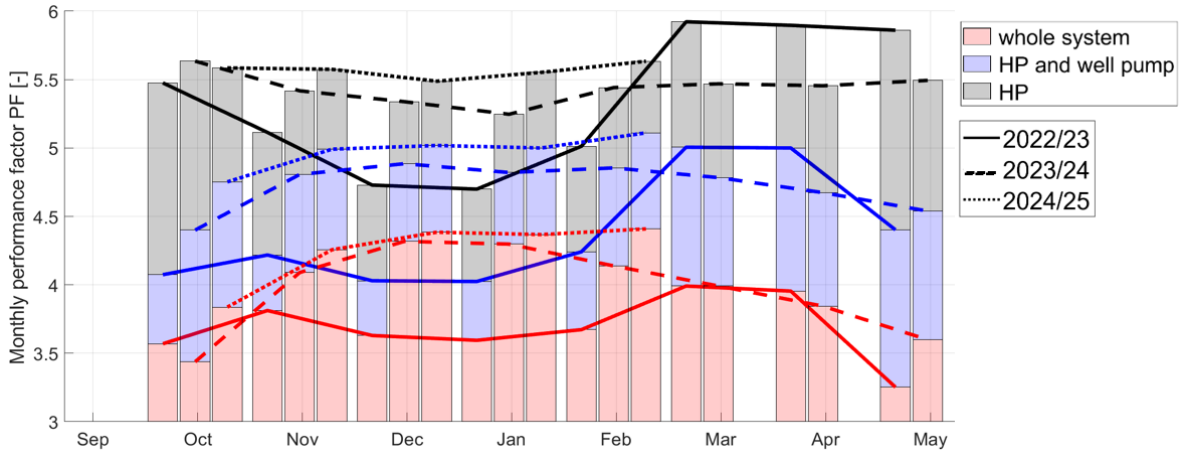


Figure 4. Monthly PF for different system boundaries and heating periods «Campagne Innsbruck»

Figure 4 compares the monthly PF for the past three heating periods 2022/23–2024/25. The bars from left to right show the monthly PF for the years 2022/23 to 2024/25. While a continuous increase in performance was achieved in the core winter, this trend unfortunately did not continue in the transitional periods. The increase in performance is primarily due to a reduced setpoint temperature. Moreover, if the different system boundaries from the HP to the whole system is considered (lines and colors in Figure 4), a notable decrease of the PF in the range of 1-1.5 is stated. Thus, centralized or decentralized systems with the associated temperature levels and heat generators have to be carefully designed to achieve the desired high performance, also considering the system energy losses and auxiliary expenses for the source and distribution system and related temperature implications. As already demonstrated in [9], a net positive energy balance (or zero CO_2-balance) can only be reached with very low energy demand and highest possible PV generation (on-site). In case of (multi-story) multi-apartment buildings (MFH) with a high density (as here e.g. for Campagne Innsbruck), the net balance cannot be reached on the district footprint.

The reduction of the electric energy demand by means of a very high building envelope quality and a very efficient heat generation and distribution system is crucial. First monitoring results show potential for further improvements concerning the control of the central HP, since the groundwater well is currently significantly over-dimensioned with only 4 connected buildings of the 16 in the final stage.

3.2. Renosource Baden, CH – Source integration for retrofitting of two larger MFH

The project Renosource in Baden, AG, CH is related to a heat source integration for boiler replacement in two larger MFH depicted in Figure 5. In particular in retrofitting, limitations for individual sources may occur in densely built areas as a major obstacle for HP application.

The MFH of totally 56 flats on 4200 m^2 and an installed boiler capacity above 200 kWh have an energy consumption is 600 MWh/yr. The original concept has foreseen a 300 m deep borehole field (BHX) with regeneration by an air heat exchanger (AHX). However, during the drilling artesian water was found, which led to an additional drilling depth limitation of 120 m by the cantonal authorities. Due to the steep surrounding, the BHX was limited to the parking lot between the two MFH.

A simulation study approved that limitations of individual sources of AHX and BHX can be overcome by dual-source integration and synergies among sources can provide performance and even economic benefits [10]. For this application case the simulations approved that by extending the AHX for base load coverage and a depth reduced BHX for peak load coverage is feasible for the boiler replacement. The system has been installed in 2024 as reduced BHX and is currently monitored in a P&D project, of which interim results are presented in [11].



Figure 5. «Renosource» MFH in Baden, CH



Figure 6. District «Rüsdorfer Kamp», Heide, DE

3.3. Rüsdorfer Kamp Heide, DE – Retrofitting of existing buildings with renewable heating grid

A main goal of the project "Quarree100" is the implementation of a climate-neutral and resilient energy concept for the "Rüsdorfer Kamp" district in Heide, Schleswig-Holstein, DE depicted in Figure 6. The buildings' thermal energy supply is to be changed from gas, oil and electricity to a renewable centralized local heating with HP. The main processing steps comprise the creation of a building register with building type, year of construction, heat demand as well as solar cadaster, including roof orientation and solar yield. Afterwards, thermal load profiles and design of a heating network let to a modelling and simulation of concepts followed by an energetic, ecologic and economic evaluation, which was iterated over the project. Figure 7 shows an ecologically preferred variant.

Assuming a conservative connection rate, 134 buildings will be connected to the heating network. This corresponds to 58% of the buildings (after taking future densification into account), 47% of which are existing buildings. The total heat demand is 6,562 MWh/a. In the preferred energy system, PV is installed on the district buildings. The electricity is fed to the energy center via an operating grid (according to a legal review, it is currently not possible to use the local PV electricity to cover the electricity requirements of the buildings, even if this would be ecologically preferable).

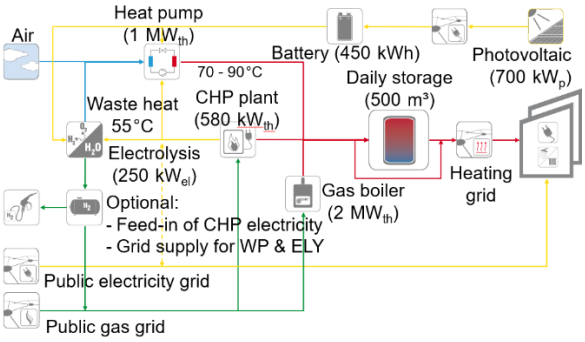


Figure 7. System configuration for the renewable energy system in "Quarree 100"

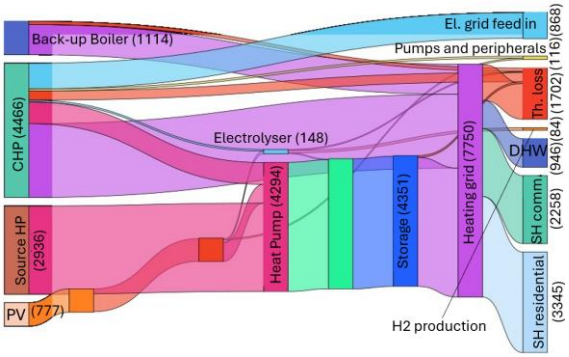


Figure 8. Energy flow diagram as results of the simulations (energies in MWh)

The local PV electricity is primarily used in the centralized 1 MW air-to-water HP. Surplus can be used in an electrolyzer to produce hydrogen, which is primarily designed for scientific operation with the aim of testing various hydrogen uses such as mobility and feed-in to a natural gas grid. In addition to PV electricity, the HP can be operated with grid electricity, if this is ecologically and economically advantageous. A CHP plant is also integrated to optimize economic efficiency.

The electricity produced can be used by the HP. A gas boiler is planned as redundancy. The heat produced can be stored on a daily basis in order to decouple heat demand and supply and enable more flexible system operation. For the simulation of the PV yield, the individual roof areas of the buildings are used according to the solar cadaster. Figure 8 shows simulated results of the annual energy flows from the sources PV, HP, CHP and gas boiler via the heat storage and heating network to the consumers.

Even without the use of grid electricity, more than 50% of the heat fed into the thermal grid can be covered by the HP. The system offers the flexibility to significantly increase this proportion in the future by using grid electricity. This supports a sustainable, renewable and resilient energy concept. Real implementation currently depends on the economic viability of the project.

3.4. sEnSys project Erlangen, DE – Model retrofitting of MFH with smart control

In a contribution from TH Nuremberg, a retrofit concept for a MFH in the context of cooperative housing is developed and optimized by simulations, also regarding extension to a district. The demonstration focuses on a model refurbishment of a MFH based on energy-efficient, economical and grid-friendly system technology and a high level of user acceptance and renewable energies. The additional costs for components and control functions are to be offset by increased system performance and the possibility of lower energy consumption by tenant electricity.

The building, constructed in the 1970s, consists of 32 residential units on a heated gross floor area of 2600 m^2. For the simulation and the optimization of the building and system technology the MFH was divided into 32 residential, 4 stairwells, the basement and attic room zones.

The concept must be as low-loss and cost-efficient as possible to achieve climate neutrality. Three basic hydraulic variants (V) for DHW preparation and supply routing were investigated as V1 of centralized DHW heating with a 4-pipe system with circulation, V2 as decentralized DHW heating with 2-pipe system and transfer station and V3 as V2, but with additional direct electric DHW reheating. As heat generator a ground-coupled HP and a parallel buffer storage was investigated. The system components were dimensioned for each variant. Four representative tapping profiles were created based on the real consumption, which amounts to around 40 l/p/d. With a DHW demand of 10 l/week at 50 °C, DHW tapping (e.g. for cleaning) is simulated for each unit.

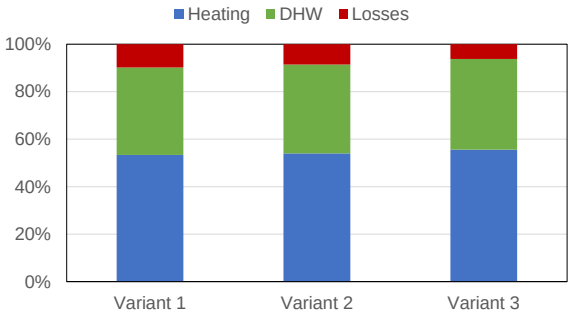


Figure 9. Energy fractions for the three variants in the model retrofitting in Erlangen, DE

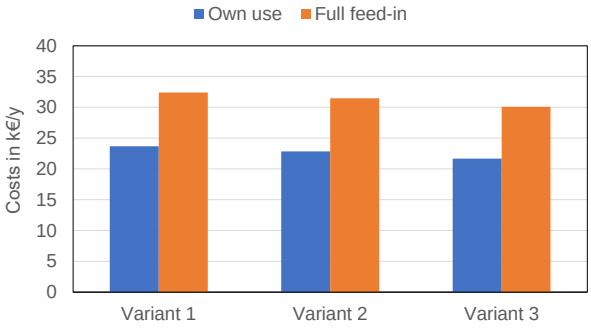


Figure 10. Operating cost of different options of PV electricity use

Figure 9 shows the final energy shares of the three variants. SH is with 48.5 MWh the largest share of 57 %. The average demand for DHW is 33.3 MWh. The variants are accompanied by a reduction in the maximum flow temperatures in the heating circuit from approx. 60 °C (V1) to 45 °C (V3), which reduces distribution losses. In addition, the maximum temperatures in the thermal storage are reduced. As result, the total heat losses are reduced by more than 40% from 8.9 MWh (V1) to 5.5 MWh (V3). Heat losses account for 6-10% of total energy. Figure 10 shows the operating cost of the hydraulic variants incl. the operator model of the PV (full feed-in or tenant electricity). The tenant electricity model allows to sell the on-site PV electricity to the tenants and thereby increase the PV self-consumption. In all variants, the monetary advantages of the tenant electricity model are clearly visible, which lead to around 28 % lower cost.

There are also slight economic advantages, e.g. the consumption costs of V2 and V3 are 3.6% and 8.5% lower than V1 in the rented electricity model. Price advantages of up to 7.5% (V3 compared to V1) can be achieved with a full feed-in.

These simulation studies can support the selection of an energy supply for MFH by comparing of different hydraulic variants within defined boundary conditions. In this case, V3 emerges as the favoured energy concept. Sub-types of this variant are currently evaluated by simulation.

4. Conclusions

IEA HPT Annex 61 investigates HP integration in districts to pave the way to a high energy performance towards PED as means for accelerating the urban energy transition. Even though reaching a PED on the district footprint remains an ambitious challenge for larger buildings, integrated energy systems based on HP integration can ideally use synergies among buildings in terms of load balancing and waste heat recovery. Based on the state-of-the-art analysis of existing PED and monitoring in Annex 61 five top-level categories for the HP integration have been derived, which are further detailed and linked to 14 HP monitoring installations. Interim results of four case studies with simulation and monitoring show technical and economic advantages and limitation of the different integration options. For the retrofit of a whole district in the case of Rüsdorfer Kamp, centralized grid-based solutions can minimize installations at the building site for a larger number of buildings and can have economic benefits by increase of on-site PV electricity use. However, for centralized systems, thorough design and evaluation taking into account also system losses and auxiliary energy have to be performed. In the new built district Campagne Innsbruck, the SPF varies in the range of 1-1.5 for the system boundary of the HP only to the whole system. On the other hand, in districts of similar building types a retrofit strategy on individual building level which is developed in the sEnSys project can serve as blueprint for the replication. Last but not least, local heat source limitations typical for boiler replacements in the built environment as found in Renosource can be overcome by source integration as a retrofit strategy for a HP integration. Results serve to elaborate technical documentation, recommendation on HP integration and best practice systems for the mainstreaming of HP in PED. This is also connected to the development of a workflow for planning of HP systems in district applications addressing also design and control issues.

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