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Integration of heat pumps in positive energy districts – Simulation and monitoring results from IEA HPT Annex 61

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Abstract

IEA HPT Annex 61 has investigated heat pump (HP) applications in positive energy districts (PED) by simulation and monitoring in order to derive recommendation for district integration of HP. HP offer unique features for load balancing and waste heat recovery which are favourable features for a high HP performance to reach ambitious objectives of PED. Based on a state-of-the-art analysis of PED definitions and realized PED, five categories of integration options have been derived from individual building to a central HP integration, which are further investigated by simulation and monitoring of 14 HP installations in PED. Presented results cover interim results from simulation and monitoring both for new built and retrofit cases. In newly built systems, special attention has to be paid to system losses and auxiliaries as well as to integration variants to preserve low temperature levels and thereby maintain high HP and system performance. As retrofit strategies, a centralised integration has the advantage of low installation expenditure on individual building level when many houses are to be connected. Centralised solutions can also exploit simultaneous generation of heating and cooling loads, if different building loads are connected by a grid increasing the performance in combined operation. However, by centralised operation, also higher grid temperatures can be caused by individual loads, which raises the importance to keep grid temperature to a minimum level. In districts with similar building types a highly reproducible model retrofit strategy can be applied, using control and shared application of on-site PV to increase the economy of the retrofitting. Results of case studies will be documented to give recommendations and best practice systems in order to contribute to a replication and multiplication of HP integration in high performance districts like PEDs.

Keywords: Positive energy districts; simulation; monitoring; heat pump integration;

1. Introduction

In many countries worldwide, the built environment plays a key role for carbon emission reduction, since in particular the existing building stock has a poor energetic quality. On the other hand, buildings can thereby also contribute to a fast emission reduction. In the EU, for instance, 36% of the carbon emissions are due to buildings, so reaching ambitious climate targets will be strongly facilitated by transforming the building sector. For new buildings, standards have developed to high performance requirements. Furthermore, buildings shall contribute to cover their own demand, leading to nearly zero energy concepts (nZEB), which has been established from January 1, 2021 in the EU member states. In addition, the USA and Canada as well as Japan and China have targets to reach Net Zero Energy Buildings (NZEB) in the time frame of 2020 to 2030

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according to declared policy targets. Ambitious targets, though, are harder to achieve in existing buildings. However, since the 2018 version of the Energy Performance of Buildings Directive (EPBD), also denoted as EPBD III [1] EU member states are also required to develop retrofit strategies to notably enhance the energy performance of the building stock, which is further elaborated in EPBD IV [2], defining so-called "zero emission buildings". These are defined as buildings with "very low energy demand, zero on-site carbon emissions from fossil fuels and zero or very low operational greenhouse gas emissions". They are to be introduced for new public buildings by 2028 and for all new buildings by 2030. Beyond 2030 the full decarbonization of the whole building stock shall be concluded at latest by 2050 in line with the EU climate neutrality targets. Thus, nZEB are only an interim target and for new dwellings, there are also examples to transcend the nZEB and reach a positive energy balance with the ability to exchange parts of on-site energy production with connected grids. This concept can be extended to clusters of buildings and districts deriving a Positive Energy District (PED), which is currently promoted to accelerate high energy performance, renewable energy production and energy flexibility for the urban energy transition.

1.1. Outline of the IEA HPT Annex 61

On this background, the Annex 61 entitled "Heat Pumps in Positive Energy Districts" in the Technology Collaboration Programme (TCP) on Heat Pumping Technologies (HPT) of the International Energy Agency (IEA) studies the application of HP for clusters of buildings and PED with the six member countries AT, CH, DE, IT, JP and US represented by 14 institutions, see also Table 1.

This paper aims at giving an overview of selected project contributions in the Annex 61 with a focus on monitored heat pump applications in cluster of buildings and districts and concludes on system integration strategies. The topic is introduced by an evaluation of technical definitions and a categorization of integration options to give a more comprehensive outline of the Annex activities compared to prior publications.

The scope of the Annex comprises smaller clusters of buildings and districts, mainly with residential and office use, and also includes strategies for existing districts to develop towards a zero energy/emission balance. Especially the high energy performance of the HP, even increased by waste heat recovery in simultaneous operation for different building services, and the provision of energy flexibility by linking electric and thermal loads are unique features of HP to facilitate the achievement of PED. Table 1 summarises the involved countries and institutions and their respective contributions to the IEA HPT Annex 61.

Table 1. Overview of contributions of participating institutions to IEA HPT Annex 61

Country	Institutions	Contributions
AT	UIBK, AIT, AEE-INTEC	• Evaluation of HP in clusters of buildings (decentral, semi-central, central) • Investigation of newly built district regarding performance and integration options by simulation/monitoring
CH	IET OST	• Simulation and monitoring of PED with centrally integrated HP • Design of larger HP for MFH and for clusters of buildings
DE	THN EnCN, siz energieplus, TUBAF, TEB Gmbh, ISFH	• Retrofit and control of clusters of buildings and districts • (Retrofit) concepts for MFHs/neighborhoods by simulation and monitoring • Plus-energy concept for mine water district and monitoring of "HP districts"
IT	Univ. Bologna	• Load structures of different building types, investigations of ground-source and multi-source HP
JP	Univ. Nagoya	• Evaluation of contributions of HP in positive energy districts to reach climate protection targets • Case studies of simulation and monitoring of HP in districts
US	NIST, ORNL	• Simulation, testing and monitoring of high performance ground-source integrated HP with different ground-source systems (horizontal/borehole)

2. Methodology

2.1. Overview of Annex Tasks

In order to assess the HP potential in districts, the Annex work follows a 4-step methodology divided into Tasks. Details on the individual Tasks is given in the following.

2.1.1. Task 1: State-of-the-art analysis

Starting from already existing HP systems in cluster of buildings and PED, the state-of-the-art is characterized and boundary conditions for the follow-on tasks are gathered. Definitions of PEDs are analysed and concepts from existing PED as well as used technologies in existing PED are compiled. The investigation is amended by existing labels and certification schemes as well as design methods and tools.

2.1.2. Task 2: Generic concept development

Task 1 is followed by Task 2 for the analysis of generic system concepts to provide a technical documentation of HP integration in PED. The generic concepts are the basis for an in-depth analysis of HP integration in clusters of buildings and districts. The main characteristics of the integration options are gathered and favourable solutions for respective applications are derived.

2.1.3. Task 3: Techno-economic analysis of concepts (January 2024 – June 2026)

Based on the favorable system concepts derived in Task 2 a more detailed techno-economic analysis is carried out by simulations. The simulations are also mainly link to 14 monitoring projects of HP in building clusters or districts. Simulation offers the opportunity to identify optimization potentials which can subsequently be implemented in the real application in order to improve the performance.

2.1.4. Task 4: Monitoring of the real performance of HP in districts (January 2024 – June 2026)

Results of Task 3 are backed up by evaluation of the real performance of HP in districts by monitoring projects. Besides the performance evaluation, the monitoring projects also serve as validation for the simulation studies, while the validated model can derive optimization potentials which in turn can be implemented in the real applications. The results of the monitoring case studies are documented as best practice systems to multiply the results derived from the real operation.

2.1.5. Task 5: Dissemination of interim results (September 2022 – June 2026)

The overarching task of the Annex in all phases is to share and publish interim results in the course of the project. All tasks are thus accompanied by dissemination activities like workshops, articles, conference papers, website information and presentations, which are performed in Task 5.

2.2. Generic integration options and monitoring projects

As outlined above 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 as well as the 61 PED evaluated in [3-5] approved that HP are the main building technologies together with photovoltaics (PV), followed by and partly integrated with district heating (DH) and combined heat and power (CHP) [3].

In the frame of Task 2 integration options have been clustered in five top-level categories depicted in Figure 1, from (1) the individual building level which is the most common integration option to date. (2) encompasses an electric-only integration which can enhance self-consumption or grid-supportive operation by the HP. (3) comprises a source integration for the collective use of a favourable heat sources like groundwater or borehole fields, while (4) includes semi-central integration options as combination of a grid-based central supply backed up by a decentral HP, e.g. as domestic hot water (DHW) booster. Finally, (5) is an entirely central integration in a heating and cooling center providing all building services by a thermal grid. Respective options are also linked to monitoring systems which deliver real world measurements for the evaluation. A selection of the different monitoring system related to the respective integration options are depicted in Figure 1.

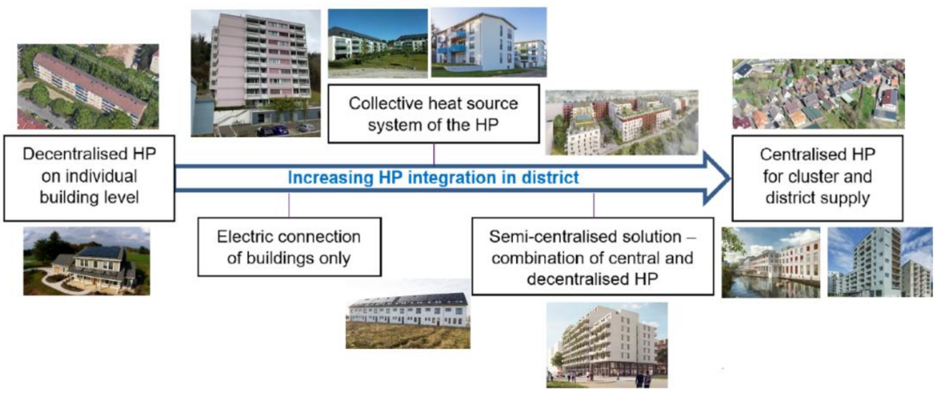

Figure 1: Integration options of HP in districts and respective monitoring projects in Annex 61

3. Results and Discussion

Starting from selected results of the state-of-the-art analysis, interim results on the simulation and monitoring work for the respective clusters of buildings and districts depicted in Figure 1 are discussed.

3.1. State of the Art of Positive Energy Districts

With the revision of the EPBD Directive (2018), the EU has set a target for the overall energy efficiency of buildings, leading to the introduction of nearly zero-energy buildings (nZEB), which have been mandatory for new buildings since 1 January 2021, The concept of Positive Energy Districts (PED) marks a shift from individual buildings to the district level in order to strengthen energy efficiency efforts and accelerate the pace of the energy transition. It is being developed as one of the central pillars of the urban energy transition in Europe. The European Commission has launched the SET Plan Action 3.2 "Smart Cities and Communities". The main objective of Action 3.2 is to develop integrated and innovative solutions for the planning, deployment and replication of PED. According to the action, by 2025, 100 PED should be in concrete planning, under construction or in operation, synergistically connected to the energy system in Europe. The Joint Programming Initiative Urban Europe JPI UE has published a booklet on 61 of these PED [4]. An evaluation regarding technologies is contained in [5, 6]. Through pilot projects funded under the Horizon 2020 program, the European Commission is supporting the widespread introduction of PED. Since the implementation of SET Plan Action 3.2, there has been a growing number of PED-oriented initiatives and projects at both EU and national level. The JPI UE also published a white paper on PED [7], which contains a definition framework for PED.

3.1.1. International and national definitions of PED

Even though the concept of PED is developed since 2015, there is no uniform definition, yet. In Seifried et al. [8] a detailed evaluation of applied definitions is provided by the analysis of five EU programs and nine prominent PED projects, of which common items and differences are analyzed. In Figure 2 left, the PED framework developed by JPI UE is depicted, which aims at creating a uniform vision for PED and states PED as "energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero GHG emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability" [6]. The definition is applied in a three-layer approach, where the generic definition can be specified on national level and implemented in labels for certification, see Figure 2 right.

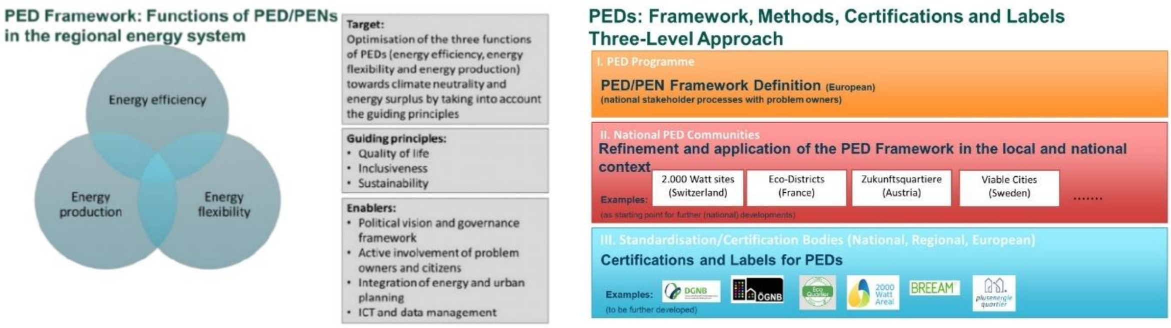

Figure 2. PED Framework definition according to JPI UE (left) and three-level approach (right) [9]

While this definition has a focus on the operational phase, a Swiss definition of a "2000-W-site" is based on the SIA 2040 efficiency path [10], which considers the whole life cycle incorporating also the embodied energy for the construction and demolition phase and the building induced mobility linked to the site as basic energy boundary. However, as can be seen in Figure 3 left that also other criteria like management and communication processes, surrounding and use are contained.

The ZEN Research Center (https://fmezen.no) has elaborated a detailed definition incorporating a set of key performance indicators (KPI) [11]. Main categories for the KPI are given in Figure 3 right. Each of the categories features a set of KPIs, where dedicated tools are available for the assessment of fulfilling the KPI. The ZEN definition and the KPI are also tested in 9 pilot regions across Norway in order to gather experience with the application of the definition and the KPI of the different categories.

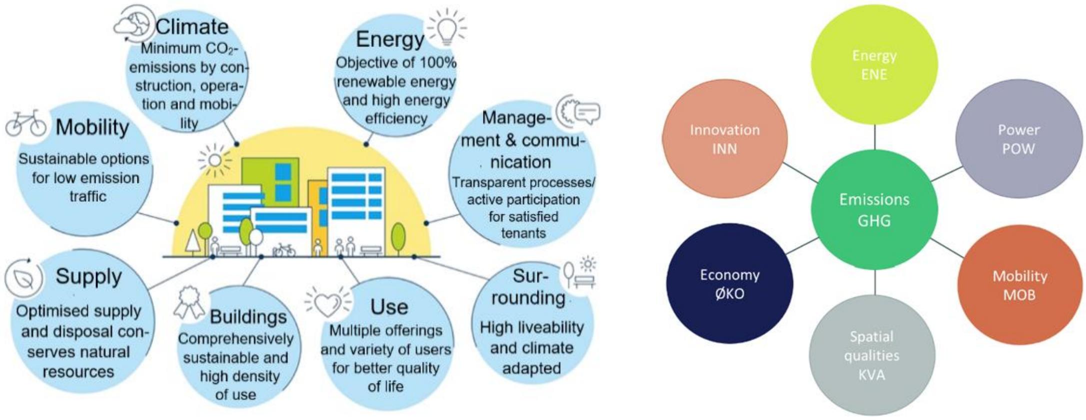

Figure 3 Swiss definition of 2000-W-sites (left, www.2000watt.swiss) and categories for PED evaluation in ZEN research center definition [11]

Furthermore, three PED definitions characterized by on-site renewable production and grid interaction are based on [12], which can also be interpreted as ambition level:

- The most ambitious definition denoted as "PED autonomous" only allows on-site renewable production within the geographical boundaries of the district. PED autonomous is completely self-sufficient, i.e., the on-site energy demand has to be entirely covered by on-site renewable energy production at any time. Energy export of surplus energy, however, by external electricity- and district heating grids is allowed.
- The "PED dynamic" definition is based on annual on-site energy production within the geographical boundary that is higher than the energy demand, but interaction with external electricity and district heating grids is allowed.
- The "PED virtual" definition allows renewable energy production and storage outside the geographical boundary, but it also requires, that the overall on-site and virtual (offsite) annual energy generation is higher the energy demand.

While "PED autonomous" requires only on-site production and storage and only allows export of surplus, PED dynamic can exchange energy over the geographical boundary, as long as the annual renewable energy export is larger than the import. PED virtual establishes a virtual boundary in terms of a contractual boundary, so renewable energy production outside the geographical boundary is allowed, but the offside renewable energy infrastructure must be an asset of the district.

Seifried et al. [7] conclude from their evaluation that there are still a lot of differences, among other things on the PED boundary, the calculation method of the energy balance and the scope for non-energy matters. An important fact is defining the fundamental purpose and application, which can lead to a universal framework.

3.2. Simulation and Monitoring results

3.2.1. 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. 78,000 m². The project involves one of the four blocks, which includes 4 multi-apartment buildings for a total of 307 apartments and 2500 m^2 of commercial space as seen in Figure 4 on the left. The buildings approach the Passive House standard, i.e., a SH demand of 15-20 kWh/(m²yr). The chosen central system combines a groundwater HP for SH, allowing the possibility of freecooling in summer, and DH for DHW as seen in Figure 4 on the right. The distribution system is a 2+2 pipe system with decentral fresh-water stations for DHW limiting requirements for the DHW temperatures to 55 °C. 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 rooms 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: First four buildings of the «Campagne District», Innsbruck (left) and hydraulic scheme of DHW and SH system of «Campagne District», Innsbruck

In Figure 5 a comparison of monthly PF for the past three heating periods 2022/23–2024/25 is depicted. The bars from left to right show the monthly PF for the years 2022/23 to 2024/25. The performance factor could be continuously increased during the core winter, primarily due to a reduced setpoint temperature, which, however, was discontinued in the transitional periods. Moreover, different system boundaries from the HP to the whole system is considered, as depicted as lines and colors in Figure 5, and the PF decreases significantly of up to a range of 1-1.5. 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. A net positive energy or zero CO_2-balance can only be reached with very low energy demand and highest possible PV on-site generation [13]. In case of (multi-storey) multi-apartment buildings (MFH) with a high density, as it is the case here for Campagne Innsbruck, the net balance cannot be reached on the district footprint, which has also been verified by consideration of energy production potential of PV integration in the façade of the buildings. Due to the compact buildings shape and self-shading, though, potentials proved to be limited.

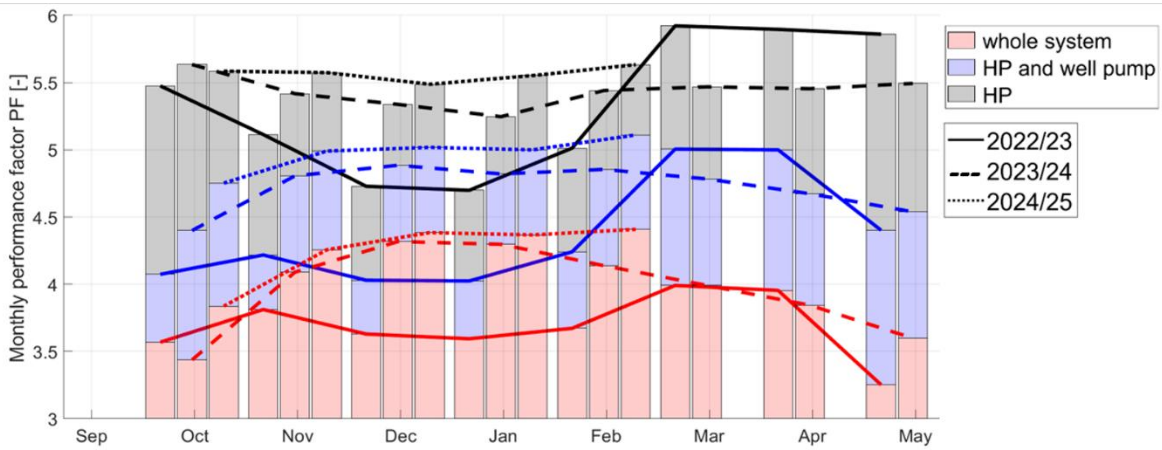

Figure 5. Monthly PF for different system boundaries and heating periods for «Campagne Innsbruck»

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 hence 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. On the other hand, the system integration is quite complex due to the separation of the system for each two of the building, implying additional pumping, valves and heat exchangers. Investigation by simulations on the system integration variants show that a simpler integration can improve the performance in the range of 0.5-1. This is due to highly reduced system losses, and if a building wise heat pump integration is considered instead of the centralised one, the energy consumption of the heat pump can be reduced by 15%.

3.2.2. 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.

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 a solar cadastre, 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 [14]. Figure 6 on the left 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).

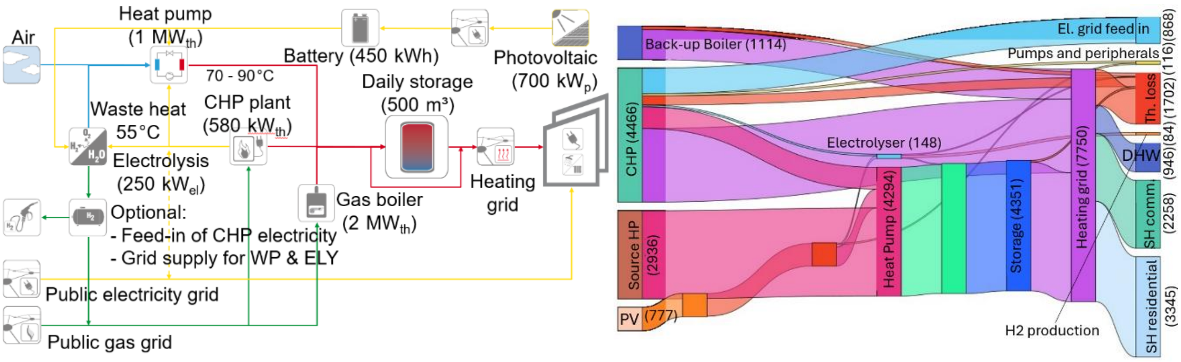

Figure 6. System configuration for the renewable energy system in "Quarree 100" (left) and simulated energy flow diagram as results of the simulations (right, energies in MWh)

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 6 on the right 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.

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

In a contribution from TH Nuremberg, a retrofit concept for a MFH with a cooperative housing company 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 renewable energies and user acceptance. The additional costs for components and control functions are to be offset by increased system performance and the possibility of lower energy consumption cost 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 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.

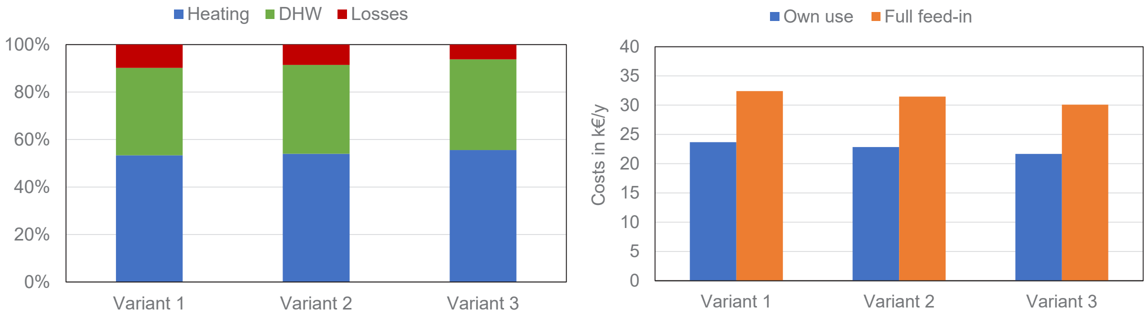

Figure 7. Final energy shares of SH, DHW and losses (left) and cost comparison of full feed-in and tenant electricity models in SenSys (right)

Figure 7 on the left 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 7 on the right 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 further evaluated by simulation [16].

3.2.4. Papieri District, Cham, Switzerland

The Papieri district in Cham, CH, is an old estate of the Paper industry, which is rebuilt to a comprehensive new district for living and working until 2035 for 1000 flats and 1000 additional workplaces in the final development stage on an energy reference area of 170,000 m^2. Figure 8 left shows a picture of the district, the first development phases are depicted in Figure 8 in the middle and the energy concept of the borehole fields connected to the central HP heating and cooling is shown in Figure 8 on the right.

Figure 8. View of the Papieri District from the river Lorze (left), development state (middle) and energy concept with borehole fields and river water heat source for the centralized HP

The neighbourhood consists of industrial heritage buildings of the paper industry which are preserved and retrofitted for a new use and amended by new buildings, which create a mix of about 30% of existing and 70% of new buildings. In the first phase depicted in Figure 8 middle, 105 condominiums and 160 rental apartments together with 4400 m^2 floor area of commercial and office use has been commissioned by the end of 2023.

The system technology is designed in a way that all building services of heating, cooling and domestic hot water are entirely supplied by renewable energy. Currently, about 60 % of the electricity use in the district is produced on-site. In the final stage the electricity is produced by a 6500 m^2 PV-system of an installed peak capacity of 1.27 MW_p and an estimated annual electricity production of 1.1 GWh, which is installed on the roofs of the new buildings. As second electricity generator a hydro power plant with an installed capacity of 230 kW and a calculated annual production 1.25 GWh is installed in the river Lorze, which runs through the district. The remaining electricity demand is imported as certified green electricity from the utility in order to reach a zero-emission balance.

The space heating and cooling as well as the DHW production is supplied entirely renewable by four central ammonia HP of each 1.7 MW capacity, which use borehole fields of totally 192 ground probes of 320 m depth as heat source. As second heat source river water is used either directly as heat source or as regeneration source for the borehole fields. The comfort cooling for the residential and office use is planned to be operated primarily by freecooling from the boreholes. Active cooling by the HP in chiller operation is only provided for peak load cooling, whereby all the recooling (waste) heat from the active chiller operation is to be recovered for either DHW production or for the regeneration of the borehole fields.

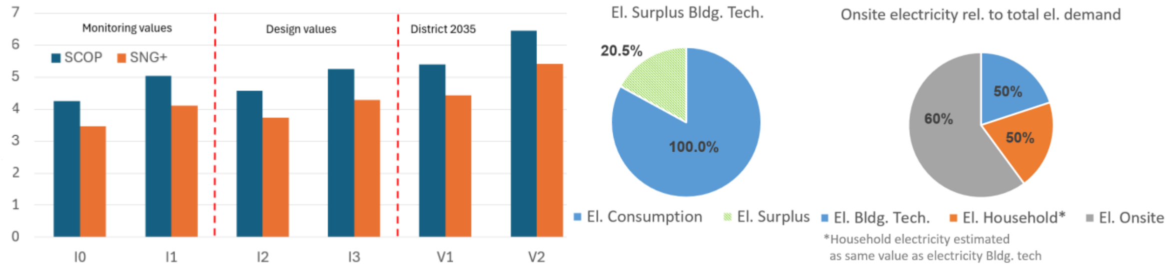

Figure 9. Simulation results of system variants (left) and electrical balance of electricity surplus (left pie diagram) and overall electricity self-sufficiency balance of the district (right pie diagram)

Since 2023 monitoring data of the district are available. Evaluation of the first year resulted in a moderate Seasonal Coefficient of Performance (SCOP) in the range of 4 and a seasonal performance factor of the whole system (SNG+) in the range of 3.5. Reasons for these values could be traced to a significantly lower DHW and space cooling demand than projected in the design values. Simulations with the design values yield a higher system performance slightly below 4 and 4.5 for the SCOP, see variant I2 in Figure 9 on the left. With the design values for the final development stage, a SCOP above 5 and SNG+ around 4.5 results. Another reason for the limited performance are high supply temperatures in the thermal grid of 67 °C due to the DHW operation. Monitored DHW demand, however, is lower than planned. Thus, also variants for only temporary charging of the decentral DHW storage tanks in so-called “charging windows” have been simulated, whereby in-between the windows, the grid temperature is lowered to 57 °C (variants I1, I3 and I5, respectively, in Figure 9 on the left). This could notably increase the SCOP in the final stage to a value above 6. However, space heating temperature are even lower, so further reduction could even further increase the performance. Regarding the overall electricity balance for PED evaluation depicted in Figure 9 on the right, the building technology is entirely covered by the self-generated electricity, and even a surplus of 20 % prevails. The whole district including household electricity, which was estimated to be in the same order as the building technology, currently exhibits a self-sufficiency of 60 %. The design value for the final stage is 75 %, which seem reachable by the current investigations of saving potentials with better HP performance. Further evaluations are dedicated to the source management and implementation of further simulation supported optimisation.

3.2.5. Case study of mine water heat storage application in Freiberg, DE

At TU Bergakademie Freiberg, in Germany, abandoned and flooded mines are investigated regarding the potential for a utilization as seasonal heat storage. In a case study different suited districts in Freiberg regarding the distance to the mine water storage and regarding available heat sources for the storage charging in relation to the heating and cooling loads were examined and evaluated based on the potential.

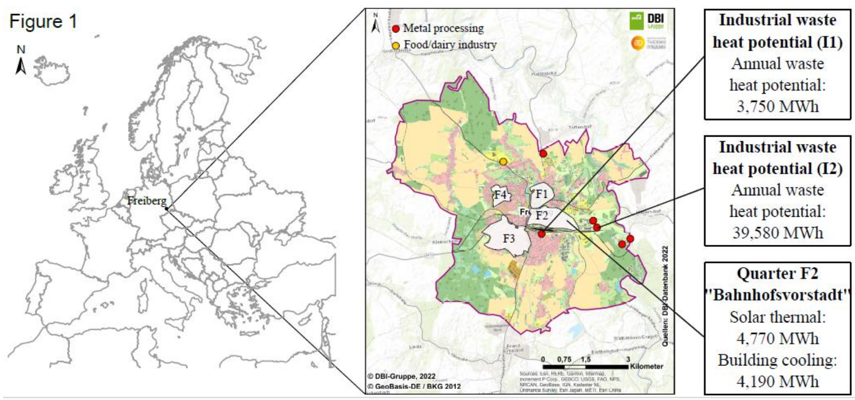

Figure 10. Districts in Freiberg considered for the case studies with respective waste heat potential from industry or recooling

According to this evaluation four districts F1-F4 as depicted in Figure 10 were investigated in more detail, creating two scenarios with low (a) and high (b) industrial waste heat share for the selected district F2 and further boundary conditions for the system integration and the economic evaluation. The investigations by simulation are accompanied also by measurements in the mine to evaluate heat losses of the mine water storage to the surrounding rock. The year-round storage efficiency is in the range of 50% as ratio between the heat extraction to heat injection [15]. As heat sources besides waste heat from industry, building recooling during summer as well as solar thermal collectors are considered with a natural gas boiler as back-up heater and a storage volume 10,000 m^3 corresponding to 3000 MWh. Heat pumps upgrade the storage heat to supply temperature levels for space heating and domestic hot water, respectively.

Figure 11 illustrates the heat mix of district F2 in scenario A, the state of charge of the mine water thermal energy storage (MTES), and the hourly energy stored and extracted. For an empty storage at the beginning of the year at a temperature of 2 °C, the storage does not contribute to the energy supply until April, while the district primarily relies on fossil fuels. When solar gains are available and/or industrial waste heat is operational, the share of fossil energy can be limited to approximately 80% during the winter months.

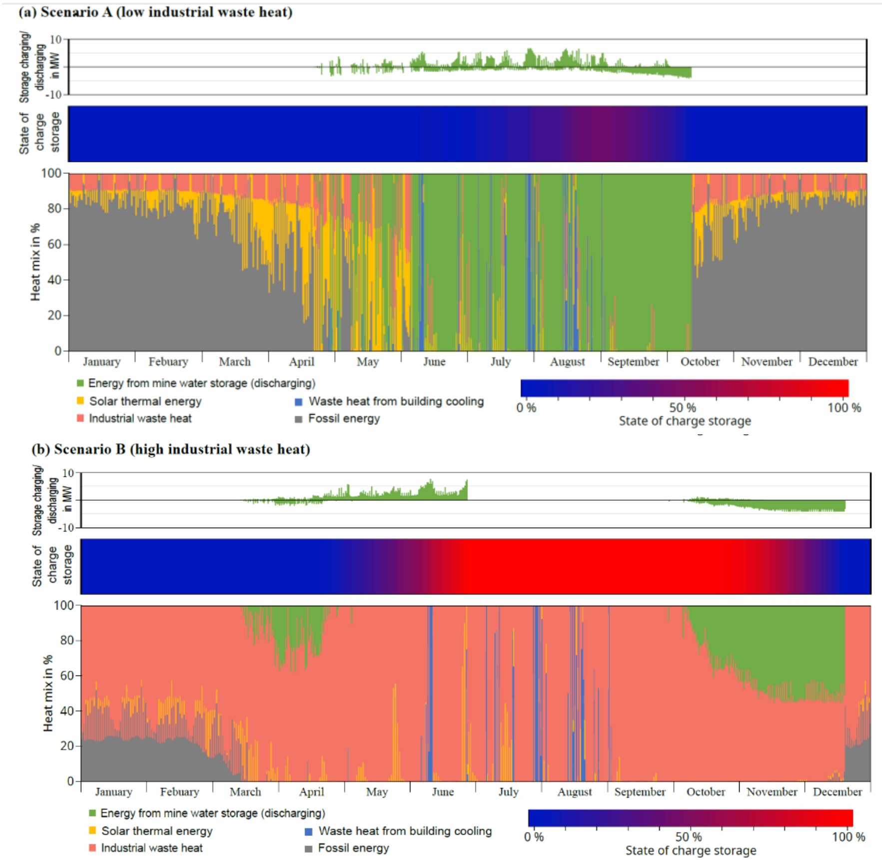

Figure 11: Results of the storage simulation on the state of charge of the annual operation and used heat source for the storage charging for scenario (a) with low industrial waste heat (top) and scenario (b) with high industrial waste heat (bottom)

From mid-April onwards, surpluses can be generated for the storage through solar thermal energy, industrial waste heat, and occasionally building cooling. As shown in Figure 11 on the top, frequent switching occurs between charging and discharging, indicating a primarily usage as daily storage during this transitional period. Continuous charging begins in May and becomes more evident in the charge state from July onwards. However, since the storage never reaches 100% capacity, it is oversized for the available heat sources in this scenario. A maximum water temperature of 18.7 °C corresponding to a state of charge of about 42% is reached. Nevertheless, energy stored is sufficient to supply the district autonomously until mid-October without using natural gas. Thus, the storage provides supply for approximately 6 weeks. Notably, even in summer, energy is extracted, indicating the use for short-term energy storage. This suggests that the available renewable heat sources are not always sufficient to meet the district's demand during summer.

In Scenario B, as shown in Figure 11 in the bottom, the storage is fully charged by the end of June, with temperatures reaching 40 °C. Additionally, especially by large amounts of industrial waste heat, the demand in summer can always be met without using the thermal storage.

Compared to Scenario A, the storage can also be utilized from mid-March, and until the end of April, it is primarily used for short-term storage. From early May onwards, almost only charging occurs, thus preparing the storage for the autumn period. In Scenario B, the yields are sufficient to utilize the storage until mid-December, meaning that only fossil energy is required to supply the district from mid-December to mid-March. The storage duration would therefore be approximately 2.5 months.

Scenario A achieves an energy autonomy of 23%, so 23% of the demand can be met with the considered heat source and the mine water storage. In scenario B, the energy autonomy is 78%. The storage in scenario B is fully charged by the end of June. To further increase the energy autonomy, doubling the storage volume to 20,000 m³ would increase the autonomy to 87%, and the stored energy could accommodate energy for over four months, which, however, would not be sufficient to supply the entire district autonomously year-round.

The economic evaluation shows that there are feasible options for an economic storage application. The cost drivers are the investment required for new heat sources and, above all, the investment needed for a district heating network.

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. Reaching a PED on the district footprint remains challenging for larger buildings, but integrated energy systems based on HP can ideally use synergies in terms of load balancing and waste heat recovery in order to reach ambitious targets. A state-of-the-art analysis revealed that PED are still rare, and not all PED effectively reach a positive energy balance, but some are rather towards PED or just have interesting features for PED. Nevertheless, PED remain a useful vision for the planning and design of future high-performance districts.

A technology evaluation confirms that heat pumps are well established in existing (towards) PED. The evaluation of existing PED and monitored case studies in Annex 61 form the basis of the derivation of five top-level categories for the HP integration, each of them being represented by the one or other of the monitoring projects in the Annex 61. In many cases, the monitoring systems are also simulated, which facilitates to discover optimisation potentials and perform variant analyses. Vice versa, simulation models can be verified by monitoring data and further developed to accompanying simulation or fully digital twins.

Interim results of five case studies with simulation and monitoring show technical and economic advantages and limitation of the different integration options. Table 2 summarises the main results of the selected projects.

Table 2. Summary of the selected districts and building clusters as contributions of the participating institutions to IEA HPT Annex 61

Project	Characteristics	Results / KPIs
Campagne Innsbruck, UIBK AT	Phase 1:4 bldgs with 307 flats in total Block GW-HP for SH/ DH for DHW	• Performance factor of the HP up to 6, reduced to ~4.5 by system losses and auxiliaries • PED balance very challenging due to dense built urban environment • Optimisation of system configurations by simulations yield SPF increase of 0.5-1
Papieri OST, CH	Phase 1: 105 condominiums & 160 rental apartm. Ground-source HP	• Monitoring SPF in the range of 3.5 due to continuously high grid temperature of 67 °C • Simulation yields SPF >6 by grid temperature decrease to 47 °C by charging windows • Overall self-sufficiency about 60 %, reached design target for final stage 75 %
SenSys THN EnCN, DE	Model retrofit of 38-flat MFH to passive house level with smart technologies	• Simulation of DHW hydraulic variants yield reduction of energy losses by 40 % • Tenant electricity model yield electricity cost savings in the range of 28 % which supports amortization of cost for deep retrofitting
Quarrée 100, siz energie-plus, DE	New heating grid for existing district	• 134 buildings connected, corresponding to 58 %, of which 47 % are existing buildings • 50 % of grid energy supply by HP with PV-electricity, higher HP share with grid electricity
TUBAF, DE	District supplied with mine water storage	• 50% mine water storage efficiency, 23 %-78 % energy autonomy, waste heat favourable • Economic feasibility dependent on heat source cost/ grid investment cost

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.

Moreover, care should be taken to keep temperatures low, since in centralised system tend to have higher supply temperature level for the grid operation as seen in the Papieri district, where part-time lowering of temperature by DHW charging windows can yield performance benefits. 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, opportunities of the site shall be used as much as possible to access favourable local heat sources like waste heat and storage systems, e.g. in the form of mine water, which can in the best case be combined to create an economically feasible operation.

Results serve to elaborate technical documentation, recommendation on HP integration and best practice systems for the replication and 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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