SECTOR COUPLING FOR PEAK HEAT SUPPLY IN BIVALENT HEAT PUMP SYSTEMS USING POWER-TO-X ENERGY CARRIERS

Summary

This study investigates how sector coupling can support the decarbonisation of heating systems by combining heat pumps with renewable peak-load technologies. Renewable electricity can be converted into storable energy carriers via Power-to-X processes and later reconverted to energy (X-to-Energy) during peak periods when heating demand and electricity prices are high, renewable electricity generation is limited and the required heating power possibly exceeds the capacity of the heat pump. The analysis compares several energy carrier candidates and evaluates their integration into bivalent heat pump systems for multifamily buildings and district heating networks. The results show that such configurations can reduce heat pump oversizing and investment costs while maintaining a reliable heat supply. By providing flexible, climate-neutral peak energy, these approaches can contribute to winter electricity reduction, improved security of supply, and a more resilient energy system.

Keywords: Sector coupling, bivalent heating system, heat pump, renewable peak load heating systems, long-duration energy storage, Power-to-X, X-to-Energy; winter electricity reduction

Field of application for the findings: Multifamily house, district heating networks, sector coupling, Power-to-X, X-to-Energy, long-duration energy storage

Addressed audience: Energy system researchers, heat pump manufacturers, district heating operators, policy makers

1. Introduction

Heating plays a crucial role in energy consumption in Central European climates, accounting for about 50% of final energy use, while buildings are responsible for roughly one-third of global final energy demand (IEA, 2022). Space heating and domestic hot water typically account for approx. 60–70% of household energy consumption within buildings in Europe (IEA, 2023). This space heating demand is highly seasonal, with most of it concentrated in winter months (Oct-March); therefore, final energy consumption for heating increases to 66% of total final demand in January, for example, in Switzerland. These peak demand periods determine the required capacity of monovalent heating systems, in which a single heat generator covers the entire heating demand of a building, and therefore strongly influence heat pump sizing. It also increases electricity demand during winter peak periods (Connolly et al., 2014).

Heat pumps are a key technology for decarbonising low- to medium-temperature heat supply in buildings and industry. In a monovalent system design, heat pump systems are typically dimensioned according to the maximum heating load occurring under extreme outdoor temperature conditions. In practice, planners often apply additional safety margins to avoid comfort complaints during extreme winters. The monovalent design approach requires the installed heat pump capacity to cover the full peak heating demand.

Fig. 1 compares installed specific heating power with heating power derived from measured demand for 251 heat pump systems, based on measurement periods of 3-9 years. The installed heating capacity is typically higher than the measured requirement, indicating systematic oversizing of heat pump systems in practice. Field studies of heat pump systems in more than 600 Swiss multifamily houses indicated a median oversizing of approx. 40% compared to heating power derived from measured demand (Bosshard et al., 2023). Oversizing increases investment costs, potentially reduces system efficiency and lifetime due to frequent cycling, and contributes to higher electricity demand during winter peak periods.

One potential approach to reduce heat pump oversizing is the use of bivalent heating systems, in which peak heating demand is covered by an auxiliary technology rather than increasing the installed heat pump capacity. This study, therefore, investigates the use of renewable X-to-Energy technologies for peak-load coverage. The objective of this work is to analyse how integrating such technologies into bivalent heat pump systems can reduce required heat pump capacity and associated system costs compared to conventional monovalent system designs in multifamily houses and district heating networks.

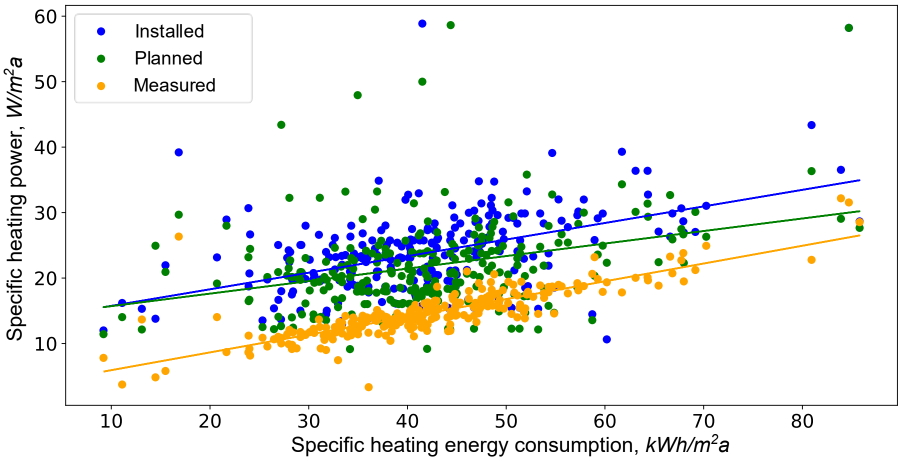

Fig. 1: Specific heating power of 251 heat pump systems as a function of measured heating energy consumption. Three values are shown: installed specific heating power (blue), specific heating power derived from design documents (green), and specific heating power derived from measurement data (orange). The coloured lines represent the average values over measurement periods of 3–9 years. Source: Bosshard et al., 2023

2. System concept and methodology

A renewable bivalent heating system approach illustrates how sector coupling can be implemented in practice: renewable electricity is chemically converted into energy carriers that can be efficiently stored for months or even years and used to provide flexible, climate-neutral peak-load heat when renewable generation is scarce. Such concepts can contribute to improve security of supply, decarbonization of the heating sector, and a more resilient energy system.

The analysis followed four main steps. First, a technology screening and comparison of X-to-Energy options was carried out to identify suitable technologies for peak-load coverage in combination with heat pump systems. Based on literature review and expert assessments, several energy carrier candidates were analysed. These were hydrogen, methane, methanol, ammonia, liquid organic hydrogen carrier (LHOC), and Renewable Metal energy Carriers (ReMEC, e.g. aluminium or iron). For each energy carrier, technology factsheets were developed, summarising key characteristics such as availability, conversion efficiency, storage and transport requirements, safety aspects, costs and environmental impacts. Second, the technical integration of X-to-Energy technologies into heat pump systems was analysed. The concept is based on bivalent heating systems, where a heat pump covers the base heating demand while peak loads are supplied by an auxiliary X-to-Energy technology. The potential reduction of installed heat pump capacity was evaluated for different system configurations, including air-source and ground-source heat pumps in multifamily houses (≥ 50 kW) and large heat pump systems in district heating networks (≥ 500 kW). Third, the economic implications of reduced heat pump sizing were assessed. Investment costs for heat pumps and associated infrastructure (e.g. borehole heat exchangers) were compared between conventional monovalent systems and bivalent configurations with X-to-Energy peak-load coverage. In addition, potential economic benefits from reduced cycling, improved load matching and longer heat pump lifetime were considered.

Finally, the overall economic viability and system implications of X-to-Energy peak-load technologies were evaluated. This involved identifying conditions under which such systems can become economically competitive and assessing their potential contribution to improving the security of heat supply in electrified heating systems.

3. Results

The comparative analysis across technical, economic, environmental, and safety dimensions highlights distinct trade-offs between the analysed Power-to-X energy carriers. No single carrier performs best across all criteria; instead, the suitability of each technology depends strongly on the application context, boundary conditions, and TRL or projected cost of new technologies.

ReMEC carriers (aluminium and iron) stand out due to their high production efficiency (above 60%), high volumetric energy density and favourable safety characteristics. Although their technology readiness level is lower, particularly for aluminium, they show strong potential for long-duration energy storage, especially in building applications where storage density (limited space) and operational safety are important. Among gaseous and liquid energy carriers, Power-to-Methane based on photovoltaic electricity offers good efficiency and compatibility with existing gas infrastructure. Lifecycle greenhouse gas emissions are moderate (30–53 gCO_2-eq/MJ), depending on whether the CO_2 is sourced from direct air capture or industrial exhaust streams (Parra et al., 2017), and production costs remain comparatively low at small and medium scales. Methanol and ammonia performed good in terms of infrastructure compatibility and energy density; however, they have certain drawbacks. Power-to-Methanol shows relatively high greenhouse gas emissions (42–68 gCO_2-eq/MJ), depending on the CO_2 source and production pathway, and its production costs are highly sensitive to electricity price and CO_2 capture costs. Power-to-Ammonia also exhibits comparatively high greenhouse gas emissions (around 54 gCO_2-eq/MJ) and requires careful handling due to its toxicity (Al-Breiki and Bicer, 2021). Although hydrogen is technologically mature achieve low greenhouse gas emissions (20-25 gCO_2-eq/MJ), it exhibits comparatively low Power-to-Storage efficiency because of the energy-intensive storage requirements for large-scale and long-duration applications, such as compression or liquefaction, and because it involves greater handling complexity. LOHC shows the lowest overall competitiveness across the analysed criteria due to lower efficiency, higher cost sensitivity and limited technological maturity.

The integration of X-to-Energy technologies as peak-load units in bivalent heating systems allows the installed heat pump capacity to be reduced compared to conventional monovalent system designs. By covering rare peak-load events with an auxiliary technology, the heat pump can be dimensioned closer to the typical heating demand rather than to the extreme peak load. Two case studies were analysed: (1) a multifamily building with a total heating power of 52 kW and a total annual heating energy demand of 116 MWh, and (2) a district heating network with a total heating power of around 4 MW and an annual heating energy demand of about 7.2 GWh.

The analysis shows that reducing the installed base-load heat pump capacity decreases total investment cost while shifting only a limited share of the annual heat demand to the peak-load unit. Even when the heat pump capacity is reduced substantially (e.g. 50%), the peak-load technology covers only a moderate fraction of around 15-20% of the total annual heat supply. Thermal storage size influences this effect. Larger storage volumes reduce the required peak-load contribution, while smaller storage volumes increase the share of heat supplied by the auxiliary technology.

Overall, the results indicate that bivalent system configurations can reduce the installed heat pump capacity as well as the investemnt costs without requiring a dominant share of annual heat supply from the peak-load unit. The economic analysis indicates that such configurations can reduce investment costs of heat pump systems, particularly for systems with ground heat exchangers, where infrastructure costs increase strongly with installed capacity. In addition, improved load matching between heat pump capacity and heating demand can reduce cycling operation and may increase the operational lifetime of the heat pump.

Beyond economic aspects, X-to-Energy peak-load technologies may also contribute to improving the security of heat supply in highly electrified heating systems, as stored energy carriers can provide backup heat during periods of high electricity demand or limited renewable generation.

4. References

Al-Breiki, M., Bicer, Y., 2021. Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. Journal of Cleaner Production 279, 123481.

Bosshard, I., et al., 2023. OptiPower – Optimierte Dimensionierung von Wärmepumpensystemen in

Mehrfamilienhäusern. Project final report

Connolly, D., Lund, H., Mathiesen, B.V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Østergaard, P.A., Nielsen, S., 2014. Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 65, 475–489.

IEA, 2022. The Future of Heat Pumps. International Energy Agency, Paris.

IEA, 2023. Energy Efficiency 2023. International Energy Agency, Paris.

Parra, D., Zhang, X., Bauer, C., Patel, M.K., 2017. An integrated techno-economic and life cycle environmental assessment of power-to-gas systems. The International Journal of Life Cycle Assessment 22, 217–232.