Scenarios for Integration of Power to Heat Technology in Czech District Heating Systems

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Abstract

The paper addresses the sustainability of the operation of existing district heating (DH) systems in the Czech Republic, which historically used primarily fossil fuel sources and currently are under transformation. The system integration of heat with electricity sector through power to heat (P2H) technologies allows for the efficient use of DH thermal capacity to store surplus renewable energy and can also offer additional support services to the electricity transmission system. Simulation study was performed in TRNSYS for three typical typologies of DH systems in the Czech Republic. Key performance indicators (KPIs) such as CO_2 emissions, non-renewable energy or the cost of heat produced by P2H technology were assessed.

Keywords: power to heat, P2H, district heating, high temperature heat pump, solar energy, photovoltaic plant

1. Introduction

To reduce CO_2 emissions in the power sector, EU is promoting renewable energy sources for power generation. Installation of new wind and photovoltaic plants is growing in many countries in the EU . Coupling of power and heat sectors can significantly contribute to both renewable energy integration and decarbonization (Bloess et al., 2018). Potential of P2H technology integration in DH system was evaluated in other studies in the Germany (Böttger et al., 2014) or in the Sweden (Schweiger et al., 2017) with specific results for every state. Technical P2H potential in Germany accounts 6 GW_{el} in 2015 and 20 GW_{el} in 2030. The P2H potential in Sweden was estimated from 0.2 to 8.6 TWh. In 2017, an overview of the status of P2H technology in DH systems in Europe was conducted (David et al., 2017). The analysis revealed that 149 units with capacities exceeding 1 MW were integrated into DH systems across Europe. For a greater number of installations, it is essential to analyse sources of low-potential heat in relation to areas served by DH systems, this approach was implemented in a study conducted for Denmark (Lund and Persson, 2016). Another review explores various configurations for integrating heat pumps into heating and cooling systems (Barco-Burgos et al., 2022). The review concludes that energy conversion approach through P2H technology has the potential to be a cost-effective solution, supporting the decarbonization of the DH sector. Other analyses focus on the economic perspective, for example, one study (Østergaard and Andersen, 2018) compares DH systems supplied by heat pumps using air, seawater, or groundwater as heat sources and examines three low-temperature DH schemes. Another study analyses the techno-economic potential of P2H technology in DH systems (Fambri et al., 2023), highlighting their role in enhancing electricity grid flexibility by absorbing surplus renewable energy and optimizing system efficiency. A case study, based on data from the DH and electricity network of the city of Turin in Italy, was analysed.

For now, potential of P2H technology in Czech Republic has not been deeply evaluated. In 2022, the heat supply in the Czech Republic was composed of 54% from coal-fired sources, 26% from gas, and 9.2% from biomass. So far, the only industrial heat pumps in the Czech Republic used on an industrial scale is in Decin (2 x 3.28 MW) for the DH system. Several projects for the use of electric boilers or low-potential heat in heat supply systems using heat pumps are expected to be implemented by 2030. Simultaneously, the capacities of fluctuating renewable electric energy sources (wind and solar power) is estimated to increase from 3.8 GW in 2024 to 11.5 GW in 2030. This paper deals with technology model focused on advanced methods of dynamic

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simulation of DH systems with use of TRNSYS and PYTHON. Model is designed to be scalable to generate different KPIs for different P2H solution integration options for different scale of DH system while requiring the least number of inputs from heat distributor.

2. Model of different typologies of DH systems

Based on analysis of the available data of the DH systems in the Czech Republic in strategic documents, the typologies were divided to 6 categories depending on the declared total heat output of heat sources belong to the given DH system. The chosen scale represents all types of systems from the smallest, local or municipal heat networks, through small and medium-sized urban heat networks, to the largest urban or regional heat networks. The largest urban or regional DH systems have specific boundary conditions (temperatures higher than 150 °C) and usually the planning of new heat sources is more specific to every case. Due to this fact the three largest categories were not studied due to small potential of replication in national level. In any case, there is a statistically very significant number of relatively small DH systems in the Czech Republic. The focus of simulation study was on the typically most common three categories of DH systems, which cover approximately more than 70 % of DH systems in the Czech Republic and contributes approximately 39 % of the total heat supply. 3 typologies were selected for the general parametric study which represent:

- medium urban network with a combination of conventional and low-emission DH sources with a predominance of residential consumption (maximum **heat output 20 MW**, annual heat supply 180 TJ, length of DH system 15 km, winter temperature difference 95/65 °C, annual heat losses 10 %, fuel composition - 30% of coal, 30% of natural gas, 40% of biomass);
- small urban network with a predominance of low-emission DH sources with a predominance of residential consumption (maximum **heat output 10 MW**, annual heat supply 135 TJ, length of DH system 10 km, winter temperature difference 85/65 °C, annual heat losses 8 %, fuel composition – 70% of natural gas, 30% of biomass);
- small municipal network with a predominance of low-emission heat sources and residential consumption (**maximum heat output 5 MW**, annual heat supply 65 TJ, length of DH system 4 km, winter temperature difference 70/50 °C, annual heat losses 8 %, 40% of natural gas, 60% of biomass).

A detailed numerical model in TRNSYS was developed to evaluate technical KPIs such as CO_2 emissions, non-renewable energy or the cost of heat produced. Inputs for the model are following: location and climate data, the ratio of consumption profiles by category (industry, commercial, residential), the desired peak and off-peak temperatures and heat output in the DH system, the annual heat supply, length of the DH system, etc.). The model is designed to support various P2H scenarios integrating an industrial electric boiler, industrial air-to-water (bivalence limit temperature of 5 °C was considered) and water-to-water heat pump into a system with an existing fuel source. However, two scenarios of water-to-water heat pump were compared with heat extracted from river water (average annual water temperature 10 °C) and heat extracted from waste heat (average annual temperature 20 °C). In this study only heat pumps as a P2H technology were observed.

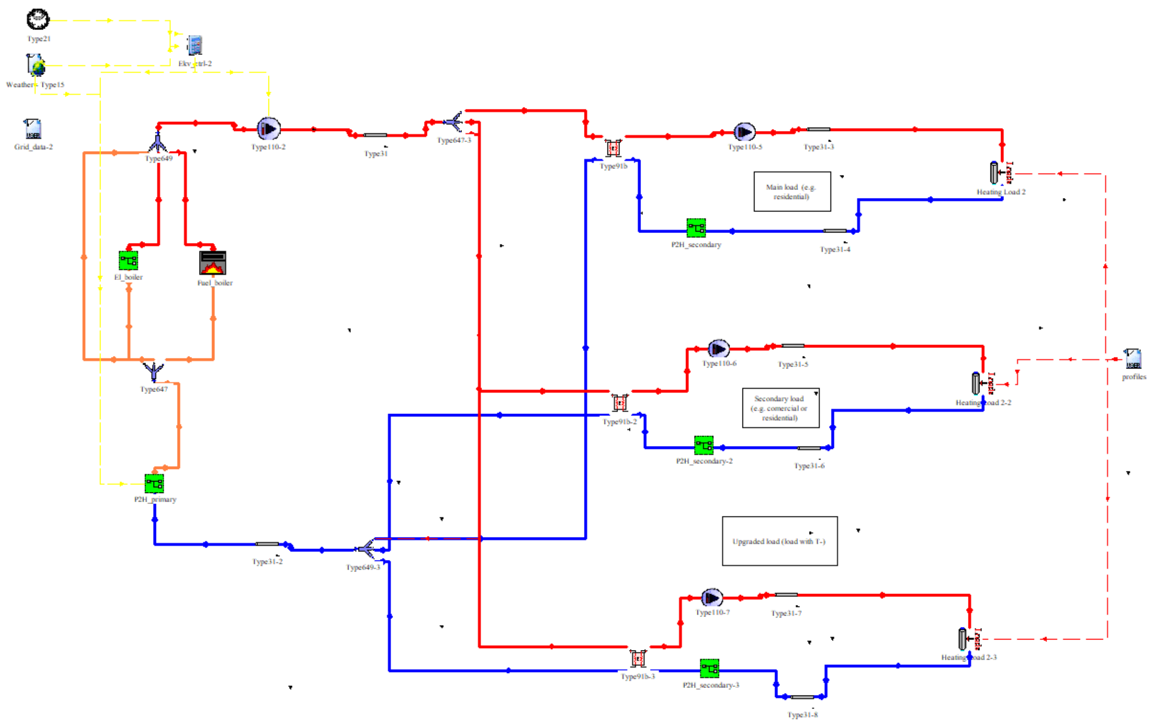

Fig. 1: Numerical model in TRNSYS simulation tool

P2H technologies are modelled based on performance maps for a wide range of boundary conditions. Heat pump considered for simulation used refrigerant R1234ze. The P2H technology is considered to be connected in series before fossil-based source of heat. The simulated operation of heat pumps within the DH systems is significantly influenced by the temperature level in the DH system. If the heat pump does not have sufficient capacity to deliver the required temperature, higher than the simulated return water temperature level, the device is switched off. In the P2H technology configuration, a storage tank with a specific volume of 0.15 $m^3.kW^{-1}$ is considered. Furthermore, the settings vary according to the type of heat pump for air-to-water and water-to-water. The model also provides information on electricity consumption divided into auxiliary (hydraulic pump consumption) and P2H technology consumption. Furthermore, electricity generation from renewable sources is also included in the simulation. In this study, a photovoltaic (PV) plant with a nominal capacity of 1 MW_p and 2 MW_p is considered. Annual specific electric production is 152 $kWh.m^{-2}.a^{-1}$. The progress of heat supply, water-to-air heat pump output and temperatures in DH system are in Fig. 2. The progress of the electricity consumption tied to the operation of the DH systems and the expected production from PV plant is shown in Fig. 3 for a typology with 20 MW heat output class. This figure also shows the considered carbon intensity profile of the grid (for Czech Republic), which is used to calculate the equivalent CO_2 emissions linked to the operation of P2H technology.

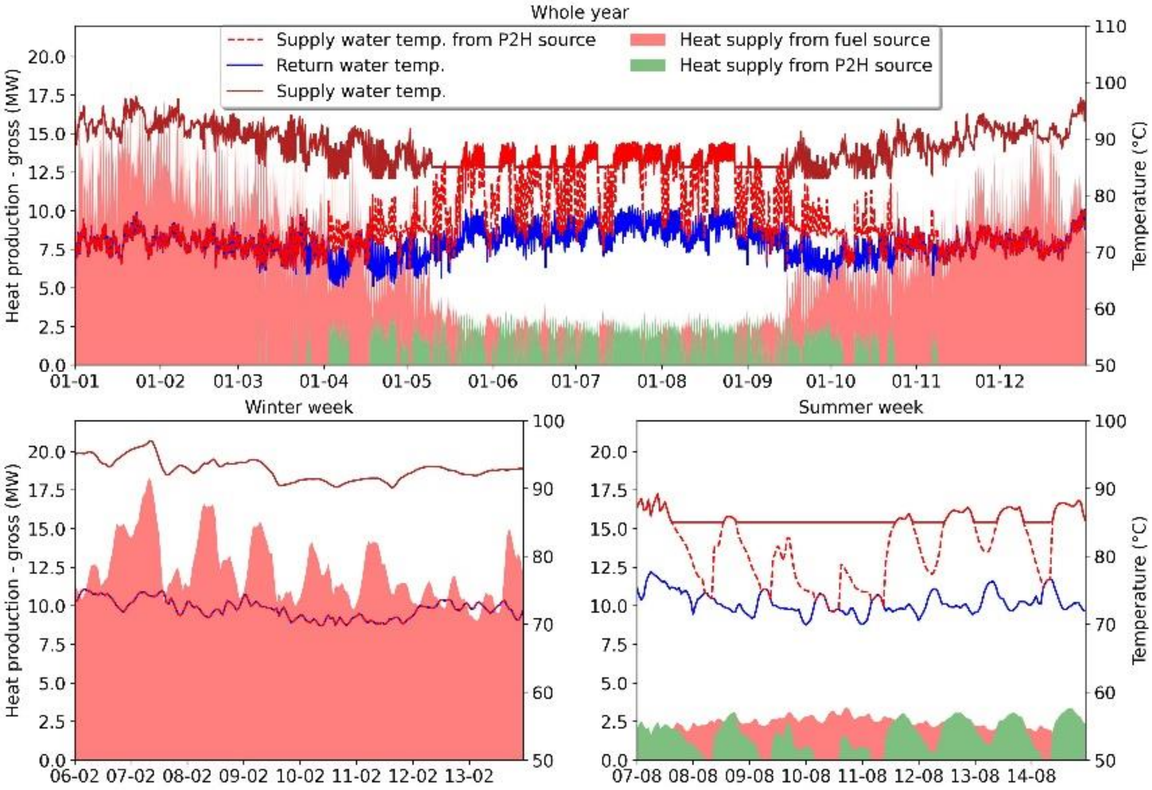

Fig. 2: Example of one typology (20 MW heat demand) and integration of air-to-water heat pump

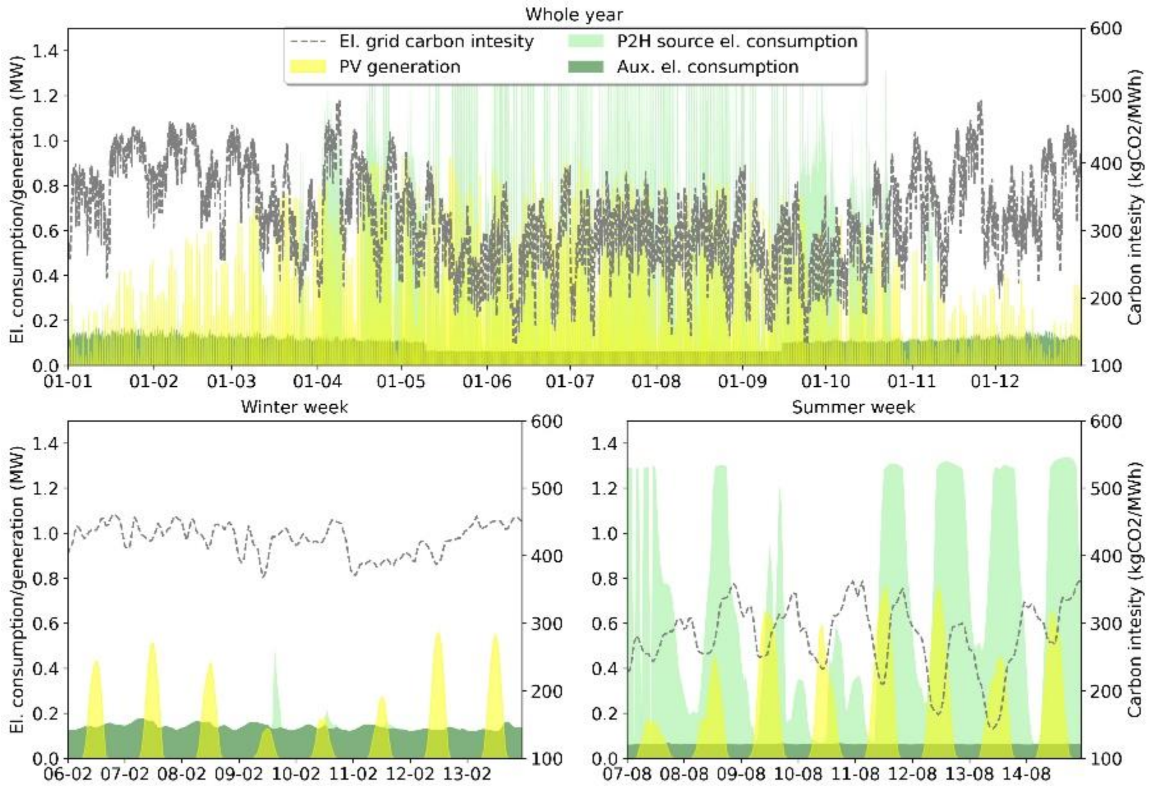

Fig. 3: Example of one typology (20 MW heat demand) and integration of air-to-water heat pump

3. Simulation results

Impact assessment of P2H technology integration into three typological DH systems in Czech Republic was done for nine different scenarios of P2H integration and PV production, see in Tab. 1. Energy delivered by different sources is shown in Fig. 4. to 6. For two largest DH systems 2.4 MW installed thermal capacity of P2H technology was considered (for the smallest sized DH system 1.2 MW). In general, for all types of integration of the selected P2H technologies it can be stated that they are very sensitive to the temperature conditions in the DH systems. If there is a better-quality heat source on the evaporator side of the water-to-water HP (e.g. waste heat from waste-water treatment plant, data centre), the plant achieves sufficient capacity to partially cover the demand even for DH system at higher temperature levels and its operation does not need to be significantly limited. For low-temperature DH systems (from 60 to 85 °C), all types of heat pumps usually have sufficient capacity and achieve the maximum possible operating time. In Fig. 4. to 6. shows the change in the source composition on the total heat supply (including the inclusion of the combustion efficiency of the individual fuels).

Tab. 1: Scenarios of P2H integration into three typologies of DH systems

REF	Reference case
1	HP air-to-water
2	HP air-to-water with PV plant 1 MW_p
3	HP air-to-water with PV plant 2 MW_p
4	HP water-to-water (river)
5	HP water-to-water (river) with PV plant 1 MW_p
6	HP water-to-water (river) with PV plant 2 MW_p
7	HP water-to-water (waste heat)
8	HP water-to-water (waste heat) with PV plant 1 MW_p
9	HP water-to-water (waste heat) with PV plant 2 MW_p

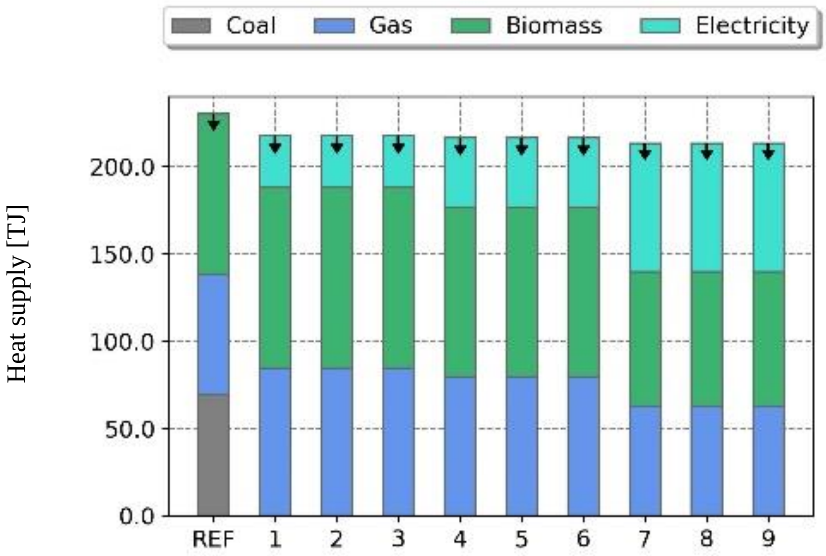

Fig. 4: Energy delivered by different sources – typology with heat output class 20 MW

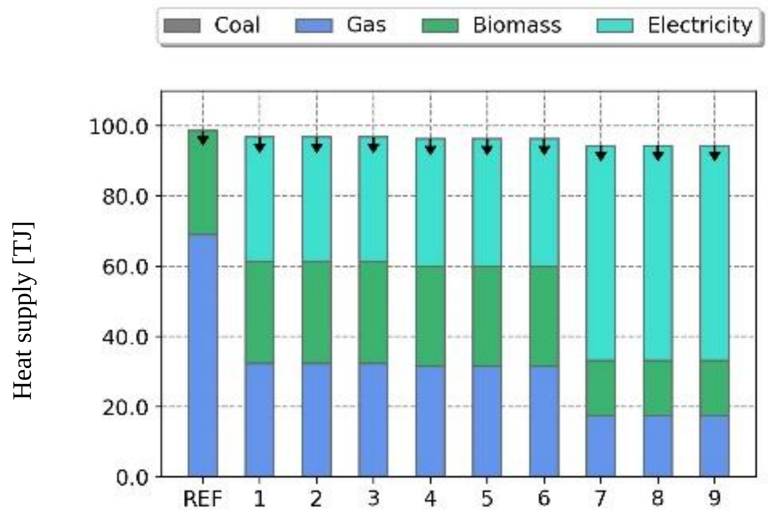

Fig. 5: Energy delivered by different sources – typology with heat output class 10 MW

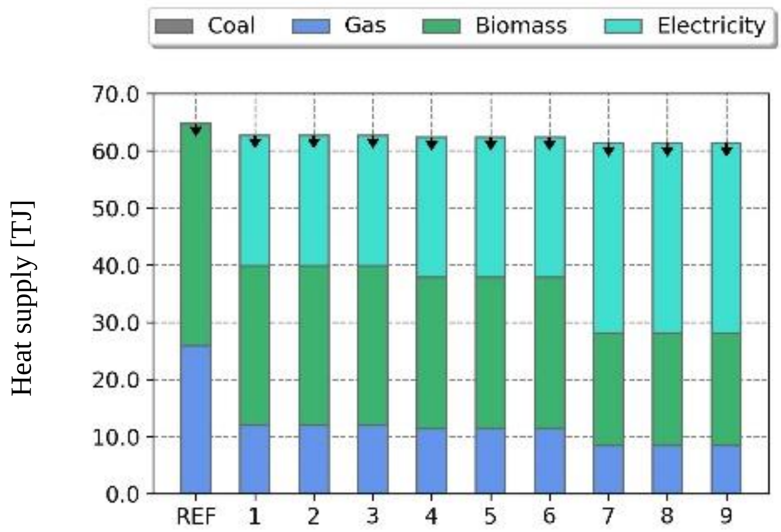

Fig. 6: Energy delivered by different sources - typology with heat output class 5 MW

Projected increase in electricity consumption, as well as consumption covered by local PV and possible export to the grid is shown in Fig. 7. to 9. PV generation is considered primarily for self-consumption within the DH system and PV plant. Self-consumption or possible export of PV generation is included in the evaluation of economic indicators (specific heat prices of P2H) and sustainability indicators (primary non-renewable energy, carbon intensity of DH system).

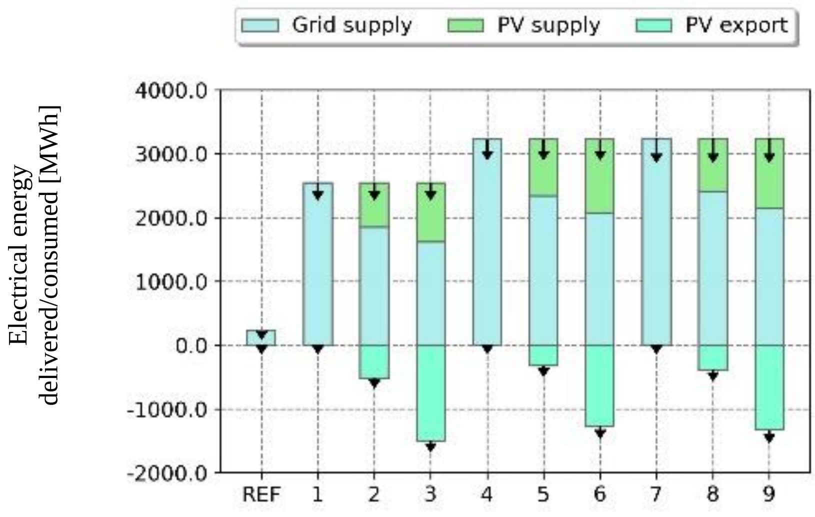

Fig. 7: Results of electricity consumption of P2H technology with fraction which is used and exported – typology with heat output class 5 MW

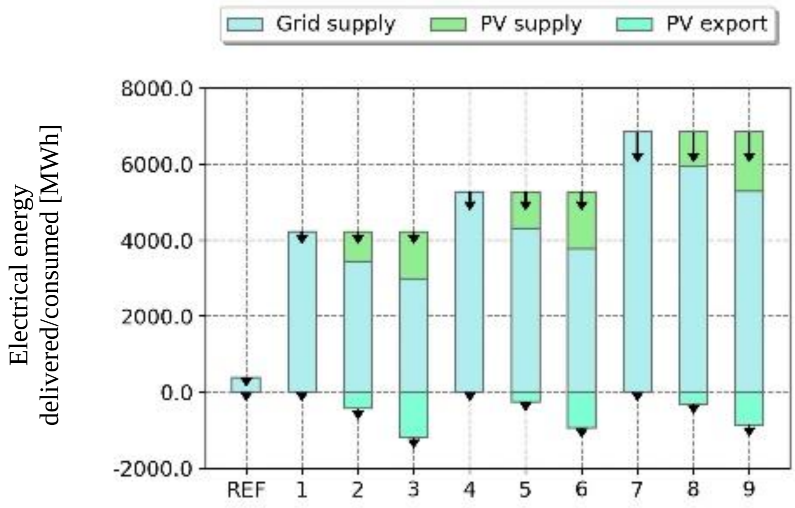

Fig. 8: Results of electricity consumption of P2H technology with fraction which is used and exported – typology with heat output class 10 MW

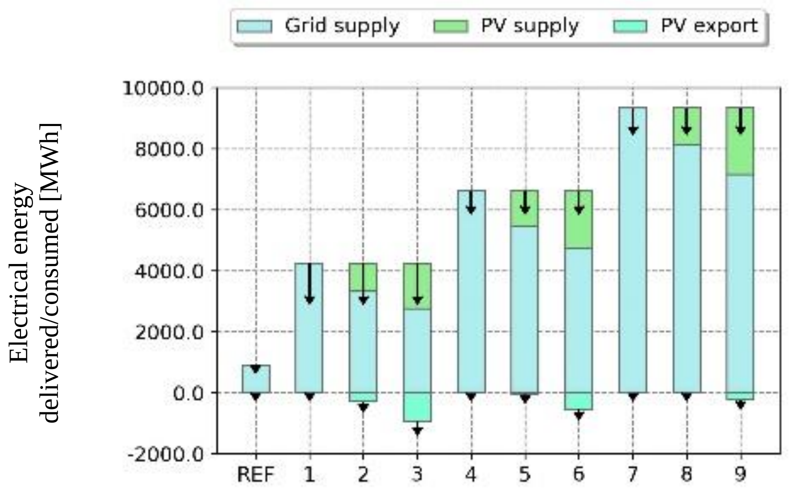

Fig. 9: Results of electricity consumption of P2H technology with fraction which is used and exported – typology with heat output class 20 MW

Detailed results are shown only for typology with 20 MW and 5 MW heat output class. Indicators related to annual coefficient od performance (COP), operating time, and fraction of electricity from PV used for P2H technology are shown in Tab. 2 and 3. All types of P2H technologies can be effectively combined with PV. Most cases show solar fraction from 13 to 35% of with a production utilisation of 61 to 100%. The results of combining with PV are mainly indicative in this study to evaluate the potential impact on the economics and sustainability of the operation. The integration of air-to-water heat pump is characterized by a relatively high COP in the range of 2.5 and 2.7. For this type of heat pump, it is necessary to assume a bivalence limit (in this case the heat pump is not operated at an outdoor air temperature below 5 °C), which in principle does not allow annual operation and the operating time of this type of heat pump will depend on the climatic conditions. Another factor limiting the efficient operation of these devices is mainly the temperature of the return water. For conservative operation without considering the interaction with the electricity grid (dynamic tariff, ancillary services), an operating time of this type of heat pump in the range of 4000 to 6000 hours can be considered, depending on the typology. Air-to-water heat pump is suitable as an efficient secondary source to cover off-season demand. The integration of water-to-water heat pump with river water as a source results in a lower annual COP in the range of 1.9 and 2.3. Due to the more stable temperature on the evaporator side with an average temperature of 10 °C, this type of heat pump allows year-round operation. Its operating time is mainly limited by the return water temperature. High return water temperatures do not allow operation with sufficient efficiency and can limit the operating hours to 6700 hours, almost to the level of operating hours of air-to-water pump. Due to the year-round operation, a higher share of the total heat production can be assumed. However, this share is limited by lower efficiency at certain times of the year and it may be more advantageous to use a bivalent peak source (e.g. natural gas).

Tab. 2: Summary of energy performance results - typology with heat output class 20 MW

	COP [-]	Operation period [h]	Coverage of heat production by P2H technology [%]	Solar fraction [%]	Use of PV production [%]
Ref	0	4056	13,7	0	0
1	2,5	4056	13,7	0	0
2	2,5	4056	13,7	22	76
3	2,5	6741	18,4	35	61
4	1,9	6741	18,4	0	0
5	1,9	6741	18,4	17	95
6	1,9	8751	34,5	28	77
7	2,4	8751	34,5	0	0
8	2,4	8751	34,5	13	100
9	2,4	8751	34,5	23	90

Tab. 3: Summary of energy performance results - typology with heat output class 5 MW

	COP [-]	Operation period [h]	Coverage of heat production by P2H technology [%]	Solar fraction [%]	Use of PV production [%]
Ref	0	0	0	0	0
1	2,7	6202	36,3	0	0
2	2,7	6202	36,3	27	57
3	2,7	6202	36,3	37	38
4	2,3	8697	39,3	0	0
5	2,3	8697	39,3	27	73
6	2,3	8697	39,3	36	47
7	3,1	8754	54,1	0	0
8	3,1	8754	54,1	25	67
9	3,1	8754	54,1	34	45

The integration of water-to-water heat pump with waste heat recovery achieves relatively high COP in the range of 2.4 and 3.1. Due to the constant and relatively high temperature 20 °C on the evaporator side, this type of pump allows year-round operation with high efficiency. The operating hours stably reach values of 8751 to 8756 hours without limitation related to the temperature level of the return water. The high operating temperatures of the SCZT in this case are mainly reflected in a reduction of the COP. If suitable temperature conditions are provided, a heat supply with a high COP heating factor can be expected to enable the heat pump to effectively take a high share of heat production. For smaller municipal installations this configuration can be considered for installation as a single heat source without an additional peak source.

4. Conclusion

Taking into account the current carbon intensity of the electricity grid, P2H technology can clearly be considered as a low-emission solution, see in Tab. 4 and 5. The inclusion of the selected P2H technologies in the studied DH systems leads in most cases to a reduction of the carbon intensity of the delivered heat. As expected, the largest reductions can be achieved in the medium urban grid typology (20 MW) where the coal source has been shut down under this scenario. However, even for networks with a low-carbon source base, represented here by a small municipal network (5 MW), additional CO_2 reductions can be achieved by incorporating P2H technologies, especially if a combination with PV is considered. For recalculation of non-renewable energy, the available conversion efficiencies by energy carrier and the factors given by Czech legislation (Decree 264/2020 Coll.) were used. Emissions of CO_2 were evaluated based on factors related to IPCC emission factor database. For electricity, a dynamic annual intensity profile based on the efficiency of the electricity network in 2023 was used, based on the methodology for calculating the average carbon intensity in a given hour according to the resource utilisation available on the ENTSOE portal(ENTSOE, 2021). The prices of individual commodities and capital costs were determined according to the current market situation in 2023 and also include regulated components. The non-renewable energy consumption, carbon intensity (from 0.08 to 0.14 tCO_2/MWh), and cost of heat produced from P2H technology (from 36 to 81 EUR/MWh) were analyzed for two typologies.

This simulation study was focused on a simple integration of high temperature heat pumps into DH system. However, the developed model is suitable for analyses of the impact of temperature level changes in DH system, analysis of the profitability of operation according to spot prices, or analysis of operation for electricity network support services. Three analyzed typologies are small to medium scale DH systems where technical feasibility and stronger linkage between the DH distributor and the municipality can be assumed. The result of a large number of simulations will be used for design of simplified tool for communication of decarbonization plan between heat producer and municipality in Czech Republic.

Tab. 4: Summary of KPIs - typology with heat output class 20 MW

	Nonrenewable primary energy [TJ]	Carbon intensity of delivered heat [$tCO_{2,ekv}$/MWh]	Specific cost of heat production from P2H [EUR/MWh]
Ref	155,6	0,182	68
1	131,0	0,112	74
2	119,6	0,108	64
3	108,2	0,106	56
4	147,6	0,120	81
5	136,3	0,115	73
6	124,9	0,112	66
7	155,2	0,120	61
8	143,8	0,114	57
9	132,5	0,110	53

Tab. 5: Summary of KPIs - typology with heat output class 5 MW

	Non-renewable primary energy [TJ]	Carbon intensity of delivered heat [$tCO_{2,ekv}/MWh_t$]	Specific cost of heat production from P2H [EUR/MWh]
Ref	30,6	0,097	67
1	37,9	0,089	62
2	26,5	0,079	50
3	15,1	0,075	41
4	43,6	0,102	68
5	32,2	0,089	57
6	20,8	0,084	48
7	40,2	0,094	51
8	28,9	0,081	42
9	17,5	0,077	36

5. Acknowledgments

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6. References

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