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Low-Carbon Industrial Heating in the EU and UK: Integrating Waste Heat Recovery, High-Temperature Heat Pumps, and Hydrogen Technologies

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Abstract

This research introduces a two-stage, low-carbon industrial heating process, leveraging advanced waste heat recovery (WHR) technologies and exploiting waste heat (WH) to drive decentralised hydrogen production. This study is supported by a data-driven analysis of individual technologies, followed by 0D modelling of the integrated system for technical and feasibility assessment. Within 10 years, the EU industry will be supported by two main strategies to transition to low-carbon energy: (a) shifting from grid-mix electricity towards fully renewable sources, and (b) expanding low-carbon hydrogen infrastructure within industrial clusters. On the demand side, process heating in the industrial sector accounts for 70% of total energy consumption in industry. Almost one-fifth of the energy consumed to fulfil the process heat demand is lost as waste. The proposed heating solution is tailored for process heat in industry and stands apart from the dual-mode residential heating system (i.e., heat pump and gas boiler), as it is based on integrated and simultaneous operation to meet industry-level reliability at higher temperatures, focusing on WHR and low-carbon hydrogen. The solution uses a cascaded heating approach. Low- and medium-temperature WH are exploited to drive high-temperature heat pumps (HTHPs), followed by hydrogen burners fuelled by hydrogen generated on-site by electrolysers, which are powered by advanced WHR technologies. The results revealed that the deployment of the solution at scale could fulfil ~14% of the process heat demand in EU/UK industries by 2035. Moreover, with further availability of renewable energy sources and clean hydrogen, it could have a higher contribution to the total process heat demand as a low-carbon solution. The economic analysis estimates that adopting the combined heating solution—benefiting from the full capacity of WHR for the HTHP and on-site hydrogen production—would result in a levelised cost of heat of ~EUR 84/MWh, which is lower than that of full electrification of industrial heating in 2035.

Keywords: industrial heating; industrial decarbonisation; high-temperature heat pump (HTHP); waste heat recovery (WHR); green hydrogen; electrolysis; organic Rankine cycle (ORC); levelised cost of heat (LCOH)

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1. Introduction

Clean hydrogen is anticipated to be an essential pathway to decarbonising the EU/UK economy. As proof of concept, local trials of hydrogen towns were scheduled in early 2023 to evaluate hydrogen technologies for residential heating. However, in May 2024, the UK hydrogen town trial initiative was pushed back until at least 2026 by the government

due to a lack of low-carbon hydrogen supply, safety concerns, and doubts about the cost-competitiveness of the solution compared to alternatives like air-source heat pumps (HPs). These concerns were strongly grounded in unambiguous scientific evidence [1,2]. However, the situation for industrial heat is different. The first concern is the technical viability of HPs, as unlike residential applications, heat pumps cannot fully address industrial heat demand. Secondly, while hydrogen emerges as a potential solution for heating, the government's temporary withdrawal of support for hydrogen in residential heating might hinder the advancement of hydrogen technologies for industrial heating [3]. Therefore, it is essential to conduct further research to (a) clarify and unlock the full potential of hydrogen and HPs in industrial heating; and (b) provide decision-makers with early scientific evidence on the role of these two technologies in future industrial heating to support the hydrogen and heating roadmaps and avoid mid-term policy reversal [3]. Thus, the present study will develop an integrated solution where hydrogen and HPs complement each other and play a dominant role in industrial heating decarbonisation. Moreover, with further availability of renewable energy sources (RESs) and clean hydrogen, along with hydrogen blending technology, it could meet up to 40% of the total process heat demand as a low-carbon solution.

On the other hand, it is worth noting that heat accounts for ~70% of industrial energy demand both in the UK and globally [4]. It is predominantly supplied by fossil fuel combustion, which is responsible for ~50% of the sector emissions. For example, the process heat demand in UK industry is estimated at ~170 TWh, accounting for almost 25% of the UK heat demand, equivalent to 11% of the final UK energy demand [5]. The potential of process heating for industrial decarbonisation is compounded by the fact that up to 23% of heat is dissipated into the environment and remains unused, necessitating further focus on overcoming technological barriers.

Looking at the literature, many investigations focus on using hydrogen for heating homes [6]. Knosala et al. conducted a techno-economic analysis comparing different scenarios of HPs and hydrogen boilers in Germany. Based on the results, depending on the price of hydrogen and electricity, each may be economically viable [7]. Several investigations also explore hybrid solutions, evaluating different options of HPs, hydrogen boilers, and gas boilers for residential heating [8,9]. Another subset of the literature focuses on hydrogen blending for boilers, but again for residential buildings [10]. As is clear from the literature review, there is limited combination of solutions for buildings, and the scope of industrial heating remains a gap; hence, the present research aims to valorise the full capacity of low-carbon solutions supporting process heating in industry.

1.1. Novelty and Contributions to the Field

Despite progress in low-carbon industrial heating, key research gaps remain in hydrogen adoption for industrial heating in combination with existing solutions. In that context, this research introduces novel contributions at both the system and component levels. At the system level, it involves a novel configuration for the adoption of clean heat technologies with the aim of (a) maximising the synergy among technologies with the highest potential for industrial heating decarbonisation, and enhancing interconnection capacity, (b) improving the security and resilience of industrial sites and their interactions with future green hydrogen and electricity networks, and (c) leveraging economic opportunities arising from a combination of emerging low-carbon technologies. This will include the uptake of enabler technologies (WHR and on-site electrolysis) for cost savings. Further innovation is brought by each technology, as they are selected from state-of-the-art solutions, particularly those expected to be market-ready within the next decade. Among those are the HTHP, rapid-response electrolysis, and H2P technologies, all of which support the proposed solution going beyond traditional concepts, providing additional flexibility.

In particular, the contributions of this research include (a) achieving carbon neutrality in industrial process heating, and (b) supporting the adoption of WHR technologies in process heating while informing decision-makers through the development of guidelines.

1.2. Research Framework and Case Study

According to the key industrial decarbonisation roadmaps in the EU/UK [11], several technological solutions have been developed over the years to support the decarbonisation of heating process in industries, including electrification; heat-to-power (H2P) technologies; utilising renewable energy sources (RESs) and green hydrogen as a feedstock, carrier, or a fuel for heat; and HPs being more pronounced and found more favourable for investment. However, there are barriers such as the pending status in fulfilling industrial criteria, including the Technology Readiness Level (TRL) or economic viability.

Due to their different maturity levels, the selection of technologies should be based on a whole-systems analysis considering the economies of scale. Moreover, given the heterogeneity of the building stock as well as existing infrastructure, there is a benefit in adopting a portfolio of heating technologies. In that context, this project comprises a mixture of technologies and aims to investigate the synthesis and consolidation of a brand-new heating route and explore the interdependencies between a series of technologies under development, to provide an innovative and sustainable design system for industrial process heating. Figure 1 represents the outline of industrial process heat in 2035—integrating the combined industrial heating solution. Each of the following energy system elements brings innovation into the integrated system, unlocking the full potential of industrial waste heat (WH) from industry [12], and driving waste heat recovery technologies like organic Rankine cycles (ORCs) [13–15] to supply the power for on-site electrolysis—which itself also generates waste heat [16]. Another portion of the WH serves as the heat source for high-temperature heat pumps (HTHPs) [17]. The hydrogen generated on-site, along with external green hydrogen, feeds into the hydrogen burners.

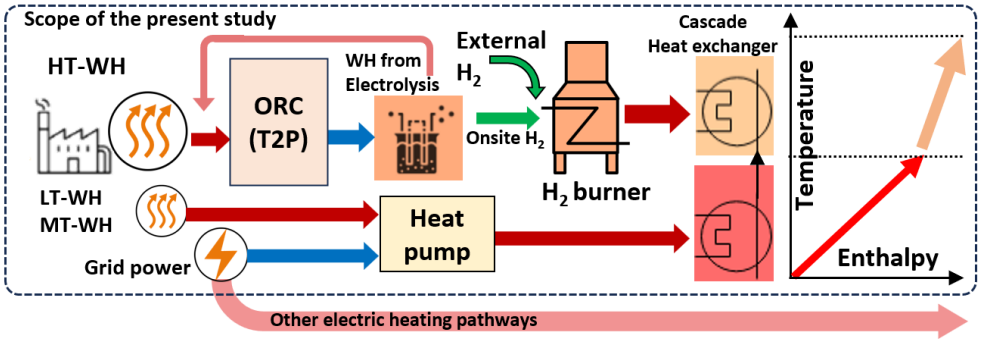


Figure 1. Outline of the proposed low-carbon industrial heating in Horizon 2035, representing the two-stage heating using an HTHP and a hydrogen burner.

Supply of green hydrogen: Developing a global hydrogen economy requires addressing the causality dilemma of growing supply and demand in tandem, where a balanced expansion is expected for both. The supply of green hydrogen provides low-carbon fuel with an established roadmap for a dedicated hydrogen network in the UK and most EU countries. Currently, almost 7% of hydrogen demand is unambiguously dedicated to industrial heat. However, according to the EU hydrogen roadmaps, out of the 15.7 Mt/y of clean hydrogen production projects by 2030, projects representing 7.2 Mt/year have not yet specified or disclosed how their hydrogen will be used. This echoes the unbalanced growth stage of different aspects of the hydrogen economy, in which hydrogen generation has dominated the investment, while hydrogen utilisation continues to lag behind [18,19].

Supply of grid power: In May 2024, global renewable energy supported >30% of electricity supply for the first time, aligning with the energy innovation roadmap. The UK, as a leader in RESs, achieved a record high of 40% in its electricity mix in 2023. The share of RESs in the power system is expected to reach 60% by 2030, with a goal of full decarbonisation of the power system by 2035, according to the Net Zero Growth Plan [20]. The role of RESs in industrial heating and cooling is fully reflected in Art. 22a of the EU Council, which adopted the amended Renewable Energy Directive ("RED III") with a target annual increase of 0.8% per year [21].

WHR technologies: As a key intervention with double targets, it has the potential to reduce the need for energy supply and improve resource and energy efficiency; additionally, it provides carbon-free power for on-site hydrogen production by electrolysis. The concept for WH to power is not limited to ORC; there are alternatives like the trilateral flash cycle, sCO_2 cycles, thermoelectric conversion, magnetocaloric conversion, and the Stirling cycle [22–24]. However, the ORC is selected for the purpose of examining the proposed heating solution. WHR technologies are fed from the WH, primarily sourced from the industrial process itself, along with the WH from the electrolysis process.

Electrolysis: Using carbon-free power from WH to feed the electrolysis process is effectively the same as using RES power: no additional emissions are produced. A range of electrolysis solutions can be integrated based on the inherent characteristics of the WH. Among those with higher TRLs, alkaline water electrolysis (ALK) and polymer electrolyte membrane (PEM) electrolysers have a significant historic pedigree on different scales. Moreover, several studies, including the investigation by Zhao et al., demonstrate that optimisation of the ALK electrolyser configuration can lead to more efficient industrial electrolysis tailored for the target industrial plant [25]. There are also Solid Oxide Electrolyser Cell (SOEC) electrolysers at a lower TRL, which have a high energy conversion efficiency and require high temperatures, making them particularly suitable for industrial applications with access to WH sources. Anion exchange membrane (AEM) electrolysers combine high load flexibility, a compact design, and low reliance on critical raw materials, but they are less mature and led by a few manufacturers. However, they are highly compatible with an intermittent power supply and suitable for variable RESs, making them a fit for decentralised applications [26].

Integrating WH-driven on-site electrolysis and HTHPs aims to reduce the dependency of hydrogen heating on hydrogen networks, preserving more hydrogen for other uses. This is somewhat reflected in the government's statement on halting the pilot of household hydrogen heating, with a clear concern that hydrogen should be reserved for use in heavy industry [3], rather than being seen as a general solution for all types of heating. The same rationale is used in developing hybrid heating for industrial settings, allowing hydrogen to play a role where needed.

Moreover, it is notable that hydrogen heating in the proposed solution does not conflict with but works alongside electrification, which is currently a key part of the UK/EU decarbonisation strategies. Indeed, in low- or medium-temperature industrial heat applications, both solutions are viable. However, the benefits of hydrogen heating, which burns at temperature of up to 2100 °C, are more pronounced in high-temperature applications like steelmaking, cement, and chemical industries, which require intense heat that is challenging to achieve solely with electricity. The other advantage of hydrogen heating stems from its compatibility with the existing infrastructure, as hydrogen can often be blended with existing fuel sources and used in existing industrial equipment with minor modifications.

2. Methodology

2.1. Waste Heat Potential

The waste heat potential (WHP) required for the present study is taken from the literature on EU industries (see Section 3.6). Referring to recent literature on actual WHP assessment [27], the WHP is then adjusted by the Carnot efficiency (η_C) to better account for the effect of the WH temperature. The Carnot waste heat potential (CWHP) is calculated using Equation (1):

$$CWHP = WHP \times \eta_C \quad (1)$$

2.2. Two-Stage Heating

This section provides details for estimating the heating capacity for each technology. The heating system comprises two stages: an HTHP followed by hydrogen combustion. As shown in Figure 1, this two-stage approach delivers heat output through cascaded heat exchangers to the industrial process where the input to the HTHP stage ($Q_{in,HTHP}$) is calculated using Equation (2) using low-temperature waste heat (WH^{LT}), which is a part of the total waste heat available in industry, typically defined as WH below 100 °C [28]. The HTHP output ($Q_{out,HTHP}$) is also calculated using the coefficient of performance (COP) of the heat pump and the heat input (Q_{in}) using Equation (3). Assuming that this heat is delivered to the heat transfer fluid (HTF) circulating through both stages, the temperature change in the HTF in the first stage—using an HTHP—can be derived using Equation (4). The equation uses the mass flow rate (m_{HTF}) and specific heat capacity ($C_{p,HTF}$) of HTF to estimate the increase from ambient temperature ($T_{HTF,amb}$) to the HTHP outlet temperature ($T_{HTF,HTHP}$).

$$Q_{in,HTHP} = \left(\frac{WH^{LT}}{WH^{total}}\right) \times CWHP \quad (2)$$

$$Q_{out,HTHP} = Q_{in,HTHP}(1 + 1/(COP - 1)) \quad (3)$$

$$Q_{out,HTHP} = m_{HTF}C_{p,HTF} \times (T_{HTF,HTHP} - T_{HTF,amb}) \quad (4)$$

In the second stage, heat is generated along a different pathway, in which the remaining WH is introduced into the ORC as a representative WHR technology for power generation. The power generated supplies the electrolysers, which produce hydrogen at the rate of m_{H_2}. The electrolysis process generates some WH (WH^{elec}), which is included in the WH fed into the ORC (see Figure 1). The electricity produced drives the electrolyser to supply on-site hydrogen production (see Equation (5)).

$$m_{H_2,electrolyser} = \left[\left(1 - \frac{WH^{LT}}{WH^{total}}\right) \times CWHP + WH^{elec} \times \eta_C\right] \times \eta_{ORC} \times \left(\frac{1}{SEC_{electrolyser}}\right) \quad (5)$$

The total mass flow rate of hydrogen is the sum of the hydrogen (Equation (6)) generated on-site as well as hydrogen supplied from an external source of the hydrogen network.

$$m_{H_2,total} = m_{H_2,electrolyser} + m_{H_2,network} \quad (6)$$

In the present analysis, a parameter is defined as the H_2 network ratio (α_{H_2}), which is the ratio of hydrogen taken from the network to H_2 from the electrolyser, defined as Equation (7).

$$\alpha_{H_2} = m_{H_2,network}/m_{H_2,electrolyser} \quad (7)$$

The useful thermal energy delivered to the HTF is derived using Equation (8), in which the heat is delivered by the hydrogen burner and is calculated using the total hydrogen

mass flow rate, the lower heating value (LHV) of hydrogen, as well as the thermal efficiency of the burner.

$$Q_{out,burner} = m_{H_2,total} \times LHV \times \eta_{burner} \quad (8)$$

When the heat from the second stage is transferred to the same HTF that passed through the first stage, it raises the HTF temperature as described in Equation (9).

$$Q_{out,burner} = m_{HTF} C_{p,HTF} \times (T_{HTF,Final} - T_{HTF,HTHP}) \quad (9)$$

Assuming that $Q_{out,HTHP}$ and $Q_{out,burner}$ are calculated independently based on the waste heat availability and the temperature-based classification of waste heat, combining Equations (4) and (9), the final HTF temperature ($T_{HTF,Final}$) can be calculated by Equation (10):

$$T_{HTF,Final} = \frac{Q_{out,burner}}{Q_{out,HTHP}} \times (T_{HTF,HTHP} - T_{HTF,ambient}) + T_{HTF,HTHP} \quad (10)$$

Moreover, Table 1 is a list of key assumptions required for the technical modelling of the low-carbon heating solution in the present research.

Table 1. Technical assumptions and key input parameters.

Parameter [Unit]	Value	Reference
Electric heater efficiency [%]	85–95	-
Burner efficiency [%]	45–80	[29,30]
ORC efficiency	Refer to Section 3.5	-
Electrolysis efficiency	Refer to Section 3.3	-
Electrolysis WH [%]	13.2 to 25.3	[13]
H_2 LHV [kWh/kg]	33.3	[19]
H_2 HHV [kWh/kg]	39.4	[19]

Based on the heat output of all components—namely, the HTHP and the hydrogen burner—the supply-to-demand ratio (R_i) for each heating pathway is estimated using Equation (11), in which IH_{Total} refers to the industrial heat demand in the EU (see Section 3.6).

$$R_i = \frac{Q_i}{IH_{total}}, i \in \{HTHP, H_2 burner, electric\} \quad (11)$$

In particular, for the proposed solution—comprising an HTHP and hydrogen heating—the sum of their R_i values represents the total fraction of industrial heat demand met by this system.

2.3. Levelised Cost of Heat

The economic comparison of the pathways in this study is based on the levelised cost of heat (LCOH) for the i-th pathway, defined as Equation (12), which includes capital expenditures of pathway (CAPEX), fixed operating and maintenance (FOM) costs, and fuel costs (either power or external hydrogen supply) associated with the delivered heat (Q_i). The capital recovery factor (CRF)—given by Equation (13)—is used to annualise the CAPEX and is calculated based on a discount rate (r) to account for the time value of money over the technology lifetime (n).

$$LCOH_i = \left(CRF \times CAPEX_i + FOM_{i,annual} + EnergyCost_{i,annual}\right) / Q_i \quad (12)$$

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (13)$$

The overall LCOH is calculated as Equation (14), which is the weighted average of the LCOH of all pathways involved. The weights are based on each pathway's contribution to the total industrial heat demand at the EU scale.

$$\mathrm{LCOH} = \sum_{i} \mathrm{LCOH_i} \times \mathrm{R_i}, \mathrm{i} \in \{\mathrm{HTHP}, \mathrm{H_2burner}, \mathrm{electric}\} \quad (14)$$

Other economic assumptions for all technologies involved are listed in Table 2.

Table 2. Key economic inputs for the economic assessment.

Technology	CAPEX [EUR/kW]	FOM
Decentralised electrolysis	1837, 1548, 928 (year of 2025, 2030 and 2050) [31]	1.5–3% of CAPEX [31]
H_2 boiler	114, 124, 124 (year of 2025, 2030, 2050) [31]	
HTHP	465 [32,33]	
ORC	2122 [34], 1800–2500 [35], 2136 [36], 1630 [37] ~6% cost drop by 2030 [38]	
Electric boiler/heater	110, 100, 95, 90 (year of 2025, 2030, 2040, 2050) [31]	1.1 EUR/kW [31]

Also, the economic assumptions for currency conversion and energy prices are listed in Table 3.

Table 3. Economic assumptions for currency conversion and energy prices.

Item	Value
Power cost (3-year average from 2022 to 2024 EU27 + UK)	Current: 10.99 EUR/MWh excluding taxes and levies, and VAT [39] 23% reduction in 2030 [40]
Hydrogen price	6.6 [41] ~3 EUR/kg in year 2035 [41–43]
Currency exchange rate (per EUR)	USD/EUR 0.933 | GBP/EUR 1.168 [44]
EU-average discount rate	7% [45]

3. Results and Discussion

3.1. Technology Assessment Approach

The proposed solution is an integrated system including multiple technologies—namely, a boiler, heat pump, ORC, and electrolysis. As the overall assessment strongly relies on the assumptions regarding individual technologies, separate assessments are conducted for each technological component to reach reliable key performance indicators (KPIs) for each technological component. The assessment for each technology involves a scan of the literature and market data for each key technology, compiling publicly available data to support the discussion around the span of KPIs for each technology. Ultimately, the average value serves as a reliable input for the techno-economic assessment. This approach—combining literature and commercial data to derive representative performance indicators—is supported by previous studies, which also compiled data from both academic sources and manufacturers to establish benchmark values for an HTHP [46,47]. This will improve the reliability of the outcome and support the sensitivity stage after the modelling.

3.2. Technology Assessment—Hydrogen to Heat

Data for hydrogen burners or boilers were collected from a range of commercial boilers from the literature as well as industrial data sheets. In the data screening, only those

entries that are labelled as hydrogen-ready and capable of fuel switching are included. This technology provides flexibility to the solution to be fully fed either by gas (the business as usual) or hydrogen (a long-term horizon of 2050), as well as the transitional stage where industry can benefit from blending with natural gas. As shown in Figure 2, the blending ratio from all the sources of data ranges from 5% to 100%, but the median is 20% vol%, which stems from the small-scale hydrogen-ready boilers for buildings. In the present study, it is assumed that the specification data, i.e., the efficiency of the referenced boilers and burners, are also valid for systems operating on 100% hydrogen, and can therefore be used in Equation (8). Larger industrial boilers have adaptability to be fed by a larger H_2 content up to 100%. In the same way, the temperature ranges from 90 to above 2040; the lower limit stands for home boilers, while the upper limit is the hydrogen flame temperature. The corresponding water or steam capacity as well as heat output and NOx emissions are also reported for more than 220 boilers and burners [48–67].

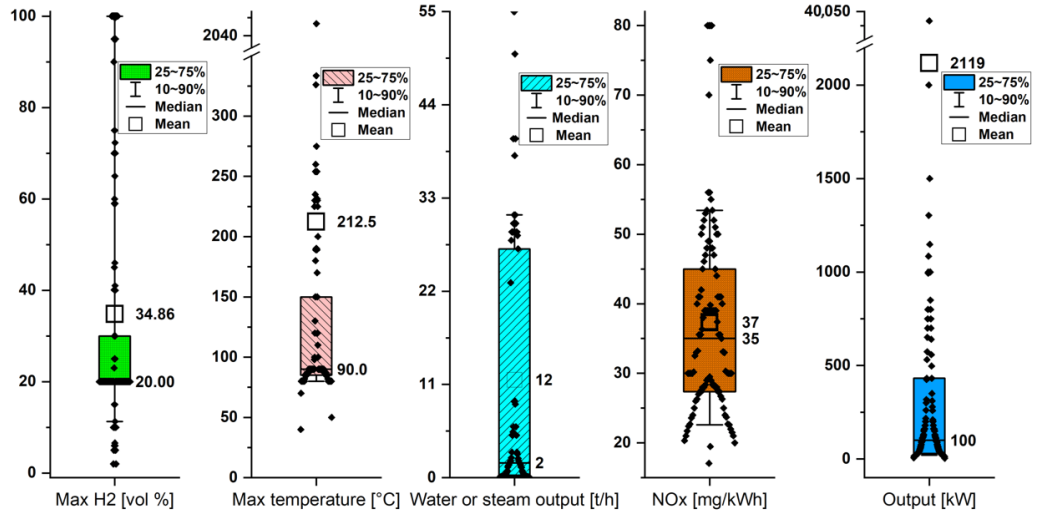


Figure 2. Literature- and market-based technology assessment for H_2-ready boilers. Note: X-axis scattering is for visual clarity only.

3.3. Technology Assessment—Power to Hydrogen

Extensive data collection is carried out, drawing on a range of electrolysers available on the market. Data collection includes electrolysers in various scales and technologies—namely, ALK, PEM, and AEM with TRLs of 7 to 10 [68]. Figure 3 presents a comparative performance summary of more than 240 electrolysers, compiled from the literature and commercial sources [69–80]. This assessment explores a range of capacities of electrolysis units from the lab to the industrial scale. The electrolyser KPI includes the specific energy consumption required for technical analysis in the overall framework, found to be 55 kWh per kg of hydrogen production, which can be used in Equation (5). Additional analysis is also provided in this figure for the power input as well as the H_2 production, which can inform future scale-up and storage assessments.

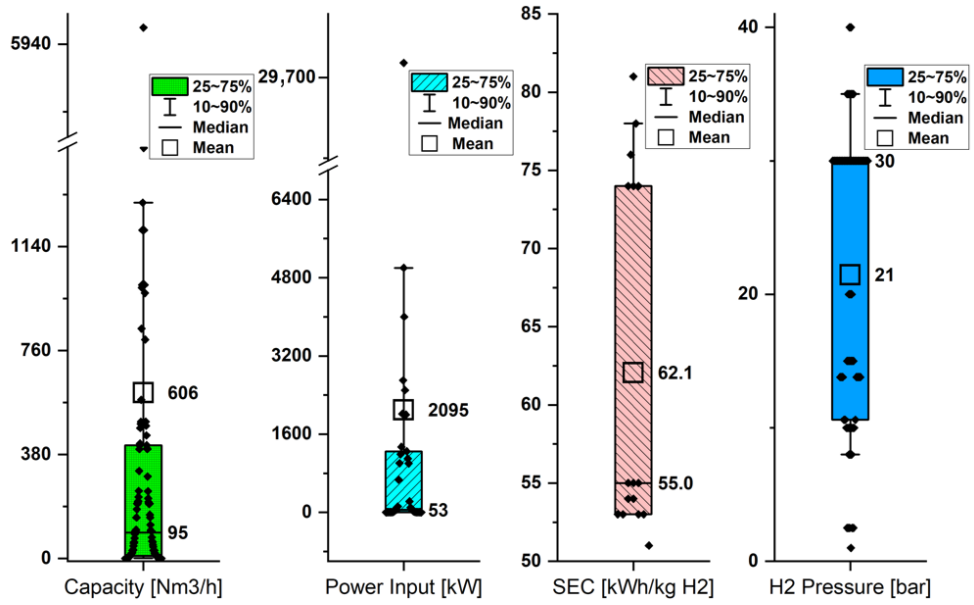


Figure 3. Literature- and market-based technology assessment for electrolyser data (SEC: specific energy consumption). Note: X-axis scattering is for visual clarity only.

3.4. Technology Assessment—Heat Upgrading

Another technology with a key role to play is the heat pump for heat upgrading–including conventional air-source or ground-source HPs with TRLs of 9 to 10 [68], which usually operate below 100 °C, and high-temperature HPs with TRLs of 7 to 8 [68], which are more suitable for industrial needs. However, the main focus of this assessment is on HTHPs; as can be seen in Figure 4, the heat output starts from 100 °C and can reach up to ~280 °C, with a mean value of ~130 °C. Referring to the literature [81–129], the COP of HTHPs spans from 1 to 7, with a mean value of ~3.49, which is considered an input for Equation (3). It is worth noting that the temperature lift, internal layout, thermal fluid, and source temperature for each of the literature sources may vary, but expanding the size of the database allows for reaching reliable and valid KPIs, essential for the next stage of assessment in the present research.

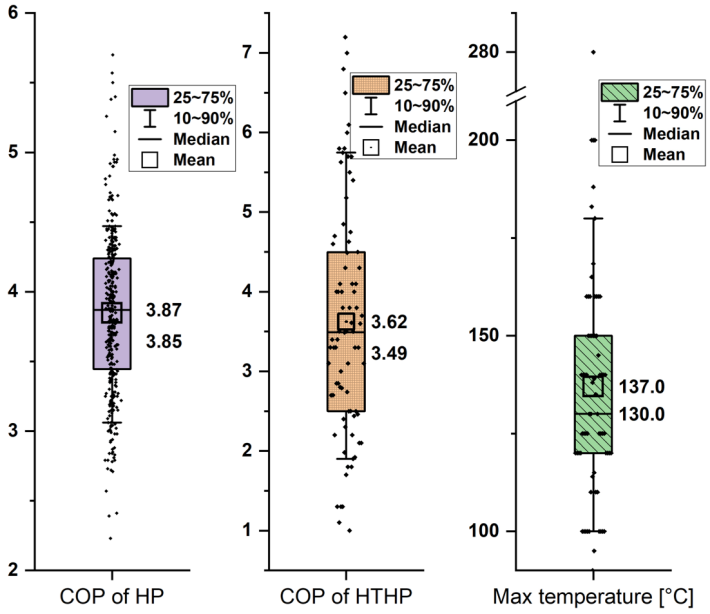


Figure 4. Literature- and market-based technology assessment for HP and HTHP data [81–129]. Note: X-axis scattering is for visual clarity only.

3.5. Technology Assessment—Heat to Power

Another part of the energy conversion chain is heat-to-power technology. The ORC is chosen as a mature enough technology with a TRL of 9 to 11 [68], capable of recovering low-, medium-, and high-temperature heat for power generation. Several investigators have identified ORC as a potential solution for various types of WH sources in different industries, ranging from exhaust gas of power generation to exhaust gas of onboard energy systems. The summary of reported values in the literature is illustrated in Figure 5, representing the KPI for ORC technology, which includes approximately 45 references in the database, where the average thermal efficiency is estimated at approximately 13%, which can inform the next level of assessment using Equation (5). Moreover, the capacity range is also demonstrated from a kW to an MW scale, which can support future assessment for solution scale-up. The source temperature range also provides detail for the technical requirement for the thermal loop design when transferring WH to the ORC. It is worth noting that in industries with WH at >300 °C, it does not necessarily mean that the ORC is directly exposed to the high-temperature WH, but the heat is exchanged from a high-temperature WH source to the ORC through a closed loop circulating a heat transfer fluid.

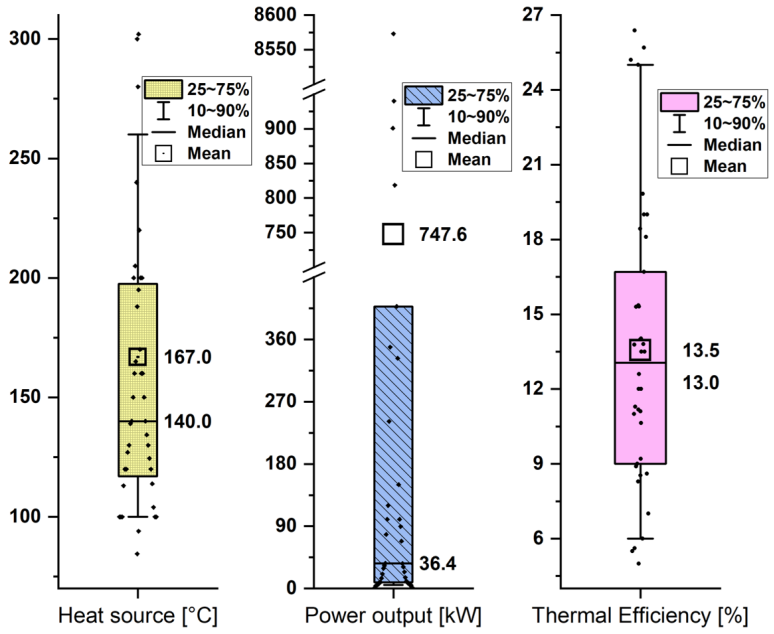


Figure 5. Literature- and market-based technology assessment for ORC data [130–176]. Note: X-axis scattering is for visual clarity only.

3.6. Industrial Heat and Waste Heat Assessment—EU Scale

The success of the proposed low-carbon heating solution largely depends on WH availability and the WHP in the target sector—EU industries. A dedicated assessment is conducted to determine how much heat is needed and to clarify the process heat demand at the EU scale, which is found to be in the range of 1400 to 2400 TWh per year, with an average of 1861 TWh [177–184]—see Figure 6. An additional literature survey is carried out to complement the previous part—determining the WHP percentage in industry. The WHP percentage in the literature varies by industrial sector; it tends to be higher in the iron and steel industry. However, the assessment considers the overall range, and the mean value is estimated at 14.2% for the entire EU industries, considering several references [185–193]. Assuming that this fraction of the total process heat is waste heat, the amount is estimated to be ~261 TWh, which aligns with findings from a WH assessment conducted by the European Commission [194].

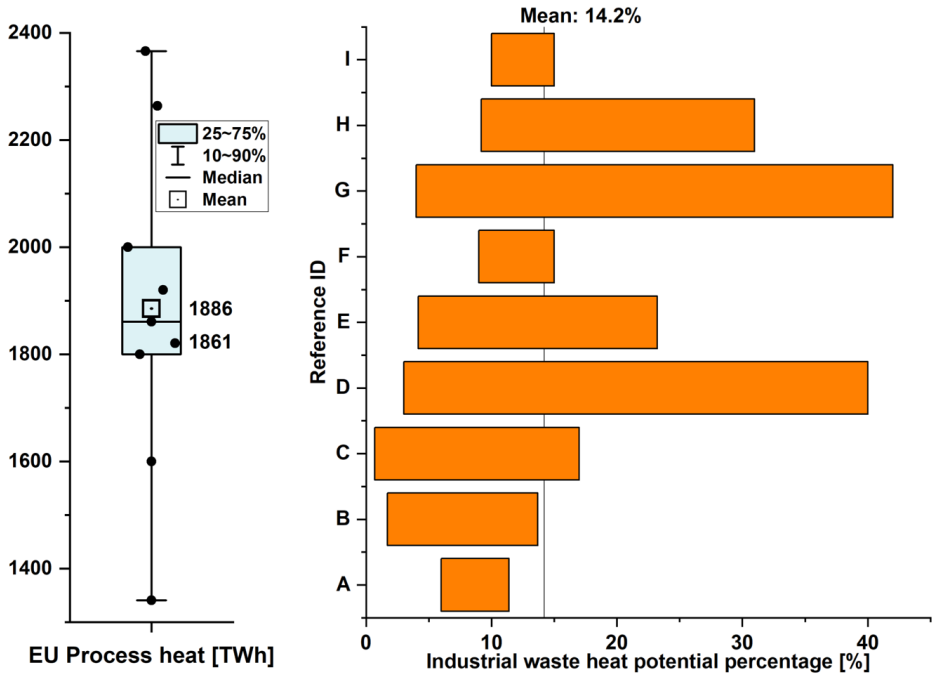


Figure 6. Literature-based assessment of waste heat potential (A [185], B [186], C [187], D [188], E [189], F [190], G [191], H [192], I [193]).

3.7. System Assessment—Energy Flow Analysis

To better describe the system and comparatively analyse the interconnection of the technologies, the Sankey diagram of a baseline scenario is demonstrated in Figure 7, where, as discussed before, the HTHP delivers the heat, benefitting from the LT-WH, while the remaining is fed into the ORC, followed by electrolysis, to support the hydrogen demand required for topping up the heat to reach higher temperatures if required. It is evident that the share of WH taken from the electrolyser itself is negligible; furthermore, the contribution of hydrogen generated through the WH-to-electrolyser pathway can only be meaningful when supplemented by external H_2 sources.

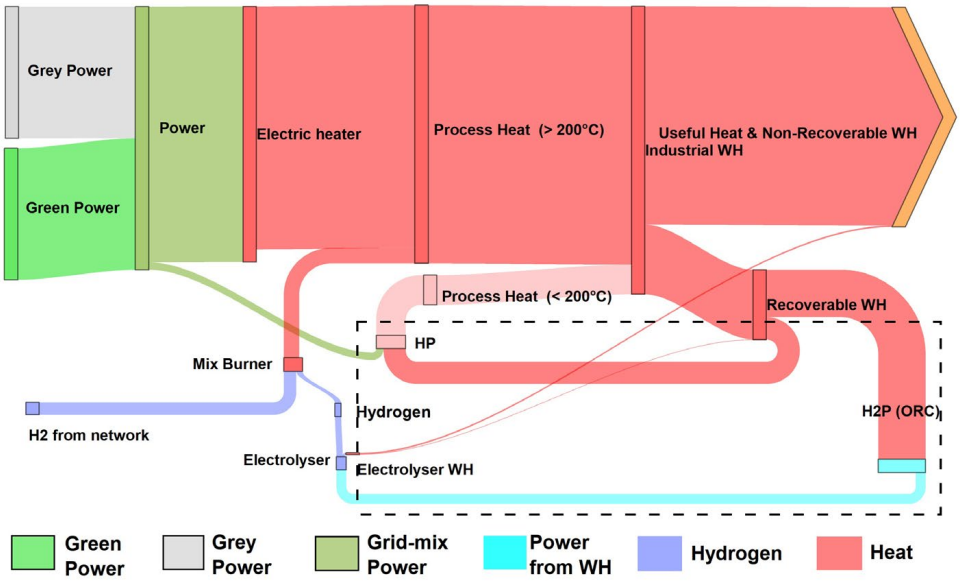


Figure 7. Energy diagram of low-carbon heating using hydrogen and HP pathways.

3.8. System Assessment—Sensitivity Analysis

So far, the model shows a contribution to low-carbon heating driven by WH, on-site electrolysis, as well as external sources of green power from the grid and green hydrogen from the network. It is necessary to determine which parameters have the greatest impact and assess uncertainties in the input data and assumptions. A sensitivity analysis is conducted with a focus on nine inputs or assumptions, including (a) parameters related to WH sources: WHP and waste heat temperature, the share of medium-temperature waste heat (MT-WH) and high-temperature waste heat (HT-WH) with a temperature >100 °C within the total WH, as well as the WH from the electrolysis process; (b) inputs related to external sources, such as the ratio of the H_2 network to the H_2 generated on-site; and (c) the technical performance of the involved technologies, including the efficiency of the hydrogen burner and ORC, specific energy consumption of the electrolyser, and COP of the HTHP. The range of variation in parameters is not the same but is based on practical and feasible ranges in industry. In particular, the ranges of variation in WH and associated input parameters are taken from Section 3.6. In the same way, the ranges of efficiency and performance of technologies are taken from the previous assessment in Sections 3.2–3.5. The sensitivity outcomes are presented in Figure 8, in which parameters are ranked by order of impact. The WH potential is found to have the greatest impact, and it is considered wide enough to be valid for a range of parameters, i.e., low WH potential, like in the textile and leather sector in the EU, or high WH potential, like in iron and steel as well as chemical and petrochemical sectors [27]. The contribution of external H_2 also plays a key role in meeting the heat demand. In particular, when increasing the external-to-internal hydrogen ratio from 0 to 20, the contribution rises from 8 to 21. The mean WH temperature is also considered to cover the wide range of WH temperatures available in industry from 100 to 1200 °C.

The COP of the HTHP comes next after these two, which highly impacts the contribution of the solution to low-carbon heating. The remaining parameters are less impactful; the least impact is from the WH taken for the electrolysers, which is inherently substantial but relatively small compared to the main WH streams (see Figure 7). The mean contribution of all studied parameters, as determined from the sensitivity analysis is found to be approximately 14% of the process heat demand in the EU industry.

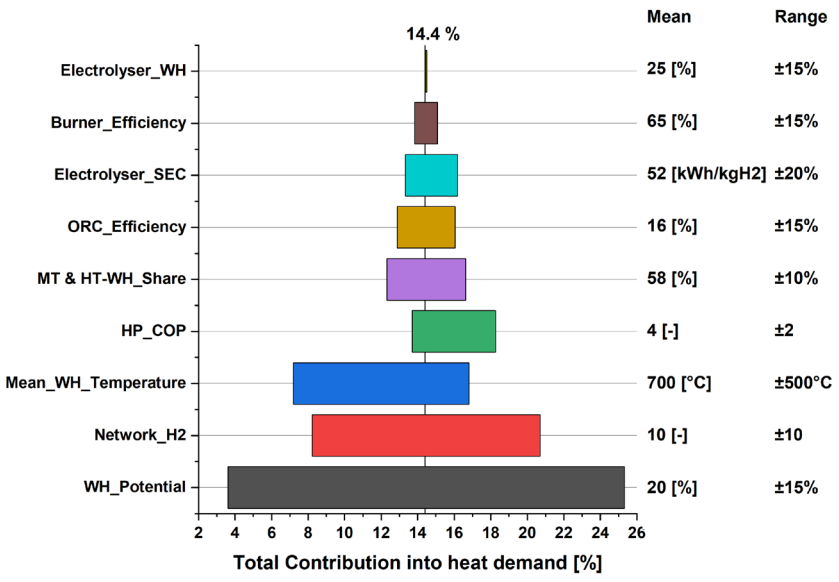


Figure 8. Model sensitivity to key inputs and assumptions.

To further explore the impact of parameters, the sensitivity analysis also represents the role of each within two pathways: HTHP for low-carbon heating up to 200 °C, and the hydrogen for higher temperatures. The breakdown of contribution is shown in Figure 9. It is worth noting that the variation in parameters involved in the H_2 pathway, like electrolyser efficiency, has no impact on the HTHP. The mean value of each pathway is found to be 6.7% for hydrogen and 7.6% for the HTHP.

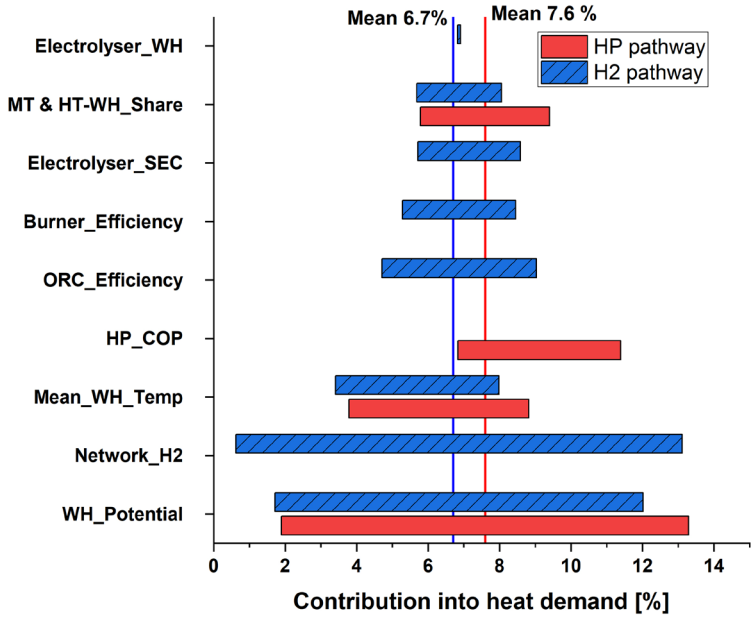


Figure 9. Sensitivity of the sub-models of HP and H_2 to key inputs and assumptions.

Additional assessment is required to ensure that two-stage heating—comprising initial heating by an HTHP followed by the hydrogen burner—can reliably meet the process heat demand. As the two pathways operate independently, their integration introduces uncertainty from their combined operation, which needs thorough justification. In this context, the feasible temperature at various H_2 network ratios (Equation (7)) is calculated using Equation (10). The temperature and the corresponding contribution to the EU process heat demand are demonstrated in Figure 10. Considering the EU 2050 target for using clean H_2 for heating—which stands at 15 MtH_2/y, equivalent to more than 300 TWh/y of heat [195]—the required H_2 network ratio is determined to be ~10, and the maximum achievable temperature is ~350 °C. However, this is based on the worst-case assumption in which all the required heat is first generated only by the HTHP and then all of it is topped up by the hydrogen burner. In reality, only a fraction of industrial heat demand lies above 200 °C, which will require supplementary heating via hydrogen.

3.9. System Assessment—Policy Alignment

This research and the associated plan for the establishment of the dedicated research pipeline are strategically aligned with the UK Net Zero Growth Plan [20] and the Net Zero Industry Act [196], with a focus on the long-term industrial decarbonisation trajectory and how it can support EU/UK industry in reaching Net Zero targets. This contributes to improving industrial energy efficiency, which brings benefits beyond energy security, by lowering the cost of decarbonisation. Further alignment is also explored in various aspects of energy infrastructure, the hydrogen market stage as a key contributor to the proposed solution, as well as the readiness of the technologies involved.

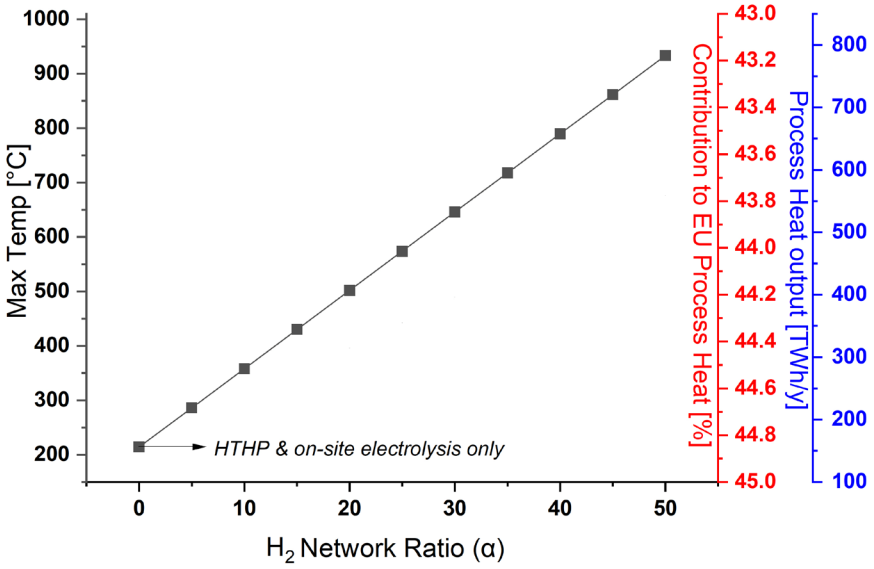


Figure 10. Role of external hydrogen supply in meeting the temperature requirement (ratio of external to on-site hydrogen).

(a) From an infrastructural perspective, the research plan aligns well with the latest developments in the EU hydrogen economy deployment. In particular, the year 2025 will be a milestone in the commissioning of green hydrogen from renewables, as well as blue hydrogen production to serve industrial clusters. All these changes are part of an industry conversion programme, highlighting the role of hydrogen and the growing focus on it in supporting deep decarbonisation, alongside the integration of mature solutions such as carbon capture. Moreover, the EU hydrogen roadmap [18] outlines a development timeline in which the hydrogen infrastructure will reach the industrial clusters in four phases from 2022 to 2037. In this context, the proposed research plan for finding efficient and cost-effective methods for hydrogen utilisation in industry aligns with the completion of the infrastructural development [197].

(b) From an economic standpoint, the levelised cost of green hydrogen production is reported to be almost twice that of hydrogen from natural gas reforming, which means it is not yet cost-competitive. However, the global ambition to develop the hydrogen economy is expected to change the green hydrogen market. The green hydrogen production outlook is already considered in research planning. The current cost of an installed electrolyser (including the equipment, gas treatment, plant balancing, and engineering, procurement, and construction costs) is in the range of EUR 1400–EUR 1700/kW, and the projected cost is estimated to fall as low as EUR 500/kW by 2030 [198]. The lower cost of the electrolyser, along with the development of renewable energy source (RES) availability and infrastructure, impact the cost of green hydrogen production, which is currently three times more expensive than producing grey hydrogen, but is projected to become much cheaper, at an estimated EUR 1–2/kgH_2 [199,200] by 2035. Globally, green hydrogen is expected to reach cost parity with blue hydrogen within the next decade [201]. This reduction in cost is well reflected at the industrial scale by the bids submitted in April 2024 to the first EU-wide auction for renewable hydrogen, which ranged from EUR 0.37 to EUR 4.50/kg of renewable hydrogen, where the winning bidders plan to produce 1.58 Mt of H_2 over ten years [202].

(c) From a technological perspective, considering the expected advancement of on-going research and development from a 10-year perspective, the analysis also reveals the potential in current and future timeframes. For example, hydrogen-ready boilers and burners are gaining maturity in utilising pure or blended hydrogen and reaching

the fully commercialised stage, and HTHP technology is expected to be at a ready-to-deploy stage, being adapted at scale. This is fully aligned with the UK call for evidence on 'hydrogen-ready' industrial equipment in 2022 detailed in the UK Hydrogen Strategy [26]. As discussed in Sections 3.2–3.5, most of the technologies involved are at TRLs 8 to 10. The main challenge for scaling up the solution is the electrolysers, which due to high market demand, are struggling with a 3- to 4-year lead time in supply [13]. According to the IRENA report from 2020, the fifth generation of electrolysers is being introduced, where upscaling from MW to GW scale takes place, with lower costs, higher durability (>50,000 h), and higher efficiency, which requires technological breakthroughs [26].

3.10. Economic Assessment

The full potential of the proposed solution can only be realised if its competitiveness is justified against the alternatives. In this context, LCOH (see Section 2.3) is evaluated for all involved heating technologies, namely an HTHP, hydrogen heating, and electric heating. As the solution targets decarbonisation of the EU industries, heating solutions based on fossil fuel, gas, or coal are no longer included in the discussion or comparison. The cost-competitiveness calculation results are shown in Figure 11, in which the HTHP has the lowest LCOH; however, the technological capability is limited by its upper temperature limit. The analysis considers two hydrogen heating approaches: one is the hydrogen supplied from a pipeline distribution network, while the other is hydrogen generated by on-site electrolysis.

The LCOH for external hydrogen is found to be much higher than others in 2025 due to the high cost of hydrogen, which is above 6 EUR/kg in the EU. In 2035, it is estimated that hydrogen cost will be as low as ~3 EUR/kg, which will make LCOH more competitive with alternatives and reach levels as low as electric heating. Despite the higher CAPEX of on-site hydrogen generation, due to the cost of WHR and electrolysis technology, this approach comes with significant benefits as it exploits the waste heat, thereby cutting the fuel (H_2) cost. Moreover, regardless of the cost of hydrogen, on-site hydrogen generation is more economically viable than the external hydrogen supply. Yet, waste heat resources are finite and are not sufficiently scalable to meet all industrial heat demand.

Looking at the LCOH of the combined solution (calculated by Equation (14)), which benefits from the full capacity of HTHP, on-site electrolysis driven by WH, and a remaining heat demand fulfilled by external hydrogen and electric heating, it is worth noting that while the LCOH is close to that of electric heating, hydrogen's role in industrial heating stems from its high-temperature capabilities, essential for industries that require temperatures above 400 °C, such as cement, aluminium, and metal sectors. Moreover, it can replace fossil fuels in many existing combustion systems with minimal adjustment [195,203,204].

Figure 12 complements the previous discussion by showing that in the combined solution, the cost of power and cost of hydrogen dominate the LCOH, forming ~50% of the LCOH. Also, the analysis confirms that the CAPEX component associated with the electrolyser, WHR technology (i.e., ORC), is less impactful than the cost of fuel or power.

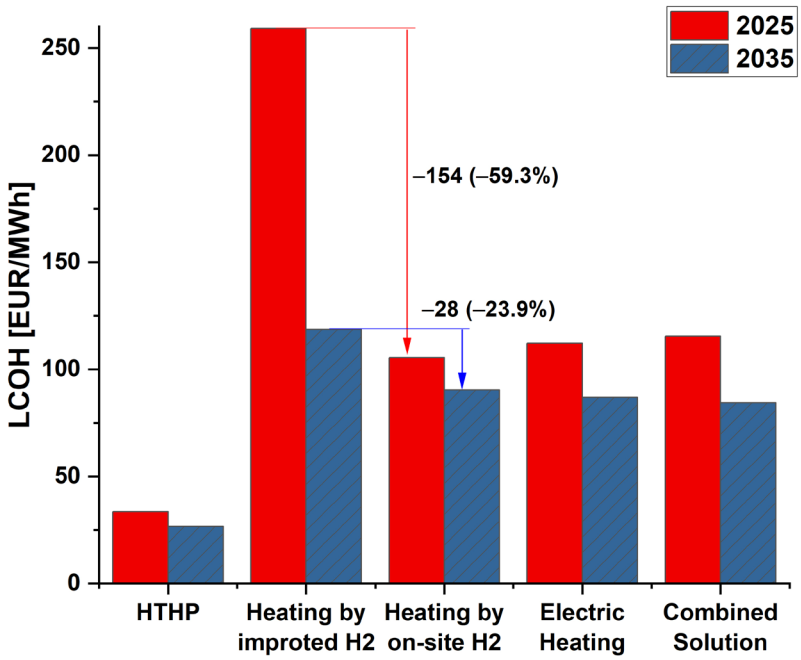


Figure 11. Levelised cost of heating (LCOH) for different low-carbon pathways: current values and future projections.

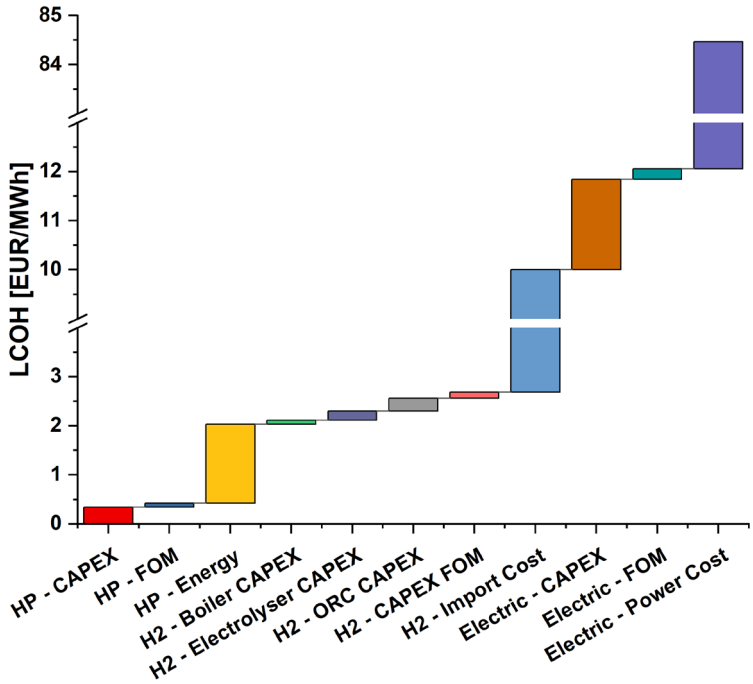


Figure 12. Breakdown of the levelised cost of heating (LCOH) for the combined heating solution in 2035.

4. Conclusions

In the present research, a different approach to low-carbon industrial heating is explored, which stands out from existing hybrid solutions in four key respects: (a) the integration of advanced technologies with significant market potential in ten years; (b) a hybrid heating process where technologies play complementary roles, distinct from hybrid designs for residential heating, which operate in alternating modes; (c) WH utilisation, boosting power supply and thermal efficiency; and (d) decentralised hydrogen generation, minimising the reliance on external supply chains.

1. The results point to a potential contribution of the low-carbon, WH-driven combined heating solution in meeting the process heating demand in EU industry of ~14%, with the following key findings:
2. The analysis using the WHR model revealed that the breakdown of contribution is ~6.7% from the hydrogen pathway and ~7.6% from the HTHP. The contribution could support and accelerate progress in the electrification of heating. However, given the projected green hydrogen production capacity in the EU by 2035 and 2050, this solution cannot offer a replacement for electrification, though it can play a key complementary role.
3. The most critical parameters through the combined solution, as found through the sensitivity analysis, are WH potential (highly dependent on the nature of the process and industrial sector), temperature of the WH, COP of the heat pump, and share of high-grade WH within the total WH.
4. The hydrogen pathway benefits from the hydrogen intake from the future hydrogen infrastructure, supporting the achievement of higher temperatures. The base scenario integrates an HTHP for heat upgrading of low- and medium-temperature WH and delivery up to ~200 °C, with the hydrogen burner providing top-up heat. Without hydrogen intake, the temperature can reach 210 °C; however, including green hydrogen uptake from the network allows the system to fully meet industrial requirements, reaching much higher temperatures—i.e., 700 °C.
5. The solution offers industry flexibility in process heating, which stems from the diversity of energy sources (green hydrogen, renewable power, and WH). It is also a technically viable solution for the transition phase, since hydrogen-ready systems are compatible with natural gas, hydrogen, or their blends. As a result, the solution can be deployed under a business-as-usual gas supply scenario and gradually adapted as hydrogen infrastructure expands to reach industrial clusters, enabling a smooth energy transition towards a Net Zero industry.
6. The LCOH of the combined solution is competitive with the direct electrification of heating; however, integrating a WHR-driven HTHP and on-site electrolysis enables industries requiring high-temperature heating to more effectively benefit from hydrogen heating technologies and also helps reduce costs.

This solution reveals the potential of an integrated approach to WHR in industry, which can act as a driver of low-carbon heating. The maturity of the involved technologies—namely, HTHP, ORC, electrolysers, and hydrogen burners—is close to market uptake, meaning they can be considered a "ready for deployment" (early commercialisation) solution for transitioning from fossil fuel-driven process heating to low-carbon solutions.

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AEM	Anion exchange membrane
ALK	Alkaline water electrolysis
CAPEX	Capital expenditures
COP	Coefficient of performance
CRF	Capital recovery factor

CWHP	Carnot waste heat potential
FOM	Fixed operating and maintenance cost
H2P	Heat to power
HHV	Higher heating value
HP	Heat pump
HT	High temperature
HTF	Heat transfer fluid
HTHP	High-temperature heat pump
IH	Industrial Heat
KPI	Key performance indicator
LCOH	Levelised cost of heat
LHV	Lower heating value
LT	Low temperature
MT	Medium temperature
ORC	Organic Rankine cycle
PEM	Polymer electrolyte membrane
RES	Renewable energy source
sCO_2	Supercritical CO_2
SEC	Specific energy consumption
SOEC	Solid oxide electrolyser cell
TRL	Technology Readiness Level
WH	Waste heat
WHR	Waste heat recovery
WHP	Waste heat potential

References

1. UK Government. *Hydrogen Heating Town Pilot: Letter to Gas Distribution Networks—Update*; Department for Energy Security and Net Zero: London, UK, 2024. Available online: https://www.gov.uk/government/publications/hydrogen-heating-town-pilot-open-letter-to-gas-distribution-networks (accessed on 1 July 2025).
2. Rosenow, J. A meta-review of 54 studies on hydrogen heating. *Cell Rep. Sustain.* **2024**, *1*, 100010. [CrossRef]
3. Department for Energy Security and Net Zero (formerly BEIS). Hydrogen Heating Town Pilot: Letter to Gas Distribution Networks—Update (9 May 2024). Available online: https://gov.uk/government/publications/hydrogen-heating-town-pilot-open-letter-to-gas-distribution-networks (accessed on 1 July 2025).
4. Department for Business, Energy & Industrial Strategy (BEIS). Industrial Decarbonisation Strategy. Presented to Parliament by the Secretary of State for Business, Energy & Industrial Strategy, March 2021; ID: CCS0221092964 03/21, CP 399. Available online: https://gov.uk/government/publications/industrial-decarbonisation-strategy (accessed on 1 July 2025).
5. Paardekooper, S.; Lund, R.S.; Mathiesen, B.V.; Chang, M.; Petersen, U.R.; Grundahl, L.; David, A.; Dahlbæk, J.; Kapetanakis, I.A.; Lund, H.; et al. Heat Roadmap Europe: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps; Deliverable 6.4, ID: H2020-EE-2015-3-MarketUptake/D6.4 PU; August 2018. Available online: https://vbn.aau.dk/ws/portalfiles/portal/288075507/Heat_Roadmap_Europe_4_Quantifying_the_Impact_of_Low_Carbon_Heating_and_Cooling_Roadmaps.pdf (accessed on 1 July 2025).
6. Rosenow, J. Is heating homes with hydrogen all but a pipe dream? An evidence review. *Joule* **2022**, *6*, 2219–2239. [CrossRef]
7. Knosala, K.; Langenberg, L.; Pflugradt, N.; Stenzel, P.; Kotzur, L.; Stolten, D. The role of hydrogen in German residential buildings. *Energy Build.* **2022**, *276*, 112480. [CrossRef]
8. Ameli, H.; Strbac, G.; Pudjianto, D.; Ameli, M.T. A Review of the Role of Hydrogen in the Heat Decarbonization of Future Energy Systems: Insights and Perspectives. *Energies* **2024**, *17*, 1688. [CrossRef]
9. Beccali, M.; Bonomolo, M.; Martorana, F.; Catrini, P.; Buscemi, A. Electrical hybrid heat pumps assisted by natural gas boilers: A review. *Appl. Energy* **2022**, *322*, 119466. [CrossRef]
10. Martire, M.; Kaya, A.F.; Morselli, N.; Puglia, M.; Allesina, G.; Pedrazzi, S. Analysis and optimization of a hybrid system for the production and use of green hydrogen as fuel for a commercial boiler. *Int. J. Hydrogen Energy* **2024**, *56*, 769–779. [CrossRef]
11. UK Research and Innovation (UKRI). *Enabling Net Zero: A Plan for UK Industrial Cluster Decarbonisation*; UKRI: Swindon, UK, 2023. Available online: https://www.ukri.org/publications/enabling-net-zero-a-plan-for-uk-industrial-decarbonisation/ (accessed on 1 July 2025).

12. Niknam, P.H.; Barberis, S.; Sciacovelli, A. High Temperature Industrial Thermal Energy Storage—Assessment of Potential Applications and Benefits Toward Industrial Decarbonization. In Proceedings of the EUROTHERM 2023 Conference, Lleida, Spain, 24–26 May 2023.
13. Niknam, P.H.; Fisher, R.; Ciappi, L.; Sciacovelli, A. Optimally integrated waste heat recovery through combined emerging thermal technologies: Modelling, optimization and assessment for onboard multi-energy systems. *Appl. Energy* **2024**, *366*, 123298. [CrossRef]
14. Fisher, R.; Ciappi, L.; Niknam, P.H.; Braimakis, K.; Karellas, S.; Frazzica, A.; Sciacovelli, A. Innovative waste heat valorisation technologies for zero-carbon ships—A review. *Appl. Therm. Eng.* **2024**, *253*, 123740. [CrossRef]
15. Jouhara, H.; Khordehgah, N.; Almahmoud, S.; Delpech, B.; Chauhan, A.; Tassou, S.A. Waste heat recovery technologies and applications. *Therm. Sci. Eng. Prog.* **2018**, *6*, 268–289. [CrossRef]
16. Danfoss Impact. Green Hydrogen: A Critical Balancing Act, Issue No. 5, 2024. Available online: https://assets.danfoss.com/documents/latest/512571/BE512836614058en-000201.pdf (accessed on 1 July 2025).
17. Zini, A.; Socci, L.; Vaccaro, G.; Rocchetti, A.; Talluri, L. Working Fluid Selection for High-Temperature Heat Pumps: A Comprehensive Evaluation. *Energies* **2024**, *17*, 1556. [CrossRef]
18. Clean Hydrogen Monitors November 2023, Hydrogen Europe. Available online: https://hydrogeneurope.eu/wp-content/uploads/2023/10/Clean_Hydrogen_Monitor_11-2023_DIGITAL.pdf (accessed on 1 July 2025).
19. Electrolytic Hydrogen Production Working Group, Electrolytic Hydrogen Production. 2023. Available online: https://hydrogen-uk.org/wp-content/uploads/2023/09/HUK-Electrolytic-Hydrogen-Production-Report.pdf (accessed on 1 July 2025).
20. Government of the United Kingdom. *Powering Up Britain: Net Zero Growth Plan. Policy Paper*; UK Government: London, UK, 2023.
21. Amendment 2023 of RED III, PE-CONS 36/23 WST/JGC/di. Available online: https://data.consilium.europa.eu/doc/document/PE-36-2023-INIT/en/pdf (accessed on 1 July 2025).
22. European Commission. SET Plan Action 6 on Energy Efficiency in Industry: Implementation Plan, Revision 2021 (Final Version 07/12/2021). Endorsed by the SET Plan Steering Group. European Strategic Energy Technology Information System (SETIS), Publications Office of the European Union. 2021. Available online: https://setis.ec.europa.eu/system/files/2022-02/EE-in-industry_Implementation-Plan_Rev2021_Final-Endorsed.pdf (accessed on 1 July 2025).
23. Daniarta, S. Techno-Economic Survey of Enhancing Power-to-Methane Efficiency via Waste Heat Recovery from Electrolysis and Biomethanation. *Renew. Sustain. Energy Rev.* **2024**, *194*, 114301. [CrossRef]
24. Wieland, C. Innovations for Organic Rankine Cycle Power Systems: Current Trends and Future Perspectives. *Appl. Therm. Eng.* **2023**, *225*, 120201. [CrossRef]
25. Zhao, P.; Wang, J.; Sun, L.; Li, Y.; Xia, H.; He, W. Optimal electrode configuration and system design of compactly-assembled industrial alkaline water electrolyzer. *Energy Convers. Manag.* **2024**, *299*, 117875. [CrossRef]
26. IRENA. *Green Hydrogen: A Guide to Policy Making—Cost Reduction*; IRENA: Abu Dhabi, United Arab Emirates, 2020. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf (accessed on 1 July 2025).
27. Bianchi, G.; Panayiotou, G.P.; Aresti, L.; Kalogirou, S.A.; Florides, G.A.; Tsamos, K.; Christodoulides, P. Estimating the waste heat recovery in the European Union Industry. *Energy Ecol. Environ.* **2019**, *4*, 211–221. [CrossRef]
28. Turek, V.; Kilkovský, B.; Daxner, J.; Babička Fialová, D.; Jegla, Z. Industrial Waste Heat Utilization in the European Union—An Engineering-Centric Review. *Energies* **2024**, *17*, 2084. [CrossRef]
29. Peconet, Inc. Eclipse ThermJet PCA Burner Datasheet (Bulletin 20600dga). 2007. Available online: http://peconet.com/products/EclipseBulletins/02%20Furnace%20Type%20Burners/206_ThermJetPCA/20600dga.pdf (accessed on 15 July 2025).
30. Techrite Controls Australia. Eclipse ThermJet Burner Datasheet 3018; Edition 05.23 (EN); Techrite Controls: Springvale, Australia, 2023. Available online: https://techritecontrols.com.au/cms/uploads/Techrite-Controls-Product-Eclipse-Thermjet-Burner-3018.pdf (accessed on 15 July 2025).
31. European Commission. 2040 Climate Target. Available online: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en (accessed on 14 July 2025).
32. Obrist, M.D.; Kannan, R.; McKenna, R.; Schmidt, T.J.; Kober, T. High temperature heat pumps in climate pathways for selected industry sectors in Switzerland. *Energy Policy* **2023**, *173*, 113383. [CrossRef]
33. Arpagaus, C.; Bless, F.; Bertsch, S.; Krummenacher, P.; Flórez Orrego, D.A.; Pina, E.A.; Maréchal, F.; Calame Darbellay, N.; Rognon, F.; Vesin, S.; et al. Integration of high temperature heat pumps in Swiss industrial processes (HTHP CH). In Proceedings of the 14th IEA Heat Pump Conference 2023, Chicago, IL, USA, 15–18 May 2023; Paper 494. Available online: https://www.hpc2023.org/wp-content/uploads/gravity_forms/3-7075ba8a16c5f78b321724d090fb2a34/2023/05/0494_HPC2023_Full_Paper_Arpagaus_v02.pdf (accessed on 14 July 2025).
34. Sun, J.; Peng, B. Experimental Study on Steady-State Operation of Organic Rankine Cycle System under Different Operating Conditions. *Sci. Rep.* **2025**, *15*, 1041. [CrossRef] [PubMed]

35. Astolfi, M.; Romano, M.C.; Bombarda, P.; Macchi, E. Binary ORC (Organic Rankine Cycles) Power Plants for the Exploitation of Low–Medium Enthalpy Geothermal Brines. *Energy* **2014**, *66*, 662–672. [CrossRef]
36. Quoilin, S.; Declaye, S.; Tchanche, B.F.; Lemort, V. Thermo-Economic Optimization of Waste Heat Recovery Organic Rankine Cycles. *Appl. Thermal Eng.* **2011**, *31*, 2885–2893. [CrossRef]
37. Pantaleo, A.M.; Simpson, M.; Rotolo, G.; Distaso, E.; Oyewunmi, O.; Sapin, P.; De Palma, P.; Markides, C.N. Thermoeconomic Optimisation of Small-Scale Organic Rankine Cycle Systems Based on Screw vs. Piston Expander Maps in Waste Heat Recovery Applications. *Energy Convers. Manag.* **2019**, *200*, 112053. [CrossRef]
38. Tsiropoulos, I.; Tarvydas, D.; Zucker, A. Cost Development of Low Carbon Energy Technologies: Scenario Based Cost Trajectories to 2050. 2017 ed.; EUR 29034 EN; Publications Office of the European Union: Luxembourg, 2018; ISBN 9789279774799. [CrossRef]
39. UK Department for Business, Energy & Industrial Strategy. International Energy Price Comparisons. Gov.UK Collection. Available online: https://gov.uk/government/collections/international-energy-price-comparisons (accessed on 21 July 2025).
40. International Energy Agency. *Net Zero by 2050: A Roadmap for the Global Energy Sector*; IEA: Paris, France, 2021; (revised October 2021).
41. Bolard, J.; Dolci, F.; Gryc, K.; Eynard, U.; Georgakaki, A.; Letout, S.; Mountraki, A.; Ince, E.; Shtjefni, D.; Rózsai, M.; et al. *Clean Energy Technology Observatory: Water Electrolysis and Hydrogen in the European Union—2024 Status Report on Technology Development, Trends, Value Chains and Markets*; Publications Office of the European Union: Luxembourg, 2024; EUR 40075, JRC 139364. ISBN 978-92-68-20995-0. ISSN 1831-9424. [CrossRef]
42. International Energy Agency (IEA). *Northwest European Hydrogen Monitor 2024*; IEA: Paris, France, 2024; Licence CC BY 4.0. Available online: https://iea.org/reports/northwest-european-hydrogen-monitor-2024 (accessed on 21 July 2025).
43. EY & Hyvolution. *European Hydrogen Index—Hyvolution/EY: European Hydrogen Monitor 2025*; EY & Hyvolution: Paris, France, 2025. Available online: https://ey.com/content/dam/ey-unified-site/ey-com/fr-fr/insights/climate-change-sustainability-services/documents/ey-hyvolution-ey-european-hydrogen-20250214.pdf (accessed on 21 July 2025).
44. OFX. Historical Exchange Rates—Yearly Average Rates. Available online: https://ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/ (accessed on 15 July 2025).
45. International Energy Agency; Nuclear Energy Agency. *Projected Costs of Generating Electricity 2020*; IEA & OECD Nuclear Energy Agency: Paris, France; Luxembourg, 2020.
46. Jesper, M.; Juhani, H.; Petter, L.; Mats, R.; Erik, D. High temperature heat pumps for industrial heat demand. *Energy* **2018**, *165*, 968–978. [CrossRef]
47. Madsen, J.; Martin, J.; Schlosser, F.; Vajen, K. Performance Evaluation of Heat Pumps in the European Market: A Comprehensive Survey of 58 Devices. *Energies* **2023**, *16*, 3733. [CrossRef]
48. Mahajan, D.; Tan, K.; Venkatesh, T.; Kileti, P.; Clayton, C.R. Hydrogen blending in gas pipeline networks—A review. *Energies* **2022**, *15*, 3582. [CrossRef]
49. Öztuna, S.; Büyükakın, M.K. Effects of hydrogen enrichment of methane on diffusion flame structure and emissions in a back-pressure combustion chamber. *Int. J. Hydrogen Energy* **2020**, *45*, 5971–5986. [CrossRef]
50. Xin, Y.; Wang, K.; Zhang, Y.; Zeng, F.; He, X.; Takyi, S.A.; Tontiwachwuthikul, P. Numerical simulation of combustion of natural gas mixed with hydrogen in gas boilers. *Energies* **2021**, *14*, 6883. [CrossRef]
51. Yilmaz, I.; Ilbas, M. An experimental study on hydrogen–methane mixtured fuels. *Int. Commun. Heat Mass Transf.* **2008**, *35*, 178–187. [CrossRef]
52. İlbaş, M.; Yılmaz, İ. Experimental analysis of the effects of hydrogen addition on methane combustion. *Int. J. Energy Res.* **2012**, *36*, 643–647. [CrossRef]
53. Cellek, M.S.; Pınarbaşı, A. Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels. *Int. J. Hydrogen Energy* **2018**, *43*, 1194–1207. [CrossRef]
54. Büyükakın, M.K.; Öztuna, S. Numerical investigation on hydrogen-enriched methane combustion in a domestic back-pressure boiler and non-premixed burner system from flame structure and pollutants aspect. *Int. J. Hydrogen Energy* **2020**, *45*, 35246–35256. [CrossRef]
55. Fang, Z.; Zhang, S.; Huang, X.; Hu, Y.; Xu, Q. Performance of three typical domestic gas stoves operated with methane-hydrogen mixture. *Case Stud. Therm. Eng.* **2023**, *41*, 102631. [CrossRef]
56. Wang, T.; Zhang, H.; Zhang, Y.; Wang, H.; Lyu, J.; Yue, G. Efficiency and emissions of gas-fired industrial boiler fueled with hydrogen-enriched nature gas: A case study of 108 t/h steam boiler. *Int. J. Hydrogen Energy* **2022**, *47*, 28188–28203. [CrossRef]
57. Basso, G.L.; Nastasi, B.; Garcia, D.A.; Cumo, F. How to handle the Hydrogen enriched Natural Gas blends in combustion efficiency measurement procedure of conventional and condensing boilers. *Energy* **2017**, *123*, 615–636. [CrossRef]
58. Ding, Y.; Durox, D.; Darabiha, N.; Schuller, T. Chemiluminescence based operating point control of domestic gas boilers with variable natural gas composition. *Appl. Therm. Eng.* **2019**, *149*, 1052–1060. [CrossRef]
59. Schiro, F.; Stoppato, A.; Benato, A. Modelling and analyzing the impact of hydrogen enriched natural gas on domestic gas boilers in a decarbonization perspective. *Carbon Resour. Convers.* **2020**, *3*, 122–129. [CrossRef]

60. Bălănescu, D.T.; Homutescu, V.M. Effects of hydrogen-enriched methane combustion on latent heat recovery potential and environmental impact of condensing boilers. *Appl. Therm. Eng.* **2021**, *197*, 117411. [CrossRef]
61. Boulahlib, M.S.; Medaerts, F.; Boukhalfa, M.A. Experimental study of a domestic boiler using hydrogen methane blend and fuel-rich staged combustion. *Int. J. Hydrogen Energy* **2021**, *46*, 37628–37640. [CrossRef]
62. Elco Hydrogen-Ready Products. Available online: https://elco.net/en/products.html (accessed on 29 July 2025).
63. Intergas Hydrogen-Ready Boilers. Available online: https://intergasheating.co.uk/app/uploads/2023/02/Factsheet-Products.pdf (accessed on 29 July 2025).
64. ACV Hydrogen-Ready Boilers. Available online: https://acv.com/gb/news/20-hydrogen-blend-ready-boilers (accessed on 29 July 2025).
65. Accorroni Hydrogen-Ready Boilers. Available online: https://accorroni.it/public/downloads/499_en.pdf (accessed on 29 July 2025).
66. Hoval Hydrogen-Ready Boilers. Available online: https://hoval.co.uk/en_GB/Heating-technology/Gas/c/G_gas (accessed on 29 July 2025).
67. Remeha Hydrogen-Ready Boilers. Available online: https://remeha.de/produkte/gas-brennwertkessel (accessed on 29 July 2025).
68. ETP Clean Energy Technology Guide. Available online: https://iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide (accessed on 29 July 2025).
69. Hydrogen. Available online: https://teledynees.com/what-we-do/markets/hydrogen (accessed on 29 July 2025).
70. H2B2 Electrolysers. Available online: https://h2b2.es/electrolyzers/ (accessed on 29 July 2025).
71. LONGi ALK Hi1. Available online: https://longi.com/en/products/hydrogen/alk-hi-1/ (accessed on 29 July 2025).
72. EnapterAEM Electrolysers. Available online: https://www.enapter.com/en/enapter-products-aem/ (accessed on 29 July 2025).
73. Cummins Electrolyzers Brochure. Available online: https://www.cummins.com/sites/default/files/2023-10/electrolyzer-brochure.pdf (accessed on 29 July 2025).
74. McPhy Electrolyzers. Available online: https://mcphy.com/en/equipment-services/electrolyzers/ (accessed on 29 July 2025).
75. Nel Hydrogen (Nel ASA). Water Electrolysers/Hydrogen Generators. Available online: https://nelhydrogen.com/water-electrolysers-hydrogen-generators/ (accessed on 29 July 2025).
76. Giner Inc. Electrolyzers. *Giner Labs.* Available online: https://www.ginerinc.com/electrolyzers (accessed on 29 July 2025).
77. GINERELX The Allagash Electrolyzer. Available online: https://www.messe.de/apollo/hannover_messe_2020/obs/Binary/A1014067/1014067_02199667.pdf (accessed on 29 July 2025).
78. GINERELX The Merrimack Electrolyzer. Available online: https://www.messe.de/apollo/hannover_messe_2020/obs/Binary/A1014067/1014067_02199672.pdf (accessed on 29 July 2025).
79. University of Queensland Dow Centre. *Green Hydrogen Production from Treated Wastewater*; University of Queensland: Brisbane, Australia, 2024; pp. 1–28. Available online: https://dow.centre.uq.edu.au/files/15402/Green%20Hydrogen%20Production%20from%20Treated%20Wastewater%20April%202024.pdf (accessed on 29 July 2025).
80. Salvatore, A. Sustainable Hydrogen Production from Wastewater Treatment Plants. Master's Thesis, Politecnico di Torino, Turin, Italy, 2021. Available online: https://webthesis.biblio.polito.it/17436/1/tesi.pdf (accessed on 29 July 2025).
81. Yang, Y.; Wang, Y.; Xu, Z.; Xie, B.; Hu, Y.; Yu, J.; Chen, Y.; Zhang, T.; Lu, Z.; Gong, Y. Performance Comparison of High-Temperature Heat Pumps with Different Vapor Refrigerant Injection Techniques. *Processes* **2024**, *12*, 566. [CrossRef]
82. Zhenyu Yang, M.; Sadeghi, M.; Petersen, T.; Zühlsdorf, B.; Madsen, K.S.; Arabkoohsar, A. Thermodynamic Analysis of a High-Temperature Heat Pump Using Low GWP Natural Working Fluids for Upgrading District Heating to Process Heating. In Proceedings of the 36th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2023), Las Palmas de Gran Canaria, Spain, 25–30 June 2023; pp. 715–724. [CrossRef]
83. Huang, M.; Liang, X.; Zhuang, R. Experimental investigation on the performance of a high temperature heat pump using scroll compressor. Paper P.3.3.1. In Proceedings of the 12th IEA Heat Pump Conference, Rotterdam, The Netherlands, 14–17 May 2017.
84. National Renewable Energy Laboratory (NREL). High Temperature Heat Pump Model Documentation and Case Studies; NREL/TP 5700 84560; U.S. Department of Energy, National Renewable Energy Laboratory, Golden, CO, USA, 2023. Available online: https://docs.nrel.gov/docs/fy23osti/84560.pdf (accessed on 30 June 2025).
85. Enertime. Very High Temperature Heat Pump and Steam Generation Heat Pump (HTHP). 2024. Available online: https://enertime.com/en/solutions/heat-pumps.html (accessed on 30 June 2025).
86. SPH GmbH. High-Temperature Heat Pumps for Industry. 2024. Available online: https://spheat.de/blog-en/high-temperature-heat-pumps-for-industry?lang=en (accessed on 30 June 2025).
87. Bever, P.-M.; Bless, F.; Arpagaus, C.; Bertsch, S.S. High-Temperature Heat Pumps for Industrial Use. *Chem. Ing. Tech.* **2024**, *96*, 1071–1084. [CrossRef]
88. Fluorocarbons. High Temperature Heat Pumps. Available online: https://fluorocarbons.org/applications/high-temperature-heat-pumps/ (accessed on 30 June 2025).
89. Lu, Z.; Gong, Y.; Yao, Y.; Luo, C.; Ma, W. Development of a high temperature heat pump system for steam generation using medium-low temperature geothermal water. *Energy Procedia* **2019**, *158*, 6046–6054. [CrossRef]

90. Sun, J.; Wang, Y.; Qin, Y.; Wang, G.; Liu, R.; Yang, Y. A Review of Super-High-Temperature Heat Pumps over 100 °C. *Energies* **2023**, *16*, 4591. [CrossRef]
91. Bamigbetan, O.; Eikevik, T.M.; Nekså, P.; Bantle, M. Extending ammonia high-temperature heat pump using butane in a cascade system. In Proceedings of the 7th IIR Conference: Ammonia and CO_2 Refrigeration Technologies, Ohrid, Nort Macedonia, 11–13 May 2017. [CrossRef]
92. Bamigbetan, O.; Eikevik, T.M.; Nekså, P.; Bantle, M.; Banasiak, K. Extending hydrocarbon heat pumps to higher temperatures: Predictions from simulations. In Proceedings of the 30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, San Diego, CA, USA, 2–6 July 2017.
93. Dai, B.; Liu, C.; Liu, S.; Wang, D.; Wang, Q.; Zou, T.; Zhou, X. Life cycle techno-enviro-economic assessment of dual-temperature evaporation transcritical CO_2 high-temperature heat pump systems for industrial waste heat recovery. *Appl. Therm. Eng.* **2023**, *219*, 119570. [CrossRef]
94. Wu, D.; Hu, B.; Wang, R.Z.; Fan, H.B.; Wang, R. The performance comparison of high-temperature heat pump among R718 and other refrigerants. *Renew. Energy* **2020**, *154*, 715–722. [CrossRef]
95. Chamoun, M.; Rulliere, R.; Haberschill, P.; Peureux, J.-L. Experimental investigation of a new high-temperature heat pump using water as refrigerant for industrial heat recovery. In Proceedings of the International Refrigeration and Air Conditioning Conference, Purdue University, West Lafayette, IN, USA, 18–21 July 2012. Paper No. 1165.
96. Li, X.; Zhang, Y.; Ma, X.; Deng, N.; Jin, Z.; Yu, X.; Li, W. Performance analysis of high-temperature water-source cascade heat pump using BY3B/BY6 as refrigerants. *Appl. Therm. Eng.* **2019**, *159*, 113895. [CrossRef]
97. Zhang, Y.; Zhang, Y.; Yu, X.; Guo, J.; Deng, N.; Dong, S.; Ma, X. Analysis of a high-temperature heat pump using BY-5 as refrigerant. *Appl. Therm. Eng.* **2017**, *127*, 1461–1468. [CrossRef]
98. Yu, X.-H.; Zhang, Y.-F.; Zhang, Y.; He, Z.-L.; Dong, S.-M.; Ma, X.-L.; Yao, S. Intelligent prediction on performance of high-temperature heat pump systems using different refrigerants. *J. Cent. South Univ.* **2018**, *25*, 2754–2765. [CrossRef]
99. Yu, X.; Yufeng, Z.; Na, D.; Chengmin, C.; Yan, Z. Experimental performance of high-temperature heat pump with near-azeotropic refrigerant mixture. *Energy Build.* **2014**, *78*, 43–49. [CrossRef]
100. Deng, N.; Jing, X.; Cai, R.; Gao, J.; Shen, C.; Zhang, Y.; Sui, H. Molecular simulation and experimental investigation for thermodynamic properties of new refrigerant NBY-1 for high-temperature heat pump. *Energy Convers. Manag.* **2019**, *179*, 339–348. [CrossRef]
101. Wu, D.; Jiang, J.; Hu, B.; Wang, R.Z. Experimental investigation on the performance of a very high temperature heat pump with water refrigerant. *Energy* **2020**, *190*, 116427. [CrossRef]
102. Kimura, T.; Fuchikami, H.; Nishida, K.; Kudo, M.; Machida, A.; Saito, K.; Ohta, Y.; Katsuta, M. Development of a high-temperature heat pump using reusable heat as the heat source. In Proceedings of the JRAIA International Symposium 2018, Kobe, Japan, 6 December 2018.
103. Suemitsu, R.; Sakai, M.; Togano, Y.; Kobayashi, N.; Yuki, H.; Wajima, K.; Ueda, K. Research and development for 200 °C compressed-water heat pump using exhaust heat with low GWP refrigerant for industrial use. In Proceedings of the 13th IEA Heat Pump Conference, Jeju, Korea, 26–29 April 2021. Paper No. 163.
104. Kaida, T.; Sakuraba, I.; Hashimoto, K.; Hasegawa, H. Experimental performance evaluation of heat pump-based steam supply system. In Proceedings of the IOP Conference Series: Materials Science and Engineering, 9th International Conference on Compressors and Their Systems, London, UK, 7–9 September 2015; Volume 90, p. 012076. [CrossRef]
105. Linuo Ritter. Cascade Air-Source High-Temp Heat Pump Water Heater. Available online: https://linuo-ritter.com/Cascade-Air-Source-High-Temp-Heat-Pump-Water-Heater-pd40742850.html (accessed on 30 June 2025).
106. Gómez-Hernández, J.; Grimes, R.; Briongos, J.V.; Marugán-Cruz, C.; Santana, D. Carbon dioxide and acetone mixtures as refrigerants for industry heat pumps to supply temperature in the range 150–220 °C. *Energy* **2023**, *269*, 126821. [CrossRef]
107. White, S.D.; Yarrall, M.G.; Cleland, D.J.; Hedley, R.A. Modelling the performance of a transcritical CO_2 heat pump for high-temperature heating. *Int. J. Refrig.* **2002**, *25*, 479–486. [CrossRef]
108. Pan, L.; Wang, H.; Chen, Q.; Chen, C. Theoretical and experimental study on several refrigerants of moderately high-temperature heat pump. *Appl. Therm. Eng.* **2011**, *31*, 1886–1893. [CrossRef]
109. Reissner, F.; Gromoll, B.; Danov, V.; Schaefer, J.; Karl, J. Basic development of a novel high-temperature heat pump system using low GWP working fluids. In Proceedings of the 11th IEA Heat Pump Conference, Montréal, QC, Canada, 12–16 May 2014. Paper, O.2.3.4.
110. Bamigbetan, O.; Eikevik, T.M.; Nekså, P.; Bantle, M.; Schlemminger, C. Theoretical analysis of suitable fluids for high-temperature heat pumps up to 125 °C heat delivery. *Int. J. Refrig.* **2018**, *92*, 185–195. [CrossRef]
111. Arpagaus, C.; Bless, F.; Uhlmann, M.; Büchel, E.; Frei, S.; Schiffmann, J.; Bertsch, S. High-temperature heat pump using HFO and HCFO refrigerants—System design, simulation, and first experimental results. In Proceedings of the International Refrigeration and Air Conditioning Conference, Purdue University, West Lafayette, IN, USA, 11–14 July 2018. Paper No. 1875.
112. Bellemo, L.; Gerritsen, J.; Hoffmann, K. High-temperature CO_2 heat pump integration into the spray drying process. In Proceedings of the 2nd Conference on High Temperature Heat Pumps, Copenhagen, Denmark, 5–6 March 2019; pp. 158–160.

113. Abi Chahla, G.; Beucher, Y.; Zoughaib, A.; De Carlan, F.; Pierucci, J. Transcritical industrial heat pump using HFOs for up to 150 °C hot air supply. In Proceedings of the 25th IIR International Congress of Refrigeration (ICR 2019), Montréal, QC, Canada, 24–30 August 2019. Paper ID 1184. [CrossRef]
114. Bamigbetan, O.; Eikevik, T.M.; Nekså, P.; Bantle, M.; Schlemminger, C. The development of a hydrocarbon high-temperature heat pump for waste heat recovery. *Energy* **2019**, *173*, 1141–1153. [CrossRef]
115. Bamigbetan, O.; Eikevik, T.M.; Nekså, P.; Bantle, M.; Schlemminger, C. Experimental investigation of a prototype R-600 compressor for high-temperature heat pump. *Energy* **2019**, *169*, 730–738. [CrossRef]
116. Verdnik, M.; Rieberer, R. Experimental analysis of a R600 high-temperature heat pump in sub-critical and trans-critical operation. In Proceedings of the 14th IIR Gustav-Lorentzen Conference on Natural Refrigerants (GL 2020), Kyoto, Japan, 7–9 December 2020; pp. 500–505. [CrossRef]
117. Verdnik, M.; Rieberer, R. Influence of operating parameters on the COP of an R600 high-temperature heat pump. *Int. J. Refrig.* **2022**, *140*, 103–111. [CrossRef]
118. Wilk, V.; Helminger, F.; Lauermann, M.; Windholz, B. High-temperature heat pumps for drying—first results of operation in industrial environment. In Proceedings of the 13th IEA Heat Pump Conference 2020, Jeju, Republic of Korea, 26–29 April 2021. Paper No. 075.
119. Dusek, S.; Lauermann, M.; Helminger, F.; Wilk, V. Analysis of a steam-generating high-temperature heat pump for industrial waste heat recovery. In Proceedings of the 13th IEA Heat Pump Conference, Jeju, Republic of Korea, 26–29 April 2021. Paper No. 097.
120. Marina, A.; Smeding, S.F.; Wemmers, A.K.; Spoelstra, S.; Kremers, P. Design and experimental results of a two-stage steam producing industrial heat pump. In Proceedings of the 13th IEA Heat Pump Conference, Jeju, Republic of Korea, 26–29 April 2021. Paper No. 156.
121. Arpagaus, C.; Bertsch, S. Experimental comparison of HCFO and HFO R1224yd(Z), R1233zd(E), R1336mzz(Z), and HFC R245fa in a high-temperature heat pump up to 150 °C supply temperature. In Proceedings of the International Refrigeration and Air Conditioning Conference, Purdue University, West Lafayette, IN, USA, 11–14 July 2021. Paper No. 2200.
122. Tveit, T.M.; Johansson, M.; Zevenhoven, R. Environmentally friendly steam generation using VHTHPs at a pharmaceutical research facility. In Proceedings of the 13th IEA Heat Pump Conference, Jeju, Republic of Korea, 26–29 April 2021. Paper No. 004.
123. Ramirez, M.; Trebilcock, F.; Peña, X.; Martinez-Urrutia, A.; Hassan, A.H. Development and lab-scale performance evaluation of a high-temperature heat pump for integration into a Power-to-Heat-to-Power system. In Proceedings of the 13th IEA Heat Pump Conference, Jeju, Republic of Korea, 26–29 April 2021. Paper No. 103.
124. Bobelin, D.; Bourig, A. Experimental results of a newly developed very high temperature industrial heat pump (140 °C) equipped with scroll compressors and working with a new blend refrigerant. In Proceedings of the International Refrigeration and Air Conditioning Conference, Purdue University, West Lafayette, IN, USA, 10–14 July 2012. Paper No. 1299.
125. Koundinya, S.; Seshadri, S. Energy, exergy, environmental, and economic (4E) analysis and selection of best refrigerant using TOPSIS method for industrial heat pumps. *Therm. Sci. Eng. Prog.* **2022**, *36*, 101491. [CrossRef]
126. Mateu-Royo, C.; Navarro-Esbrí, J.; Mota-Babiloni, A.; Molés, F.; Amat-Albuixech, M. Experimental exergy and energy analysis of a novel high-temperature heat pump with scroll compressor for waste heat recovery. *Appl. Energy* **2019**, *253*, 113504. [CrossRef]
127. Xu, C.; Yang, H.; Yu, X.; Ma, H.; Chen, M.; Yang, M. Performance analysis for binary mixtures based on R245fa using in high-temperature heat pumps. *Energy Convers. Manag. X* **2021**, *12*, 100123. [CrossRef]
128. Zühlsdorf, B.; Bühler, F.; Bantle, M.; Elmegaard, B. Analysis of technologies and potentials for heat pump-based process heat supply above 150 °C. *Energy Convers. Manag. X* **2019**, *2*, 100011. [CrossRef]
129. Zühlsdorf, B. *Annex 58 High-Temperature Heat Pumps. Task 1—Technologies, Task Report*; IEA Heat Pump Centre: Borås, Sweden, 2023.
130. Pintoro, A. Performance analysis of low-temperature heat source of organic Rankine cycle for geothermal application. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *308*, 012026. [CrossRef]
131. Boydak, Ö.; Ekmekçi, I.; Yılmaz, M.; Köten, H. Thermodynamic investigation of organic Rankine cycle energy recovery system and recent studies. *Therm. Sci.* **2018**, *22*, 2679–2690. [CrossRef]
132. Lin, C.-H.; Hsu, P.-P.; He, Y.-L.; Shuai, Y.; Hung, T.-C.; Feng, Y.-Q.; Chang, Y.-H. Investigations on experimental performance and system behavior of 10 kW organic Rankine cycle using scroll-type expander for low-grade heat source. *Energy* **2019**, *177*, 94–105. [CrossRef]
133. Prasetyo, T.; Surindra, M.D.; Caesarendra, W.; Taufik; Glowacz, A.; Irfan, M.; Glowacz, W. Influence of superheated vapour in organic Rankine cycles with working fluid R123 utilizing low-temperature geothermal resources. *Symmetry* **2020**, *12*, 1463. [CrossRef]
134. Abbas, W.K.; Linnemann, M.; Baumhögger, E.; Vrabec, J. Experimental Study of Two Cascaded Organic Rankine Cycles with Varying Working Fluids. *Energy Convers. Manag.* **2021**, *230*, 113818. [CrossRef]
135. Tumen Ozdil, N.F.; Segmen, M.R. Investigation of the effect of the water phase in the evaporator inlet on economic performance for an Organic Rankine Cycle (ORC) based on industrial data. *Appl. Therm. Eng.* **2016**, *100*, 1042–1051. [CrossRef]

136. Surindra, M.D.; Caesarendra, W.; Prasetyo, T.; Mahlia, T.M.I.; Taufik. Comparison of the Utilization of 110 °C and 120 °C Heat Sources in a Geothermal Energy System Using Organic Rankine Cycle (ORC) with R245fa, R123, and Mixed-Ratio Fluids as Working Fluids. *Processes* **2019**, *7*, 113. [CrossRef]
137. Özkaraca, O.; Keçebaş, P.; Demircan, C.; Keçebaş, A. Thermodynamic Optimization of a Geothermal-Based Organic Rankine Cycle System Using an Artificial Bee Colony Algorithm. *Energies* **2017**, *10*, 1691. [CrossRef]
138. Unverdi, M.; Cerci, Y. Thermodynamic analysis and performance improvement of Irem geothermal power plant in Turkey: A case study of Organic Rankine cycle. *Energy Prog. Sustain. Energy* **2018**, *37*, 1523–1539. [CrossRef]
139. Landelle, A.; Tauveron, N.; Haberschill, P.; Revellin, R.; Colasson, S. Performance Evaluation and Comparison of Experimental Organic Rankine Cycle Prototypes from Published Data. *Energy Procedia* **2017**, *105*, 1706–1711. [CrossRef]
140. Algieri, A.; Šebo, J. Energetic Investigation of Organic Rankine Cycles (ORCs) for the Exploitation of Low-Temperature Geothermal Sources—A possible application in Slovakia. *Procedia Comput. Sci.* **2017**, *109*, 833–840. [CrossRef]
141. Canbolat, A.S.; Bademlioglu, A.H.; Kaynakli, O. A modelling of electricity generation by using geothermal-assisted Organic Rankine Cycle with internal heat recovery. *Energy Sources Part A Recover. Util. Environ. Eff.* **2019**, *41*, 212–228. [CrossRef]
142. Zhang, C.; Fu, J.; Yuan, P.; Liu, J. Guidelines for Optimal Selection of Subcritical Low-Temperature Geothermal Organic Rankine Cycle Configuration Considering Reinjection Temperature Limits. *Energies* **2018**, *11*, 2878. [CrossRef]
143. Uusitalo, A.; Honkatukia, J.; Turunen-Saaresti, T.; Grönman, A. Thermodynamic evaluation on the effect of working fluid type and fluids critical properties on design and performance of Organic Rankine Cycles. *J. Clean. Prod.* **2018**, *188*, 253–263. [CrossRef]
144. Ali, M.A.; Khan, T.S.; Al Hajri, E.; Ayub, Z.H. A Computer Program for Working Fluid Selection of Low-Temperature Organic Rankine Cycle. In Proceedings of the ASME 2015 Power Conference (POWER 2015), San Diego, CA, USA, 28 June 2015. [CrossRef]
145. Pezzuolo, A.; Benato, A.; Stoppato, A.; Mirandola, A. The ORC-PD: A versatile tool for fluid selection and Organic Rankine Cycle unit design. *Energy* **2016**, *102*, 605–620. [CrossRef]
146. Agromayor, R.; Nord, L.O. Fluid Selection and Thermodynamic Optimization of Organic Rankine Cycles for Waste Heat Recovery Applications. *Energy Procedia* **2017**, *129*, 527–534. [CrossRef]
147. Lu, J.; Zhang, J.; Chen, S.; Pu, Y. Analysis of organic Rankine cycles using zeotropic mixtures as working fluids under different restrictive conditions. *Energy Convers. Manag.* **2016**, *126*, 704–715. [CrossRef]
148. Imran, M.; Usman, M.; Park, B.-S.; Yang, Y. Comparative assessment of Organic Rankine Cycle integration for low temperature geothermal heat source applications. *Energy* **2016**, *102*, 473–490. [CrossRef]
149. Wang, Y.Z.; Zhao, J.; Wang, Y.; An, Q.S. Multi-objective optimization and grey relational analysis on configurations of Organic Rankine Cycle. *Appl. Therm. Eng.* **2017**, *114*, 1355–1363. [CrossRef]
150. Li, G. Organic Rankine cycle performance evaluation and thermoeconomic assessment with various applications part I: Energy and exergy performance evaluation. *Renew. Sustain. Energy Rev.* **2016**, *53*, 477–499. [CrossRef]
151. Yang, M.-H.; Yeh, R.-H. Economic performances optimization of an organic Rankine cycle system with lower global warming potential working fluids in geothermal application. *Renew. Sustain. Energy Rev.* **2016**, *85*, 1201–1213. [CrossRef]
152. Liu, C.; Gao, T.; Zhu, J.; Xu, J. Performance Optimization and Economic Analysis of Geothermal Power Generation by Subcritical and Supercritical Organic Rankine Cycles. In Proceedings of the ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition (GT 2016), Seoul, Republic of Korea, 13–17 June 2016. ASME Turbo Expo 2016: GT2016 56821. [CrossRef]
153. Manente, G.; Da Lio, L.; Lazzaretto, A. Influence of axial turbine efficiency maps on the performance of subcritical and supercritical Organic Rankine Cycle systems. *Energy* **2016**, *107*, 761–772. [CrossRef]
154. Moloney, F.; Almatrafi, E.; Goswami, D.Y. Working fluid parametric analysis for recuperative supercritical organic Rankine cycles for medium geothermal reservoir temperatures. *Renew. Sustain. Energy Rev.* **2020**, *147*, 2874–2881. [CrossRef]
155. Lukawski, M.Z.; Tester, J.W.; DiPippo, R. Impact of molecular structure of working fluids on performance of organic Rankine cycles (ORCs). *Sustain. Energy Fuels* **2017**, *1*, 1098–1111. [CrossRef]
156. Cakici, D.M.; Erdogan, A.; Colpan, C.O. Thermodynamic performance assessment of an integrated geothermal-powered supercritical regenerative Organic Rankine Cycle and parabolic trough solar collectors. *Energy* **2017**, *120*, 306–319. [CrossRef]
157. Sun, Q.; Wang, Y.; Cheng, Z.; Wang, J.; Zhao, P.; Dai, Y. Thermodynamic optimization of a double-pressure organic Rankine cycle driven by geothermal heat source. *Energy Procedia* **2017**, *129*, 591–598. [CrossRef]
158. Sun, Q.; Wang, Y.; Cheng, Z.; Wang, J.; Zhao, P.; Dai, Y. Thermodynamic and economic optimization of a double-pressure organic Rankine cycle driven by low-temperature heat source. *Renew. Sustain. Energy Rev.* **2020**, *147*, 2822–2832. [CrossRef]
159. Manente, G.; Lazzaretto, A.; Bonamico, E. Design guidelines for the choice between single and dual pressure layouts in organic Rankine cycle (ORC) systems. *Energy* **2017**, *123*, 413–431. [CrossRef]
160. Wang, S. Thermo-economic Evaluations of Dual Pressure Organic Rankine Cycle (DPORC) Driven by Geothermal Heat Source. *J. Renew. Sustain. Energy* **2018**, *10*, 063901. [CrossRef]
161. Fontalvo, A.; Solano, J.; Pedraza, C.; Bula, A.; Gonzalez Quiroga, A.; Vasquez Padilla, R. Energy, Exergy and Economic Evaluation Comparison of Small-Scale Single and Dual Pressure Organic Rankine Cycles Integrated with Low-Grade Heat Sources. *Entropy* **2017**, *19*, 476. [CrossRef]

162. Braimakis, K.; Karellas, S. Energetic Optimization of Regenerative Organic Rankine Cycle (ORC) Configurations. *Energy Convers. Manag.* **2018**, *159*, 353–370. [CrossRef]
163. Braimakis, K.; Karellas, S. Exergetic optimization of double stage Organic Rankine Cycle (ORC) for waste heat recovery. *Energy* **2018**, *149*, 296–313. [CrossRef]
164. Liu, G.; Wang, Q.; Xu, J.; Miao, Z. Exergy Analysis of Two-Stage Organic Rankine Cycle Power Generation System. *Entropy* **2021**, *23*, 43. [CrossRef]
165. Li, T.; Yuan, Z.; Li, W.; Yang, J.; Zhu, J. Strengthening mechanisms of two-stage evaporation strategy on system performance for Organic Rankine Cycle. *Energy* **2016**, *101*, 532–540. [CrossRef]
166. Li, T.; Yuan, Z.; Xu, P.; Zhu, J. Entransy dissipation/loss-based optimization of two-stage organic Rankine cycle (TSORC) with R245fa for geothermal power generation. *Sci. China Technol. Sci.* **2016**, *59*, 1524–1536. [CrossRef]
167. Li, J.; Ge, Z.; Duan, Y.; Yang, Z.; Liu, Q. Parametric optimization and thermodynamic performance comparison of single-pressure and dual-pressure evaporation organic Rankine cycles. *Appl. Energy* **2018**, *217*, 409–421. [CrossRef]
168. Wang, M.; Chen, Y.; Liu, Q.; Zhao, Y. Thermodynamic and thermo-economic analysis of dual-pressure and single-pressure evaporation organic Rankine cycles. *Energy Convers. Manag.* **2018**, *177*, 718–736. [CrossRef]
169. Kazemi, N.; Samadi, F. Thermodynamic, economic and thermo-economic optimization of a new proposed organic Rankine cycle for energy production from geothermal resources. *Energy Convers. Manag.* **2016**, *121*, 391–401. [CrossRef]
170. Samadi, F.; Kazemi, N. Exergoeconomic analysis of zeotropic mixture on the new proposed Organic Rankine cycle for energy production from geothermal resources. *Renew. Sustain. Energy Rev.* **2020**, *152*, 1250–1265. [CrossRef]
171. Luo, X.; Huang, R.; Yang, Z.; Chen, J.; Chen, Y. Performance investigation of a novel zeotropic organic Rankine cycle coupling liquid separation condensation and multi-pressure evaporation. *Energy Convers. Manag.* **2018**, *161*, 112–127. [CrossRef]
172. Zhou, Y.; Li, S.; Sun, L.; Zhao, S.; Ashraf Talesh, S.S. Optimization and thermodynamic performance analysis of a power generation system based on geothermal flash and dual-pressure evaporation organic Rankine cycles using zeotropic mixtures. *Energy* **2020**, *194*, 116785. [CrossRef]
173. Surendran, A.; Seshadri, S. Design and performance analysis of a novel Transcritical Regenerative Series Two-stage Organic Rankine Cycle for dual-source waste heat recovery. *Energy* **2020**, *203*, 117800. [CrossRef]
174. Sadeghi, A.; Shokati, A.; Mohammadi-ivatloo, B. Thermodynamic Analysis and Multi-Objective Optimization of Various ORC (Organic Rankine Cycle) Configurations Using Zeotropic Mixtures. *Energy* **2016**, *109*, 791–805. [CrossRef]
175. Wang, Q.; Wang, J.; Li, T.; Meng, N. Techno-economic performance of two-stage series evaporation Organic Rankine cycle with dual-level heat sources. *Appl. Therm. Eng.* **2020**, *171*, 115078. [CrossRef]
176. Xu, B.; Rathod, D.; Yebi, A.; Filipi, Z.; Onori, S.; Hoffman, M. A comprehensive review of organic Rankine cycle waste heat recovery systems in heavy-duty diesel engine applications. *Renew. Sustain. Energy Rev.* **2019**, *107*, 145–170. [CrossRef]
177. Falciai, A. *The New Industrial Age Tailored Electrification Pathways for Europe's Industrial Competitiveness. Power Summit 2025 Report*; Eurelectric: Brussels, Belgium, 2025. Available online: http://powersummit2025.eurelectric.org/wp-content/uploads/2025/06/Industrial-electrification-competitiveness.pdf (accessed on 1 July 2025).
178. Cleantech Reality Check: Electrification—The Electrification Mirage for Europe? Breakthrough Energy; Cleantech for Europe; Systemiq. December 2024. Available online: http://Breakthroughenergy.org/wp-content/uploads/2024/12/EIH_CleantechReality_Serie2-compressed_2.pdf (accessed on 1 July 2025).
179. Naegler, T.; Simon, S.; Klein, M.; Gils, H.C. Quantification of the European industrial heat demand by branch and temperature level. *Int. J. Energy Res.* **2015**, *39*, 2019–2030. [CrossRef]
180. Papapetrou, M.; Kosmadakis, G.; Cipollina, A.; La Commare, U.; Micale, G. Industrial waste heat: Estimation of the technically available resource in the EU per industrial sector, temperature level and country. *Appl. Therm. Eng.* **2018**, *138*, 207–216. [CrossRef]
181. Tannous, H.; Stojceska, V.; Tassou, S.A. The Use of Solar Thermal Heating in SPIRE and Non-SPIRE Industrial Processes. *Sustainability* **2023**, *15*, 7807. [CrossRef]
182. Heat Roadmap Europe: Combined Heat and Power and District Heating—A Vision Towards 2020 and Beyond. Heat Roadmap Europe, February 2019. Available online: http://heatroadmap.eu/wp-content/uploads/2019/02/HRE_Final-Brochure_web.pdf (accessed on 1 July 2025).
183. Directorate General for Energy. Mapping and Analyses of the Current and Future (2020–2030) Heating/Cooling Fuel Deployment (Fossil/Renewables): Executive Summary. European Commission, 10 September 2016. Available online: http://energy.ec.europa.eu/document/download/3418e3a4-5e11-45d3-aac2-059b279bfda3_en?filename=mapping-hc-excecutivesummary.pdf (accessed on 1 July 2025).
184. Kim, S.T.; Hegner, R.; Özuylasi, G.; Stathopoulos, P.; Nicke, E. Performance analysis of multistage high-temperature heat pump cycle. *Energy Sci. Eng.* **2023**, *11*, 3500–3511. [CrossRef]
185. Agathokleous, R.; Bianchi, G.; Panayiotou, G.; Aresti, L.; Argyrou, M.C.; Georgiou, G.S.; Tassou, S.A.; Jouhara, H.; Kalogirou, S.A.; Florides, G.A.; et al. Waste Heat Recovery in the EU Industry and Proposed New Technologies. *Energy Procedia* **2019**, *161*, 489–496. [CrossRef]

186. Ates, F.; Ozcan, H. Turkey's industrial waste heat recovery potential with power and hydrogen conversion technologies: A techno-economic analysis. *Int. J. Hydrogen Energy* **2020**, *47*, 7421–7438. [CrossRef]
187. Brunke, J.C.; Johansson, M.; Thollander, P. Empirical investigation of barriers and drivers to the adoption of energy conservation measures, energy management practices and energy services in the Swedish iron and steel industry. *J. Clean. Prod.* **2014**, *84*, 509–525. [CrossRef]
188. Hochschule Osnabrück; Kompetenzzentrum Energie; Landkreis Osnabrück. *ReWIn—Regionales Wärmekataster Industrie. Projektlaufzeit November 2013–April 2014*; Hochschule Osnabrück: Osnabrück, Germany, 2014. Available online: http://kompetenzzentrum-energie.de/fileadmin/HSOS/Homepages/Kompetenzzentrum-Energie/ZBH/PDf/ReWIn__2014.pdf (accessed on 1 July 2025).
189. Investigation Report on Industrial Waste Heat. NEDO (New Energy and Industrial Technology Development Organization), Japan, March 2019. Available online: https://www.nedo.go.jp/content/100957934.pdf (accessed on 1 July 2025).
190. Aydemir, A.; Doderer, H.; Hoppe, F.; Braungardt, S.; Fraunhofer Institut für System und Innovationsforschung ISI. *Abwärmenutzung in Unternehmen*; Fraunhofer ISI: Karlsruhe, Germany, 2021. Available online: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/2021/AbwÃd'rmenutzung_in_Unternehmen.pdf (accessed on 1 July 2025).
191. Bestimmung der Abwärmepotenziale in Berlin: Schlussbericht (Determination of Waste Heat Potentials in Berlin: Final Report). Institute for Ecological Economy Research (IÖW) & ifeu—Institut für Energie- und Umweltforschung Heidelberg, Germany, September 2022. Available online: http://Ioew.de/fileadmin/user_upload/IOEW_ifeu_Bestimmung_der_Abwaermepotenziale_in_Berlin_Schlussbericht.pdf (accessed on 1 July 2025).
192. Fernández, A.G.; Soler, D.; Miró, L.; Labidi, J.; Cabeza, L.F. Industrial waste heat estimation for the manufacturing industry in Chile. *Int. J. Environ. Sci. Technol.* **2024**, *21*, 4331–4342. [CrossRef]
193. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Waste Heat Recovery Systems. In *Quadrennial Technology Review 2015*; Chapter 6M (Technology Assessment); U.S. DOE: Washington, DC, USA, 2016. Available online: http://energy.gov/sites/prod/files/2016/02/f30/QTR2015-6M-Waste-Heat-Recovery.pdf (accessed on 1 July 2025).
194. Lyons, L.; Kavvadias, K.; Carlsson, J. *Defining and Accounting for Waste Heat and Cold*; EUR 30869 EN; Publications Office of the European Union: Luxembourg, 2021; ISBN 978-92-76-42588-5. ISSN 1831-9424. [CrossRef]
195. Hydrogen Council; McKinsey & Company. *Hydrogen for Net Zero*; Hydrogen Council: Brussels, Belgium, 2021. Available online: http://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf (accessed on 1 July 2025).
196. European Commission. Net-Zero Industry Act Explained. Available online: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en (accessed on 1 July 2025).
197. Northern Gas Networks. *East Coast Hydrogen Feasibility Report*; Northern Gas Networks: Sunderland, UK, 2021. Available online: https://cadentgas.com/nggdwsdev/media/FRoG/ResourcesHub/East-Coast-Hydrogen-Feasibility-Report_online.pdf (accessed on 1 July 2025).
198. International Energy Agency (IEA). *Global Hydrogen Review 2023*; IEA: Paris, France, 2023. Available online: https://iea.org/reports/global-hydrogen-review-2023 (accessed on 1 July 2025).
199. Erbach, G.; Svensson, S. *EU Rules for Renewable Hydrogen*; European Parliamentary Research Service (EPRS), PE 747.085: Brussels, Belgium, 2023. Available online: https://europarl.europa.eu/RegData/etudes/BRIE/2023/747085/EPRS_BRI(2023)747085_EN.pdf (accessed on 1 July 2025).
200. Goldman Sachs Research. *Carbonomics: The Clean Hydrogen Revolution*; Goldman Sachs: New York, NY, USA, 2022. Available online: https://www.goldmansachs.com/intelligence/pages/carbonomics-the-clean-hydrogen-revolution.html (accessed on 1 July 2025).
201. DNV. *Hydrogen Forecast to 2050: Energy Transition Outlook 2022*; DNV: Høvik, Norway, 2022. Available online: https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050/ (accessed on 1 July 2025).
202. European Commission. European Hydrogen Bank: Results of the First Auction Announced. Press Release, 30 April 2024. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_24_2333 (accessed on 1 July 2025).
203. Fraunhofer IS. Direct Electrification of Industrial Process Heat: An Assessment of Technologies, Potentials and Future Prospects for the EU. Study on Behalf of Agora Industry, 2024. Available online: https://www.agora-industry.org/fileadmin/Projects/2023/2023-20_IND_Electrification_Industrial_Heat/A-IND_329_04_Electrification_Industrial_Heat_WEB.pdf (accessed on 1 July 2025).
204. Deloitte and Renewable Thermal Collaborative. Assessment of Green Hydrogen for Industrial Heat. 2023. Available online: https://deloitte.com/content/dam/Deloitte/us/Documents/Advisory/us-advisory-assessment-of-green-hydrogen-for-industrial-heat.pdf (accessed on 21 July 2025).

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