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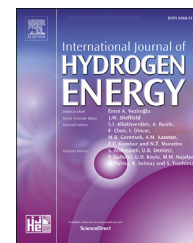
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Utilisation of waste heat from PEM electrolyzers – Unlocking local optimisation

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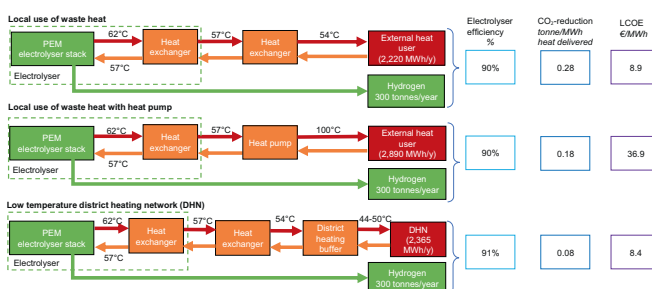
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HIGHLIGHTS

- Redundant designs for utilisation of waste heat from electrolyzers are presented.
- Techno-economic analysis for a direct heat consumer and district heating grid.
- Increased electrolyser system efficiency of 14–15% by waste heat utilisation.
- The feasibility of heat utilisation is very sensitive to the transport distance.
- LCOE of the electrolyser heat is within the range of other industrial heat sources.

GRAPHICAL ABSTRACT



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ABSTRACT

Recovery of heat from electrolyzers is potentially interesting to increase the total system efficiency, reduce CO₂ emissions, and increase the economic feasibility of both hydrogen and heat production. This study examines different designs for the utilisation of (waste) heat from a 2.5 MW_{el} polymer electrolyte membrane (PEM) electrolyser. Redundancy is important in the design, to ensure safe operation regardless of the heat demand of the heat consumer. We analysed cases with local heat consumption (with/without a heat pump) and coupling with a district heating network (DHN). Overall, 14–15% of the electricity input to the stack can be utilised by a heat consumer, increasing the total system efficiency to 90% (HHV) with CO₂-savings of 0.08 (DHN)-0.28 (direct use) tonne CO₂/MWh_{heat, used}. We performed a first-order techno-economic analysis showing that the levelized costs of the

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Waste heat	electrolyser heat (8.4–36.9 €/MWh) fall within the range of other industrial heat sources
System integration	and below lower-temperature heat sources.
District heating	© 2023 The Author(s). Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Nomenclature	
BOP	Balance of Plant
CAPEX _i	Capital expenditures for a unit i (€/unit)
c _{CO₂}	CO ₂ price (€/tonne)
C _{electricity}	Cost of electricity (€/kWh)
C _{gas}	Cost of natural gas (€/kWh)
C _{Margin}	Margin between potential savings and costs for heat (€/year)
C _{Margin with CO₂}	Margin between potential savings and costs for heat with CO ₂ pricing taken into account (€/year)
C _{savings}	Costs savings at the heat consumer (€/year)
CO _{2, reduction, heat}	CO ₂ emission reduction potential of replacing a fossil energy source with waste heat (kg)
CO _{2 savings}	Saved costs by CO ₂ -pricing of CO ₂ emission reduction (€/year)
COP _{average, heat pump}	Average coefficient of performance of a heat pump (–)
DHN	District Heating Network
EU	European Union
E _{cost}	Electricity costs (€/unit/year)
E _{Elec}	Electricity consumption of the electrolyser (kWh)
E _{electrolyser stack, eff}	Stack efficiency of the electrolyser (%)
E _{heat, used}	Heat from the electrolyser used by a consumer (kWh _{th})
E _{pump}	Pumping energy (kWh)
H _{2, produced}	Amount of hydrogen produced (kg)
HHV	Higher Heating Value
HT-ATES	High-Temperature Aquifer Thermal Energy Storage
I	Cell current (ampere)
GW	Gigawatt
kWh	Kilowatt hour
LCOE	Levelized Cost Of Energy
L	Lifetime (years)
LC _{total}	Total levelized yearly costs for the heat recovery installation (€/year)
LC _i	Levelized yearly costs for a specific system component i (€/unit/year)
LHV	Lower Heating Value
Load _{electrolyser}	Fraction of the full load of the electrolyser
MWh	Megawatt hour
N _u	Number of units
OM	operation and maintenance costs as a percentage of the CAPEX costs (%)
PEM	Polymer Electrolyte Membrane
P _{HE}	Heat exchanger capacity (kW _{th})
PPA	Power Purchase Agreement
Q _{produced}	Total amount of heat produced (Watt)
r	Discount rate (fraction)
TJ	Terajoule
U _{operating}	Operating voltage of the electrolysis cell (Volt)
U _{thermoneutral}	Thermoneutral voltage (Volt)
Greek letters	
α	Capital recovery factor
η	Efficiency (%)
Subscripts and superscripts	
el	Electricity
EL	Electrolyser
H ₂	Hydrogen
N _t	Time steps in hours
th =	Thermal

Introduction

Our future energy system needs to be reliable, affordable and clean. To reach that goal, an integrated energy system needs to be created that combines smart combinations of technologies so energy supply and demand are matched in both time and space. In this future integrated energy system, green hydrogen is increasingly seen as an essential energy carrier [1,2]. Hydrogen is a feedstock for industry as well as a zero-carbon energy carrier, that can transport and store renewable energy cost-efficiently and de-carbonize energy use in industry, transport and buildings [2–4]. As (green) hydrogen is an energy carrier, and not an energy source, it needs to be produced first by water electrolysis with renewable electricity.

The European Commission has raised the ambition of renewable hydrogen production with the REPowerEU action plan from 5.6 Mton to 10 Mton domestic EU production and 10 Mton of hydrogen imports [5]. Production of hydrogen can take place both at local hydrogen clusters ('Hydrogen valleys') as well as at or near large RES production sites in less inhabited areas (oceans, deserts) [6]. At these remote locations with high wind speeds or high solar irradiation, hydrogen can be produced, if necessary converted, and transported to areas with high demand for either hydrogen or electricity. To connect areas of supply (i.e. Africa, Iceland) with areas of hydrogen demand (i.e. Europe) [7,8] infrastructure has to be installed, which is reflected in the plans for a European hydrogen backbone [9,10].

In this paper, we focus on local hydrogen clusters, as these clusters give more possibilities for the integration of hydrogen production with other sectors and services. Because the electrolysis process is not 100% efficient, (waste) heat is produced as a by-product and could be utilised by other sectors. The new generation electrolyzers have a system efficiency of 74–79% [2,11] and a balance of stack efficiency of 77–80% (higher heating value – HHV) [12]. For most of the balance of plant processes (i.e. electricity transformation or demineralized water production) no heat can be recovered, so the technical potential of heat recovery can only be based on the balance of stack efficiency. Conventionally, the heat (at 50–80 °C) from the stacks is dissipated by dry coolers on top of the electrolyser containers. When electrolyzers are installed at short distances of heat demand, the heat produced by the electrolyser can potentially be used resulting in a higher overall system efficiency. Eventually, the utilisation of waste heat can lead to a reduction in CO₂ emissions, when the electrolyser heat is exchanged with heat from natural gas or other fossil energy sources. Besides CO₂ emission reduction, it will also reduce the dependence on fossil sources and could lower the hydrogen production cost.

Utilising waste heat from electrolyser installations is mentioned by Buttler & Spliethoff as a way of increasing the system (stack + balance of plant) efficiency from 75–80% to 86–95% (HHV based) [13]. They mention three concrete projects where heat integration was part of the activities. Firstly, the BioCat project deployed a 1 MW installation to produce hydrogen via electrolysis and converted it to methane with the help of biological methanation. The intention was to reuse both the heat from the electrolyser and methanation process in the waste water treatment plant or a renewable heat grid. Eventually, the utilisation of heat from the electrolyser was not realised in the project (p. 6 final report) [14]. Secondly, Stromlückenfuller is a project where waste heat from a 200 kW electrolyser is used in a heating network [15]. A similar project with a 1 MW electrolyser and reuse in a district heating grid is Green Hydrogen Esslingen [16]. Lastly, RWE uses heat from electrolysis (150 kW) in a gas pressure regulation station [17], but no further publications are found on how these systems work and how much heat is recovered. It is thus hard to find concrete examples of the realization of waste heat recovery, but new plans for heat utilisation are created. In Hamburg, a 100 MW electrolysis system is proposed with waste heat utilisation in the district heating network and thermal treatment of municipal waste, that should be operational in 2025 [18]. The 2050 scenario for the district heating network of Aalborg, the utilisation waste heat from a 330 MW electrolyser is mentioned as an additional heat source [19]. The Institute of Process Technology has worked out a design for a 1 GW electrolysis plant, which should be heat integration ready [20].

The scientific literature on heat utilisation of electrolyzers is limited. Bilbao [21] worked out a case study in Chile for an alkaline electrolyser, with as goal to provide the electrolyser with pre-heated water to have a higher overall efficiency. The overall efficiency increase was marginal (<1%). The reason for the small overall efficiency increase is not the amount of available waste heat, but the relatively small amount of water consumption, which is 30 times lower than the mass flow of

waste heat water. This means that the waste heat it not used to its full potential. Bilbao states that when it would be possible to utilise the full potential, it could lead to a total increase in efficiency of 13%, comparable to Buttler & Spliethoff [13], but they do not mention how this heat could be used [21]. A modelling and experimental study on an alkaline electrolyser of 46.5 kW showed that the efficiency of the electrolyzer system can be increased to >90% if heat recovery is included [22]. Frank et al. [23] notice an 18% increase in efficiency if all waste heat from their 1 MW_{el} electrolyser would be used. Huang et al. [24] consider a model predictive control strategy including the waste heat of the electrolyser and conclude that it leads to more cross-sectoral flexibility of their system, but does not quantify the amount of heat recovered. Hückebrink & Bertsch introduce a concept for a neighbourhood where both a fuel cell and electrolyser are installed in a building and their heat is used, reducing the need for a heat pump [25]. No quantification of the amount of heat from the fuel cell and electrolyser is given in this study. Böhm et al. [26] give a conceptual overview of the use of electrolyser waste heat from low-temperature and high-temperature electrolysis in district heating systems. Based on literature research and expert consultation, they conclude that there is possible synergy between power-to-hydrogen and district heating systems and a significant potential for electrolyser waste heat of temperature levels below 100 °C. They state that there is a need for more quantitative research. Overall, we conclude that both the scientific community and industry recognize the potential of electrolyser waste heat, yet both publications and practical examples are scarce. Moreover, there is a lack of detailed system design and analysis for the utilisation of waste heat from electrolysis.

Research goal

Based on the scarce availability of literature and concrete examples of waste heat utilisation from electrolysis, our research question is:

What is the potential of waste heat from electrolyzers and how could it be utilised?

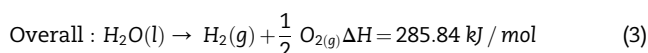
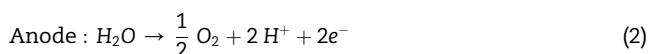
To answer this question, we will elaborate on different designs for the utilisation of electrolyser waste heat based on a 2.5 MW_{el} Polymer Electrolyse Membrane electrolysis (PEM) electrolyser (stack size) in Nieuwegein, the Netherlands. The electrolyser is part of the H-Flex project, which investigates multiple ways in which the electrolyser can be utilised next to hydrogen production, by offering flexibility to the electricity grid as well as waste heat utilisation [27]. The theoretical heat utilisation potential can be 500 kW_{th} of heat at 100% load at the start of the lifetime, based on 80% efficiency (HHV) of the electrolyser stack. How heat can be utilised will differ per use case. We will work out three different use cases that represent possible situations for local system integration. In an ideal case, there is a heat consumer that uses heat at the output temperature level of the electrolyser. As a second case, we include a heat pump for higher-temperature heat. The third use case is the delivery of heat to a local district heating system. We will perform a first-order techno-economic analysis on these three use cases including calculations on how much heat can be utilised and what the

combined system efficiency will be. Furthermore, the potential CO₂ reduction is calculated when electrolyser heat replaces heat from fossil sources. Finally, the costs of heat recovery and transportation are calculated to get a first idea of the feasibility of heat recovery in general and specifically for these three cases.

Methodology

Design of a PEM electrolyser with heat utilisation

In this publication, we focus on a 2.5 MW PEM electrolyser installation in Nieuwegein [27], although our method could potentially be applied to other electrolyser capacities as well. In water electrolysis, water is converted via an electrochemical process with two electrodes into hydrogen and oxygen. The chemical reactions in a PEM electrolyser are given in Eqs (1)–(3), with a change in enthalpy ΔH of 285.84 kJ/mol, which is the energy required to drive the reaction.



Heat sources in an electrolyser

Heat is produced in the electrolyser stack due to the irreversibility of the chemical reactions happening and the ohmic resistance of the cell. The electrolysis reaction can occur without consumption or production of heat, at the so-called thermoneutral voltage. However, at this potential, the reaction rate is too low, so there is almost no hydrogen production. Therefore, an overvoltage is applied to the cells, which increases the reaction rate and makes the electrolysis reaction exothermic, thus heat is released. The total amount of heat produced (Q_{produced} , in Watt) is the cell current (I in ampere) times the difference between the operating voltage ($U_{\text{operating}}$ in Volt) and the thermoneutral voltage ($U_{\text{thermoneutral}}$, in Volt) is given in Eq (4).

$$Q_{\text{produced}} = I \cdot (U_{\text{operating}} - U_{\text{thermoneutral}}) \quad (4)$$

In some cases, the released heat is in balance with the heat consumption for the evaporation of water in the stack, but otherwise, this heat needs to be removed from the electrolysis stack to maintain the cell temperature and prevent overheating. Heat can be extracted from the stack from three different sources in a PEM electrolyser [28,29]; from the oxygen stream, the hydrogen stream and the water recirculation loop. Both the oxygen and hydrogen flow contain some water vapour after leaving the stack from which heat can be extracted.

Based on the design of Mancera et al. [28], the one GigaWatt electrolyser project [20] and information from electrolyser manufacturers, Fig. 1 shows a simplified cooling system of an electrolyser. Heat is extracted from the recirculating water

that is separated from the hydrogen/water stream by the gas-liquid separator. The oxygen/water stream flows to an oxygen separation tank which is combined with the deionized (ultra-pure) water recirculation stream, with a heat exchanger on the stream between the oxygen separation tank and the recirculation pump. Excess heat is removed to limit the inlet temperature to the stack if the condensing heat from the oxygen flow exceeds the heat needed to raise the temperature of the demineralized water inlet. Temperature levels for PEM electrolysers are mostly reported in the 50–80 °C range [13,20,29]. We have considered here an average working temperature of the electrolyser of 65 °C, and a cooling circuit with a maximum inlet temperature of 57 °C and a ΔT of 3 °C over the heat exchangers [29].

This is an efficient design where heat is extracted from both the oxygen and (indirectly) the hydrogen stream and directly used to heat the deionized water stream to the electrolyser. If the temperature of the stack is known, then one can calculate the amount of heat necessary to heat the incoming water based on the hydrogen production. According to the thesis of Tiktak [29], this amounts to approximately 5–8% of the total available heat. The excess heat is removed by a dry cooler. In case the excess heat would be used by a third party, the design has to be adapted to make this possible with an extra tie-in on the cooling system. Choosing for and extra tie-in on the cooling system instead of replacing the dry cooler makes the system redundant.

Variance in heat production

Two factors lead to variation in heat production; the efficiency load curve of the electrolyser stack and the degradation process. Firstly, the efficiency is negatively correlated with the load, therefore we use an efficiency curve (Eq (5), visualised in Fig. 2) that varies with the load based on empirical statistics analysis [30], but with efficiency values adapted to recent developments. Eq. (5) gives an electricity consumption of about 49.25 kWh/kg at 75% load or an expected balance of stack efficiency of 80% which is the expected stack efficiency of the PEM electrolysers that are currently available [11,31].

$$E_{\text{electrolyser stack, eff}} (> 10\% \text{ load}) = \frac{\text{HHV}_{\text{H}_2}}{7.8455 \frac{\text{kWh}}{\text{kg}} * \text{Load}_{\text{electrolyser}} + \frac{43.409 \text{kWh}}{\text{kg}}} \cdot 100 \quad (5)$$

With $E_{\text{electrolyser stack, eff}}$ the electrolyser stack efficiency in %, $\text{Load}_{\text{electrolyser}}$ represented as a fraction of full load (i.e. 0.8) and the HHV_{H_2} being 39.4 kWh/kg. Eq. (5) is only valid above 10% load. Below 10% load, the efficiency sharply decreases. In this study, we will only consider electrolyser capacities above 10% load.

Secondly, the ageing and degradation of the electrolyser stack lead to a lower hydrogen production efficiency. Mainly due to the degradation of the stacks, the resistance over the membranes increases and therefore requires a higher overpotential over time. This linear voltage degradation can result in a cell voltage increase. With an 80,000-h lifetime, this would result in a voltage degradation of 1.9 V–2.06–2.22 V [13]. Therefore, the amount of heat production will increase over the lifetime of the project if the hydrogen production rate is

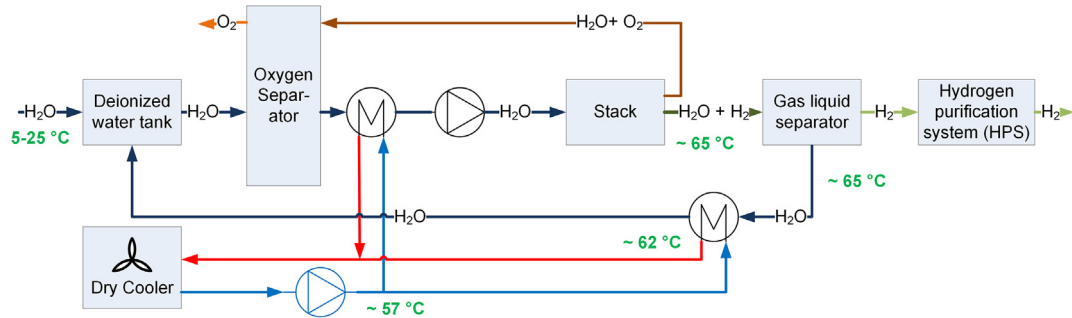


Fig. 1 – Cooling system of an electrolyser stack. In orange/brown the oxygen flow is shown, in (dark)green the hydrogen flow and in dark blue the water flow. The cooling water flow is shown in red and blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

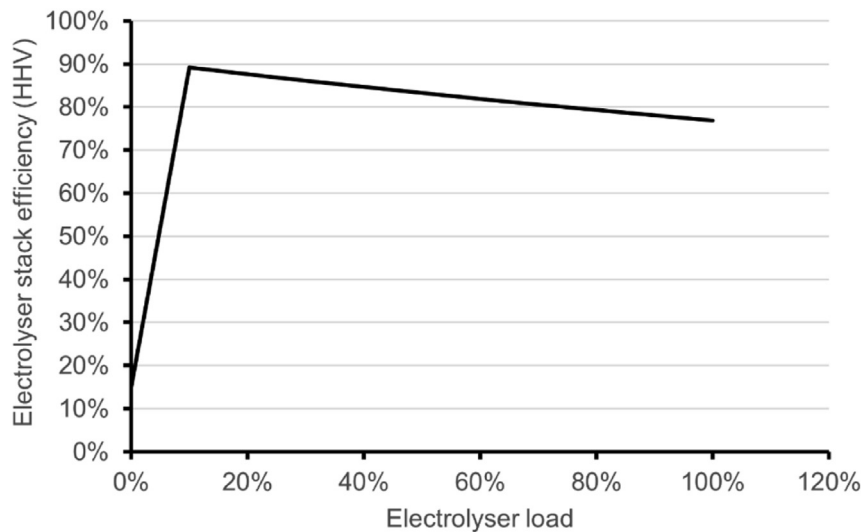


Fig. 2 – Electrolyser balance of stack efficiency in relation to the load, based on Eq (5), [11,30,31].

kept constant. An evaluation of several electrolyser projects in the EU [32] shows that these PEM electrolysers have a degradation of 0.12%/1000 h, which is the FCHJU target for 2030. The final reported value for PEM degradation is 0.19% per 1000 h, which means after a year of full production (8000 h) 1.5% extra energy consumption and 15% extra energy consumption after 10 years [32]. Suppliers on the other hand report <1.0% efficiency degradation [12]. We will adopt the lower-end values for newer generation electrolysers, thus assuming a 1.0% annual efficiency degradation which will lead to a 10% increase in energy consumption after 10 years.

HHV vs LHV

The chemical energy content of a fuel is expressed as the HHV (higher heating value). For hydrogen, this is 39.4 kWh/kg or 141.8 MJ/kg. In addition, there is also a lower heating value (LHV, 33.3 kWh/kg or 120 MJ/kg), which is only relevant when a substance is burned and no heat is recovered from flue gases. When the latent heat from flue gases is recovered, there is no burning process involved, or hydrogen is used as feedstock, it is misleading to use the LHV as it leads to an overestimation of the waste heat potential.

Let's illustrate this with an example of electrolysis (electrochemical conversion, so no burning process is involved), where the LHV would lead to an overestimation of the available heat from electrolysis. If we would assume 80% electrolyser stack efficiency on HHV, this amounts to an electricity consumption of 49.25 kWh/kg hydrogen by the electrolyser. The LHV value of hydrogen is 33.3 kWh/kg or 121 MJ. The LHV stack efficiency would then be $33.3/49.25 * 100 = 68.2\%$. Using the LHV for the calculation of the heat recovery potential of electrolysis would lead to a perceived heat recovery of 31.8%. While at HHV, a stack efficiency of 80% means there is a theoretical heat recovery potential of 20%. By using the LHV, one would thus overestimate the heat recovery potential by more than 50%. So, calculating with the HHV is required to arrive at a univocal energy balance in the electrolyser/fuel cell application. It provides more information on the actual energy content of hydrogen, as well as how much waste heat is available. In this publication, we will therefore consistently use the HHV.

Case studies

The waste heat utilisation of the electrolyser was analysed by three relevant use cases. For all cases, the electrolyser details as

presented in Table 1, based on the 2.5 MW (stack size) installation in Nieuwegein. The hydrogen production pattern was based on the yearly production target, scaled down to an hourly production target. The electrolyser is stimulated to run at 75% of its capacity, on local solar PV as much as possible (based on weather data) or during hours of low electricity prices (based on day-ahead prices). In case the production capacity stayed behind the target (based on the sum of the production), the capacity target was increased to 90%. In hours where no renewable capacity is available, the capacity was limited to 75%. In our analysis, we only considered the stack size for heat recovery, as no heat will be recovered from the auxiliary equipment. The efficiency of the total electrolysis installation is thus lower. The electrolyser worked on average at a 75% load and 80% efficiency (HHV), so the theoretical waste heat potential of the electrolyser stack would be 20% of the energy input. The technical potential for heat recovery was set at 80%, which means 16% of the electrolyser waste heat was recovered. Tiktok found a recovery percentage of 92% [29] with internal cooling in the stack inside the bipolar plates. Our design has cooling outside of the stack, with multiple heat exchangers (see Fig. 1) and more heat losses, therefore we have chosen a value of 80%. Over time, the heat potential increased (see 2.1.2) which at 75% load (1.875 kW) meant 300 kW_{th} of heat in the first year of operation which increased to 330 kW_{th} in year 10. Heat losses during heat transport are based on calculations of a DN80 pipe (90/162 mm) with insulation (class 1) based on heat loss norms for heat pipes [33]. For pump energy, a pump efficiency of 60% is assumed.

Case 1 - local use of heat

If the electrolyser is placed in an area with more industrial applications, there may be a direct consumer for the

available electrolyser heat. In the case of Nieuwegein, this is an industrial-scale laundry washing company, but it could be a different user as well. We considered two options, either the heat was directly utilised at the right temperature, or the temperature was raised by a (high-temperature) heat pump, see Fig. 3. High-temperature heat pumps with temperature levels of up to 100 °C are proven technology [34,35]. In Table 2 the chosen parameters for case 1 are shown. The maximum heat production of the 2.5 MW electrolyser (at 100% load) would be 580 kW_{th} up to 640 kW_{th} after 10 years. Yet, most of the time the electrolyser will work at a lower load (i.e. 75%) and not all heat can be recovered, hence the heat exchanger size was chosen to be 400 kW_{th}. The heat consumer has a larger heat load than the electrolyser offers and has a heat buffer available which means the electrolyser heat can be stored there outside of the working hours of the company. The heat load of the consumer is therefore not modelled in detail, but it is assumed that in general the electrolyser will be able to deliver its heat to the consumer. Yet, the buffer could be full at a certain point, therefore it is not likely that all electrolyser heat can always be utilised. We have assumed that 80% of the available heat can be used by a heat consumer.

Case 2 - low-temperature district heating network

The electrolyser heat could also be used in district heating systems. The temperature level fits best for low-temperature heating systems (4th or 5th Generation [36]), with a temperature level of 40–50 °C/25 °C (supply/return temperature). In an earlier study, we analysed a case of 2000 houses in a neighbourhood at a distance of about 3 km from the electrolyser. In the ‘Power-to-X’ scenario, the heating system consisted of a district heating network (DHN), heat extraction from surface water with a heat pump, seasonal heat storage in a high-temperature aquifer thermal energy storage (HT-ATES) system and a day buffer [37]. Space heating was supplied directly via the DHN, for domestic hot water (tap water) additional booster heat pumps are installed in buildings or houses to provide safe tap water of at least 60 °C to households. Heat demand was varied based on house type and hourly weather data via the degree-day method [38]. We have considered the use of waste heat from an electrolyser there as well, but with a strict assumption that the waste heat could only be delivered to the DHN if it would fulfil the total heat demand in that hour. Then, only 1.5% of the waste heat could be utilised [37]. In the current publication, we took a more flexible approach. Instead of delivering heat directly to the DHN, the electrolyser heat was delivered to the day buffer of the DHN, see Fig. 3 and Table 3 for details. The buffer adds the necessary flexibility so the electrolyser heat could be combined with heat from other sources. We assumed that the electrolyser heat can be added without limitations to the day buffer of the DHN. The day buffer of the DHN was estimated at 600 m³ (21 MWh_{th}) to accommodate 12 h of average heat demand (1.750 kW_{th}), while the electrolyser delivers a maximum of 400 kW_{th} of heat to the buffer in 1 h. In case the buffer is full and there is low heat demand, heat could be stored in the HT-ATES system. Moreover, in the calculation, we took into account the ageing effects of the electrolyser leading to an increase in heat availability over time.

Table 1 – Electrolyser parameters.

Electrolyser parameters	
Size of electrolyser stack	2.5 MW _{e1}
Auxiliary equipment – outside of scope	Energy use is ca. 5% of stack capacity
Production target	300 tonnes/year (capacity factor 0.71)
Hydrogen production efficiency (HHV)	80% at 75% load, see further Eq (5)
Minimum load	10%
Waste heat recovery efficiency [29]	80%
Available heat at 75% load	Year 1: 300 kW _{th} Year 10: 330 kW _{th}
Heat for water flow to stack	0.571 kWh/kg H ₂ produced (ΔT = 55 °C)
Electrolyser working temperature	65 °C
Full load hours of the electrolyser	6250
Cooling water inlet temperature [29]	57 °C
Cooling water outlet temperature [29]	62 °C
Loss over heat exchanger	3 °C
Annual efficiency degradation [13,20,32]	1.0%

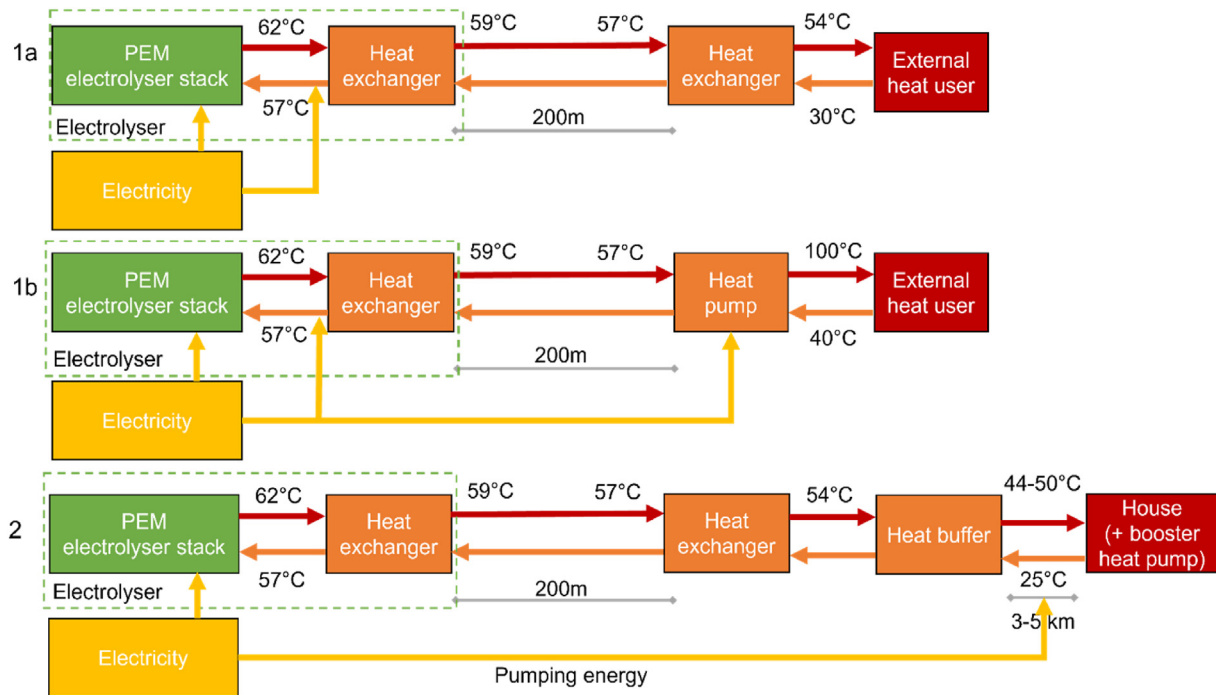


Fig. 3 – Schematic overview of the different cases; 1a – Local use of waste heat at low temperature, 1b – Local use of waste heat at high temperature, 2 – Delivery of waste heat to a low-temperature district heating network. The yellow arrows show which electricity demands are taken into consideration (pumping energy is included). Heat losses during heat transport are based on calculations of a DN80 pipe (90/162 mm) with insulation (class 1) based on heat loss norms for heat pipes [33]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Efficiency & energy balance

The amount of heat utilisation was calculated on an hourly basis with the Power-to-X techno-economic simulation model based on the Power-to-H3 concept introduced in earlier publications [37,43]. Based on varying hourly demand profiles, hourly weather data, and data about conversion and storage technologies (batteries, power-to-heat, power-to-hydrogen, long-term heat storage and hydrogen storage), an hourly energy balance was calculated for multiple years. Because the electrolyser degrades over time while the hydrogen production target is constant, the electricity demand increased over time, as well as the heat production. Both a yearly and 10-year average efficiency of the electrolyser stack (η_{EL} in %) were calculated according to Eq (6).

$$\eta_{EL} = \frac{\sum_i^{N_t} H_{2,produced,i} \cdot HHV_{H_2} + \sum_i^{N_t} E_{heat,used,i}}{\sum_i^{N_t} E_{Elec,i}} \cdot 100\% \quad (6)$$

Table 2 – Case 1 - Direct heat consumer parameters.

	Local consumer parameters
Preferred temperature level – low (1a)	54 °C
Preferred temperature level – high (1b)	100 °C
Distance between production and use	200 m
Heat exchanger capacity	400 kW _{th}
% of overlapping working hours of electrolyser and heat consumer (including buffer)	80%
High-temperature heat pump capacity (1b)	520 kW _{th}
Average COP heat pump (1b, see SI.1)	4.3

Table 3 – Parameters for heat delivery to a district heating network.

	District Heating Network
Preferred temperature level - low	45–60 °C
Total neighbourhood heat demand	55 TJ/y
Distance between production and use	3 km
Distance between waste heat production and day-buffer/HT-ATES	200 m
Size heat exchanger between electrolyser and day buffer	400 kW _{th}
Heat source	Surface water + heat storage (HT-ATES)
Average COP large-scale heat pump [39,40]	5
Day buffer charging/discharging efficiency [41]	90%/100%
Day buffer heat loss per week ^a [42]	2%

^a Data are given for 500 m³ with 2.1% heat loss, as we need a smaller tank here, we increased the heat loss to 3%.

With $H_{2,produced}$ the amount of hydrogen produced in a year (when i.e. $I = 1$ and the number of time steps in hours $N_t = 8760$) or over the total period ($i = 1$ and $n = 87,600$) in kg, HHV_{H_2} the higher heating value of hydrogen (39.4 kWh/kg), $E_{heat,used}$ the amount of useful heat from the electrolyser in kWh over the period i to N_t , and $\sum_i^I E_{Elec}$ the electricity consumption of the electrolyser in kWh over the period i to N_t in hours.

CO₂ emission reduction

If the heat from the electrolyser replaces heat from fossil sources, there is a CO₂ reduction potential. The amount of CO₂ reduction depends on the use case. For case 1, the local use of heat by a third party, we assume that this heat was otherwise produced by natural gas. For the gas boilers, we assumed an HHV efficiency of 90% (η_{boiler}) for the industrial boiler. The CO₂ emission reduction potential in kg for heat $CO_{2,reduction,heat}$ is calculated by Eq (7) for case 1a, and by Eq (8) for case 1 b, including the heat pump electricity consumption. We assumed that the electricity for the heat pump is not certified renewable electricity, and therefore a CO₂ emission factor is added. The reference situation for case 2 (DHN) is a heat pump. For the heat pumps, we calculated the maximum potential for CO₂ emission reduction by using the CO₂ emission factor for the average grid electricity mix in the Netherlands, see Eq. (9). In all cases, the pumping energy necessary for transporting the heat to the heat consumer E_{pump} (in kWh) is taken into account.

$$CO_{2,reduction,heat,case\ 1a} = CO_{2,emissionfactor,gas} \cdot \frac{E_{heat,used}}{\eta_{boiler}} - E_{pump} \quad (7)$$

$$CO_{2,reduction,heat,case\ 1b} = CO_{2,emissionfactor,gas} \cdot \frac{E_{heat,used}}{\eta_{boiler}} + CO_{2,emissionfactor,electricity} \cdot \left(\frac{E_{heat,used}}{COP_{average,heat\ pump}} - E_{pump} \right) \quad (8)$$

$$CO_{2,reduction,heat,case\ 2} = CO_{2,emissionfactor,electricity} \cdot \left(\frac{E_{heat,used}}{COP_{average,heatpump}} - E_{pump} \right) \quad (9)$$

With $COP_{average,heatpump}$ the average COP of the heat pump over the period analysed.

The emission factors ($CO_{2,emissionfactor}$) in kg/kWh are given in Table 4.

Cost calculation

The levelized yearly costs for the heat recovery installation (LC_{total} in €/year) including delivery at the consumer were

Table 4 – CO₂ emission factors for natural gas and renewable electricity, from a CO₂ emission factors database for the Netherlands [44].

	Well-to-wheel CO ₂ emissions
Natural gas – case 1 & case 2	2.085 kg/Nm ³ or 25.7 g/kWh (HHV)
Grid electricity (grid mix The Netherlands)	42.7 g/kWh

calculated by Eq (10) by summing over the number of units N_u . The calculation was made from the perspective of the electrolyser owner delivering heat to a heat consumer. General cost parameters used in the calculations are given in Table 5.

$$LC_{total} = \sum_i^{N_u} LC_i \quad \text{with} \quad (10)$$

$$LC_i = \alpha \cdot CAPEX_i + OM_i + Ecost_i \quad (11)$$

Where LC_i represents the annual levelized costs for a certain system component in (€/unit/year). The $CAPEX_i$ (€/unit) are the capital expenditures for a particular system component i such as the pumps, the pipes or the tie-in, see Table 6 for an overview of the components. More information on the specific components and their costs is given in SI.1. The calculations included the necessary costs for heat recovery at the electrolyser, transportation costs and control technology. It did not include an installation on the consumer side as it is not known how the heat will exactly be integrated into the process of the heat consumer.

The OM_i (€/unit/year) represent the operational expenditures for a particular system component, which are a percentage of the CAPEX costs. $Ecost_i$ (€/unit/year) are the

Table 5 – General cost parameters.

Parameter	Value
OM	2% of CAPEX
Discount rate (r)	5%
Installation factor pipes	1.2
Installation factor for pump, heat exchanger, tie in & electronics	1.4
Electricity costs (for pumps/heat pumps) ^a ($c_{electricity}$)	0.0834 €/kWh
Gas price industrial users ^a (c_{gas})	0.0341 €/kWh
CO ₂ price ^b (c_{CO_2})	60 €/tonne

^a Price of gas and electricity for industrial users in the 10–1000 TJ (gas) or 2000–20,000 MWh (electricity) range, including taxes, excluding VAT, average price 2016–2020. Prices are converted from GJ to kWh [45].

^b The CO₂ price is based on the middle value of the carbon pricing benchmark of the OECD [46], which is a conservative number compared to recent developments [47].

Table 6 – Individual component costs parameters. In SI.1, more information is given on the cost calculations for specific system components.

Component	CAPEX	Lifetime (L, in years)
Tie-in electrolyser	10 k€	15
Electronics, controls & monitoring	40 k€	10
Pumps	see SI.1	15
Pipes ^a	230 €/m (2019)	40
Heat exchanger	1500* $\sqrt{P_{HE}}$ (2017)	20
Heat pump (including installation) ^b – case 1 b	600 €/kWth	20

^a Based on the Polytherm pricelist (2019) [48].

^b The investment is including installation, approx. 50% of costs [49].

electricity costs for a system component i , such as the electricity costs for pumps. The capital recovery factor (α , no unit) is a fraction of the total CAPEX cost. It represents a constant yearly value of depreciation and is calculated based on the project lifetime (L , in years) and the discount rate (r , as a fraction of 1) (Eq (12)). In the cost calculations, we allocated the investments of the heat recovery installation completely to the costs of waste heat. The costs of the electrolyser were however excluded from the costs calculation of the waste heat as the investments for the electrolyser installation are done regardless of the waste heat consumption. Yet, if there is a positive business case for waste heat utilisation, this could lead to a lower hydrogen price.

$$\alpha = \frac{r}{1 - (1 + r)^{-L}} \quad (12)$$

Based on the yearly costs, the levelized costs of heat ($LCOE_{heat}$) in €/MWh were calculated according to Eq (13), with $E_{heat,used}$ the amount of heat utilised by the heat consumer in MWh_{th}/year.

$$LCOE_{heat} = \frac{LC_{total}}{E_{heat,used}} \quad (13)$$

To know if the business case is positive, we calculated the cost savings for the consumer. Then, we calculated the margin between yearly costs and savings. If the margin is positive, it means there is a possibility for a business case as the saved costs for the consumer are higher than the costs for heat delivery. The costs savings for the consumer ($C_{savings}$) in €/year were calculated in euros by using heat from the electrolyser instead of gas (case 1) or electricity (case 2). The costs savings are based on the average amount of $E_{heat,used}$ over the total project lifetime (in kWh/year), see Eq. (14) and (15).

$$C_{savings,case1} = C_{gas} \cdot \frac{E_{heat,used}}{\eta_{boiler}} \quad (14)$$

$$C_{savings,case2} = C_{electricity} \cdot \frac{E_{heat,used}}{COP_{average,heat\ pump}} \quad (15)$$

With c_{gas} the costs of natural gas in €/kWh, η_{boiler} the gas boiler efficiency (presented as a decimal value) of the heat consumer and $C_{electricity}$ the costs of electricity in €/kWh. In case 2 (DHN), the heat would otherwise have been produced by an industrial-scale heat pump. In this case, the amount of heat from the electrolyser was divided by the average COP of the heat pump $COP_{average,heat\ pump}$ over the same time period.

Finally, the margin per case ($C_{Margin,case-j}$ in €/year) between potential savings and costs for the heat, recovery installation was calculated as an outcome according to Eq. (16).

$$C_{Margin,case-j} = C_{savings,case-j} - LC_{total,case-j} \quad (16)$$

Yet, these calculations are highly sensitive to the cost assumptions of gas and electricity prices. Therefore, a sensitivity analysis was done (see section 2.7) to investigate the effects of energy prices on the business case.

Lastly, the effect of CO₂ pricing has been taken into account for every case j as optional cost savings with Eq. (17), with $CO_{2\ savings,case-j}$ the saved costs by CO₂-pricing of CO₂ emission reduction in €/year. c_{CO_2} is the CO₂ price in €/tonne.

$$CO_{2\ savings,case-j} = c_{CO_2} \cdot \frac{CO_{2,red,heat,case-j}}{1000 \left(\frac{kg}{tonne} \right)} \quad (17)$$

The CO₂ cost savings are taken into account in the LCOE as a reduction of the yearly costs according to Eq (18).

$$LCOE_{heat} = \frac{LC_{total} - CO_{2\ savings}}{E_{heat,used}} \quad (18)$$

In the margin, they are added to the other cost savings (Eq (19)).

$$C_{Margin\ with\ CO_2,case-j} = C_{savings,case-j} + CO_{2\ savings,case-j} - LC_{total,case-j} \quad (19)$$

Sensitivity analysis

To assess the effect of changes in variables that are still uncertain, or from which a large effect is expected, a local sensitivity analysis was performed. In Table 7 the parameters chosen for the sensitivity analysis are shown, including the ranges over which the parameters were varied and in which cases they are applied. The annual efficiency degradation, tie-in costs and costs for electronics are relevant and these numbers are hard to verify as there are no installations yet in place. Therefore, we assessed their influence on the LCOE to know how a change in value would affect the LCOE. The overlapping working hours, discount rate, heat pump temperature, the distance between production and use and the electricity price are likely to have a significant influence on the LCOE. Moreover, these values are likely to vary for other use cases, so the sensitivity analysis gives more general insights as well. High-temperature heat pumps with temperature levels above 100 °C are not yet standard products, but there are suppliers available with a technology-readiness level (TLR) of 7–9 for temperatures up to 200 °C [50]. Here we have chosen a maximum of 150 °C, so as to not overestimate the possible temperature lift at the heat consumer side.

The gas price is not taken into account in the LCOE but only in the saved costs by the heat consumer, therefore, we will assess this variable for the margin. As gas prices have recently been shown to be highly sensitive to geopolitical circumstances, we have taken extremely high prices into account. The range for the CO₂ price is chosen to be 0 (no CO₂ pricing) to

Table 7 – Ranges for sensitivity analysis.

	Number	Range	Case
Annual efficiency degradation electrolyser [13,20,32]	1.0%	0.5–2%	1,2
Overlapping working hours	80%	20–100%	1,2
Discount rate	5%	2–10%	1,2
Tie-in costs	10.000 €	±30%	1,2
Electronics	40.000 €	±30%	1,2
Heat pump temperature	100 °C	80–150 °C	1b
Distance between production and use/storage	200 m	100–5000 m	1,2
Electricity price	0.0834 €/kWh	–50/+500%	1,2
Gas price	0.0341 €/kWh	–25/+500%	1
CO ₂ price	60 €/tonne	0-120 €/tonne	1,2

120 €/tonne based on the high range of the carbon pricing benchmark of OECD [46].

Results & discussion

Design for heat recovery from a PEM electrolyser

To utilise the electrolyser heat, we propose a tie-in on the cooling system as shown in Fig.4. The tie-in is an add-on to the

cooling system to create a redundant design independent of the heat consumer. The electrolyser can thus either be cooled through heat consumption by an external heat consumer or by the dry cooler when there is no external heat consumption. We choose deliberately for a tie-in on the cooling system instead of replacing the dry cooler, as this makes the system redundant. Both the hydrogen producer as well as the heat consumer should continue their processes regardless of the delivery or demand of the other to give them the most flexibility.

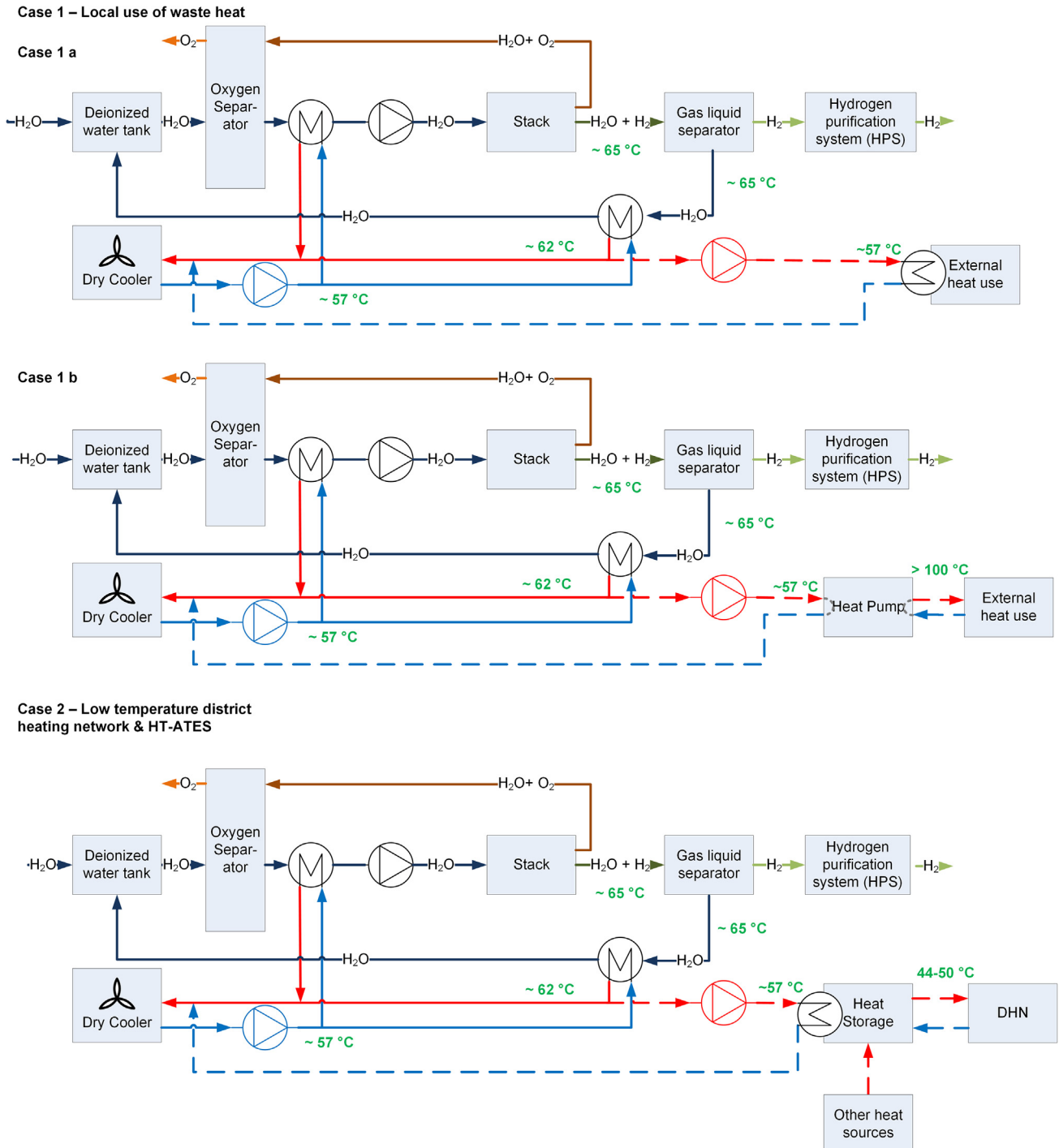


Fig. 4 – Redundant designs for heat recovery from a PEM electrolyser.

Table 8 shows the simulation results for all cases, starting with the reference case. The amount of available heat increases over time (Fig. 7) due to the degradation of the electrolyser stack (for specs see Table 1). The electric resistance increases and thereby the electricity consumption. This extra electricity consumption is not converted to hydrogen, but to heat instead. At the start, about 20% of the electricity input to the stack is converted to heat. After ten years, the total electricity consumption has raised by 10%, so now 30% of the electricity input to the stack is converted to heat, which means the heat production increased by 50%. In the reference case, this heat is not recovered leading to an average (HHV) efficiency of 76% for the electrolyser stack.

Efficiency & energy balance

The reference situation without heat utilisation can be compared to three cases where the electrolyser heat is utilised, overall results are shown in Table 8. The first case has a heat consumer that utilises the electrolyser heat directly with an 80% overlap in electrolyser heat production and heat consumption, thereby reducing gas consumption by a gas boiler. On average 2220 MWh/year of heat can be utilised by the heat consumer in case 1a, which leads to a total system efficiency of 90% (stack + waste heat, HHV based). In the Sankey diagram, all different energy flows are shown including the heat losses and amount of unused heat (see Fig. 5) based on a ten-year average. Pumping energy is about 7 MWh/year, rounded off to 5 MWh and too small to be visible in the Sankey diagram. The increase in heat production and consumption over time and the overall efficiency are shown in Fig. 7. Eventually, almost 59% of the heat that is formed in the electrolyser is utilised by the consumer. Similarly, we find that 14% of the electricity input in the electrolyser is used as heat by a heat consumer. Compared to the base scenario without heat utilisation, the average 10-year efficiency increases by 14% from 76% to 90%. In case 1b, with a heat pump to raise the temperature of the electrolyser heat, 2890 MWh/y of heat is available on average. The amount of heat delivered by the electrolyser stays equal, but electricity has been used to increase the temperature, thereby increasing the ΔT and thus the amount of heat available at the consumer. The efficiency of the electrolysis system in case 1b is thus equal to case 1a and therefore not shown separately.

In case 2, the electrolyser heat is reused in a low-temperature district heating grid (Fig. 6), and the heat from the electrolyser is supplied to the heat buffer of the DHN. The total system efficiency raises to 91% when the heat from the electrolyser is used in a low-temperature DHN. The amount of heat provided increased over the years and accounts on average for 16% of the total heat demand of the neighbourhood (2000 houses) supplied by the DHN. The variation in the percentage of fulfilled heat demand by the electrolyser is caused by a difference in heat demand over the years due to varying climate data (the years considered are 2010–2019). About 15% of the electricity input of the electrolyser is finally used as heat in the DHN. Interesting to note is that the electrolyser waste heat is not used to fill the seasonal heat buffer, but only the day buffer. Thus, the daily heat demand in

Table 8 – Results overview table. Case 1a and 1b have the same total (stack) efficiency, thus these values are only presented once.

Year	Reference case			Case 1 a			Case 1b			Case 2					
	Electricity consumption electrolyser (MWh)	H ₂ production (tonne)	Heat production (MWh)	Base efficiency (HHV)	Heat utilised (MWh)	Total efficiency (stack + heat)	CO ₂ savings (tonne/year)	Electricity consumption heat pump (MWh)	Heat utilised (Electrolyser & heat pump) (MWh)	CO ₂ savings (tonne/year)	Heat utilised (MWh)	Total efficiency (stack + heat)	Heat demand neighbour hood (MWh)	% electro-lyser of total heat demand	CO ₂ savings (tonne/year)
Y1	14,840	299	2270	79%	1820	92%	510	540	2360	430	1900	92%	19,060	10%	150
Y2	15,040	300	2400	79%	1920	91%	540	580	2490	450	2020	92%	14,420	14%	160
Y3	15,240	301	2540	78%	2020	91%	560	610	2630	480	2130	92%	15,730	14%	170
Y4	15,350	301	2660	77%	2100	91%	590	630	2740	500	2230	91%	17,080	13%	180
Y5	15,510	300	2780	76%	2190	90%	610	650	2840	510	2330	91%	12,860	18%	190
Y6	15,670	300	2910	75%	2270	90%	630	680	2950	530	2440	91%	14,040	17%	200
Y7	15,880	301	3050	75%	2360	90%	660	710	3060	560	2530	90%	15,760	16%	205
Y8	16,010	300	3180	74%	2440	89%	680	730	3170	570	2610	90%	14,750	18%	210
Y9	16,170	300	3310	73%	2520	89%	700	760	3280	590	2690	90%	15,270	18%	220
Y10	16,340	300	3450	72%	2600	88%	730	780	3380	610	2780	89%	14,450	19%	225
Average	15,605	300	2855	76%	2220	90%	620	665	2890	525	2365	91%	15,340	16%	190

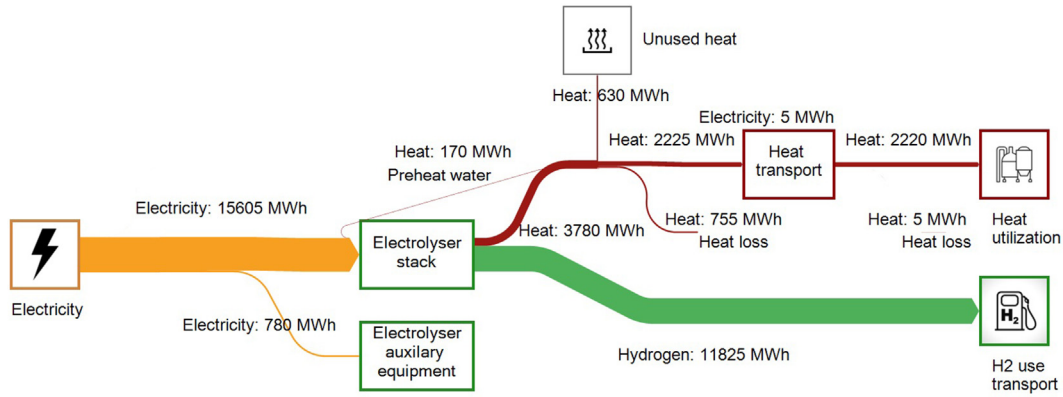


Fig. 5 – Sankey diagram for the energy balance of an electrolyser system with an industrial (local) heat consumer (1a). The 10-year average energy flows are shown.

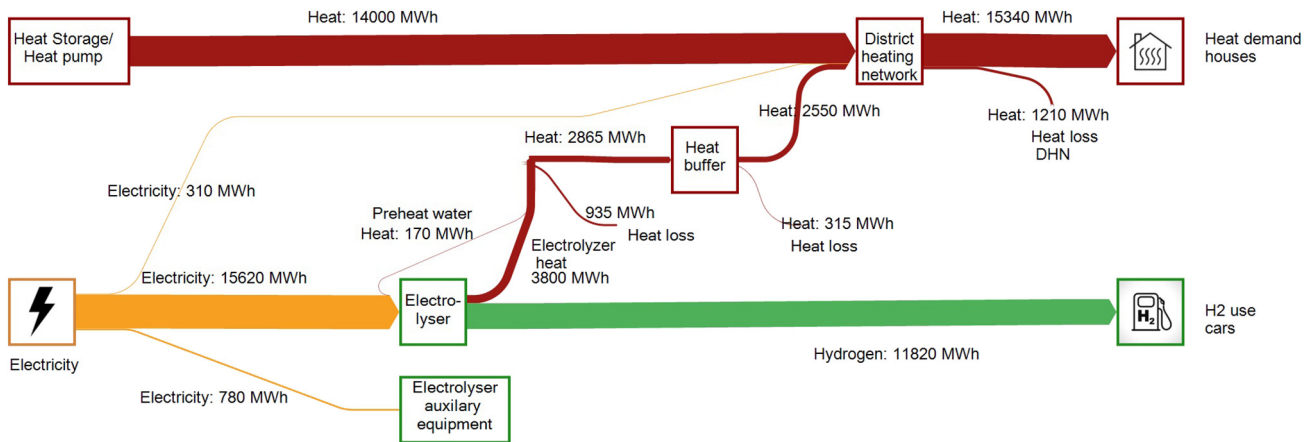


Fig. 6 – Sankey diagram with an average yearly energy balance when electrolyser heat is provided to a DHN (case 2), 10-year average flows are shown.

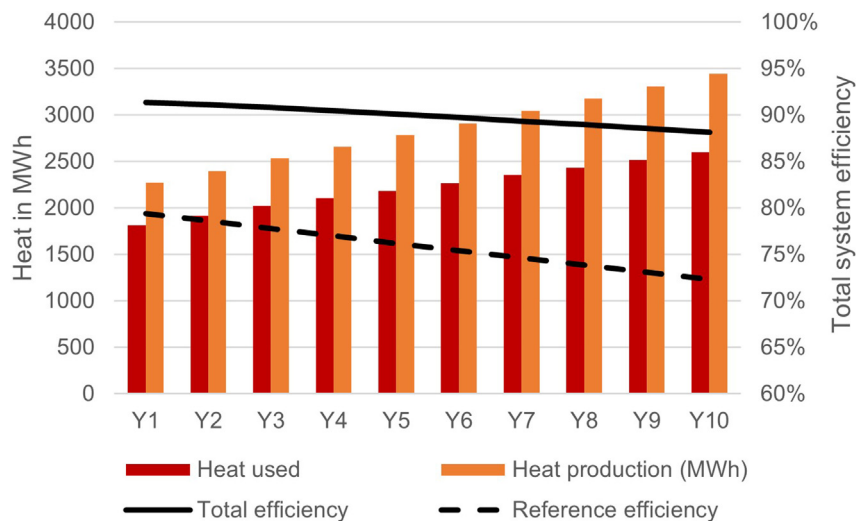


Fig. 7 – Heat production by the electrolyser and heat used by the heat consumer shown over 10 years for case a1 (local heat consumer), including the reference case of the electrolyser (without heat recovery) and the efficiency including heat recovery (total efficiency of stack + waste heat utilisation). Efficiency (HHV) is shown on a secondary axis.

summer is still high enough to take up the daily heat produced by the electrolyser.

CO₂ reduction potential for local heat use (case 1)

The current energy source of the heat consumer is natural gas. When part of its heat demand is fulfilled by the electrolyser heat, on average 620 tonnes of CO₂ are mitigated each year, or 270,000 m³ of natural gas (0.845 kg/Nm³ [51] and a boiler efficiency of 90%). In more general terms, this means 0.28 tonne CO₂ per MWh of waste heat used (MWh_{heat, used}). For the case with a heat pump (1b), the CO₂ emission reduction is 525 tonnes per year or 0.18 tonne CO₂/MWh_{heat, used}. We assumed that the electricity for the heat pump is not certified renewable electricity, which results in more CO₂ emissions for the use of electricity by the heat pump than the savings by switching from natural gas to electricity. Yet, the amount of saved natural gas is higher in this case, about 350,000 m³. If the heat consumer would buy or produce renewable electricity, the CO₂ emission reduction would be higher than in case 1a.

For the DHN network (case 2), the CO₂ emission reduction is on average 190 tonnes/year or 0.08 tonne CO₂/MWh_{heat, used}, compared to when the electricity would have been produced with a heat pump working on an average grid-electricity mix. The heat pump has an average COP of around 5, so only 1/5th of the heat demand is reflected in electricity demand. On the other hand, the CO₂ emission factor for electricity is higher than for gas (due to conversion losses). In summary, the CO₂ reduction will be the highest when the electrolyser heat would be used directly without a heat pump (1a), as long as the heat pump at the heat consumer is not running on green electricity.

Economic results

The results of the economic analysis are shown in Table 9 for all three scenarios. A detailed breakdown of the costs per component including OM costs and energy costs is given in Table S2-S5 of the supplementary information (SI). The yearly costs are similar for cases 1a and 2, but case 1b has factor 5 higher yearly costs, because of the investments in the heat pump. This effect is reflected in the LCOE, which is 36.9€/MWh_{heat}, while case 1a has an LCOE of 8.9 €/MWh_{heat}. In case 2, the LCOE is slightly lower than for 1a with 8.4 €/MWh_{heat}, because more heat can be utilised in this scenario due to the larger heat buffer.

Table 9 – Costs without CO₂-pricing - results for the cases.

	Case 1a	Case 1b	Case 2
Total yearly costs (k€/y)	19.7	106.5	19.7
LCOE _{heat} (heat production costs in euro/MWh)	8.9	36.9	8.4
Saved yearly costs (k€/y)	84.2	109.4	38.3
Margin (k€/y)	64.5	2.9	18.6

When taking the saved yearly costs into account, we note that all scenarios have a positive margin, so a possible business case. Although in the current analysis, only a heat exchanger (or heat pump) has been taken into account at the heat consumer, so there are possible other costs for adaptations at the heat consumer to use the heat that have been neglected. Thus, a margin just above zero for case 1b, makes it uncertain if a business case can be realised. For the heat delivery without a heat pump, the margin is almost 65 k€/year. For case 2 (DHN) the margin is also positive (18.5 k€/year), although it is a factor 3 less than for the industrial heat consumer, while more heat is delivered. Our reference case for the DHN was heat produced with a heat pump that has a COP of 5, and not gas boilers. Therefore, just as with the CO₂ calculations, here we see again the effect of the high COP of the heat pump. The heat pump produces heat with only 0.2 units of electricity for one unit of heat. Hence, the savings in electricity costs in case 2 are less than the gas savings in cases 1a and 1b. How the margin is divided among the stakeholders (electrolyser owner, heat user and possibly others) will finally determine the effect on the heat costs for the heat consumer as well as the hydrogen production costs. If CO₂ pricing is taken into account (Table 10), the LCOE decreases substantially while the margin increases. All margins are now at least 30 k€/year, pointing towards a high possibility for a business case. For direct heat use (case 1a) the LCOE becomes negative. In practice, this means that a company can save more money on CO₂ costs than it would cost to replace natural gas with waste heat, not even including the saved costs of the natural gas itself. Upgrading the heat with a heat pump to 100 °C could also be economically feasible if CO₂ costs are taken into account.

Sensitivity analysis

We have investigated the impact of a change in certain input parameters on the LCOE, in Fig. 8 the results of the sensitivity analysis are presented. Although in the case of Nieuwegein, the distance is known, in other cases of heat utilisation the distance between the electrolyser and heat consumer could deviate considerably. The sensitivity analysis clearly shows that the distance has a large influence on the LCOE, especially with direct heat delivery (case 1a, Fig. 8a) and delivery to a low-temperature DHN (case 2, Fig. 8c). Delivering waste heat over long distances will thus not be feasible. The CO₂ price is

Table 10 – Costs with CO₂ pricing - results for the cases.

	Case 1a	Case 1b	Case 2
Total yearly costs (k€/y)	19.7	106.5	19.7
CO ₂ emissions reduction cost savings (k€/year)	37.2	31.4	11.5
LCOE _{heat} (heat production costs in euro/MWh)	-7.9	26.0	3.5
Saved yearly costs (k€/y)	84.2	109.4	38.3
Margin including CO ₂ emissions reduction cost savings (k€/y)	101.8	34.3	30.0

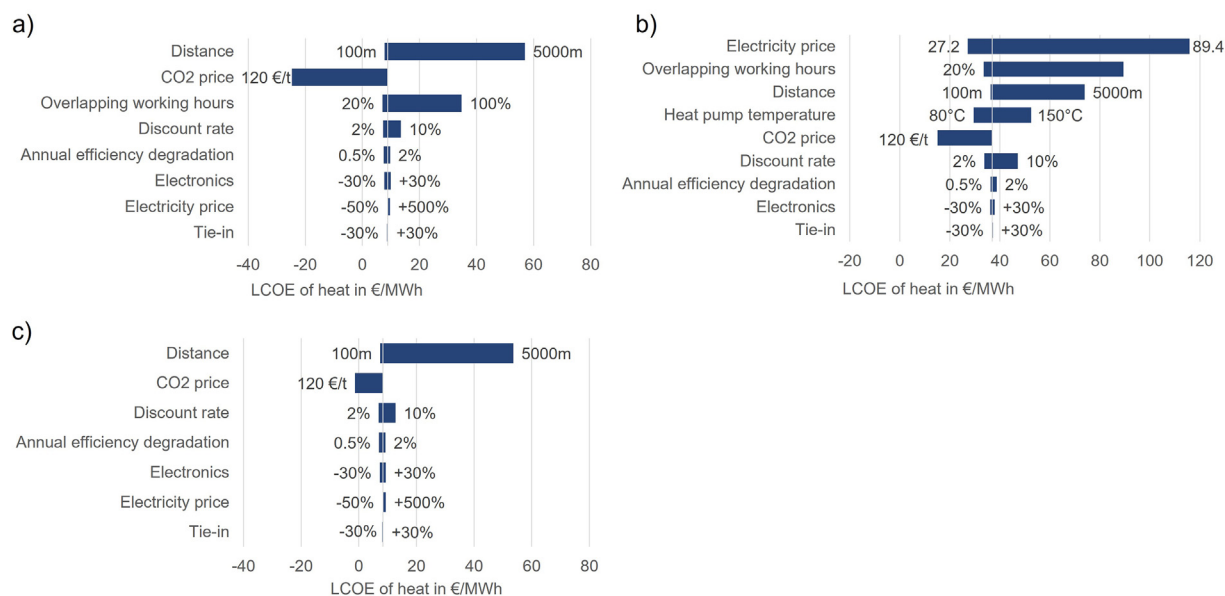


Fig. 8 – Results of the sensitivity analysis with tornado diagrams of case 1a (a), case 1b (b) and case 2 (c).

the second most important factor in case 1a and 2 that influences the LCOE, yet the adoption of a CO₂ price would positively influence the business case. When a heat pump is installed (case 1b, Fig. 8b), the electricity prices are the most important factor in determining the LCOE. Long-term contracts for electricity prices will give more certainty in the business case. Another option would be to have dedicated renewable production capacity for the heat pump electricity demand. In cases 1a and 2 (a&c), the electricity price is not such a major factor as electricity is only used for pumping the heat around. Besides the distance, the percentage of overlapping working hours shows to be sensitive as well in the case of delivery to a heat consumer (a&b). For case 1b (b), the LCOE furthermore proves to be sensitive to the heat pump temperature and to the CO₂ price as well. Of slightly less importance in all cases is the discount rate chosen.

The exact percentage of annual efficiency degradation, costs for electronics and tie-in in the electrolyser for heat recovery have a high degree of uncertainty still. Yet, the sensitivity analysis shows that their impact on the LCOE remains small. So, although we need more exact information about these parameters, they are not the most essential while developing a business case for heat recovery from electrolysis. Of these three parameters, the annual efficiency degradation has the largest impact on the LCOE.

As the distance shows to be an important factor in the business case of electrolyser heat, Fig. 9a shows more precisely how the distance influences the margin between costs and benefits (saved costs) for the consumer. If heat is delivered directly to the consumer (1a) the maximum feasible distance is around 3 km. For heat delivery to the DHN (2), this distance is 1 km. For heat delivery with the heat pump (1b), the margin is too small resulting in a negative business case above 200 m distance. These values are valid for an electrolyser size of 2.5 MW_{el}, with larger installations, the more heat is

transported, the lower the investment costs per unit of heat will be, as well as smaller heat losses [52,53].

The sensitivity of the gas price is shown with respect to the margin in Fig. 9b. We have assumed a relatively low gas price in the analysis based on historical data, but the war in Ukraine has caused a tremendous increase in gas prices. It is uncertain how the gas price will develop in the coming years, yet it is more likely to stay high. As expected, high gas prices will have a (highly) positive influence on the margin. In the analysis, the gas price and electricity price are changed by the same percentage, as the gas price will influence the electricity price. Because of the electricity consumption of the heat pump in case 1b, it has a lower margin than case 1a over the total range.

Discussion

General reflections and limitations of the study

The results presented in this study are subjected to certain limitations. The lack of literature and concrete examples of heat recovery from electrolysis, as mentioned in the introduction as a reason to perform this study, is also its limitation. We have given insight into the feasibility of using electrolyser waste heat, but we have had to make assumptions as there is no available data. Therefore, we have included a sensitivity analysis (see also 4.1.3), which has shown that uncertain parameters such as the actual efficiency degradation and exact prices for the tie-in and electronics have a limited influence on the business case. Thus, the results obtained are reliable enough regardless of the uncertainties in these parameters.

Another general comment is that every case will have its specific circumstances. The BOP will be different per supplier and will also depend on the engineering. Yet, the design we

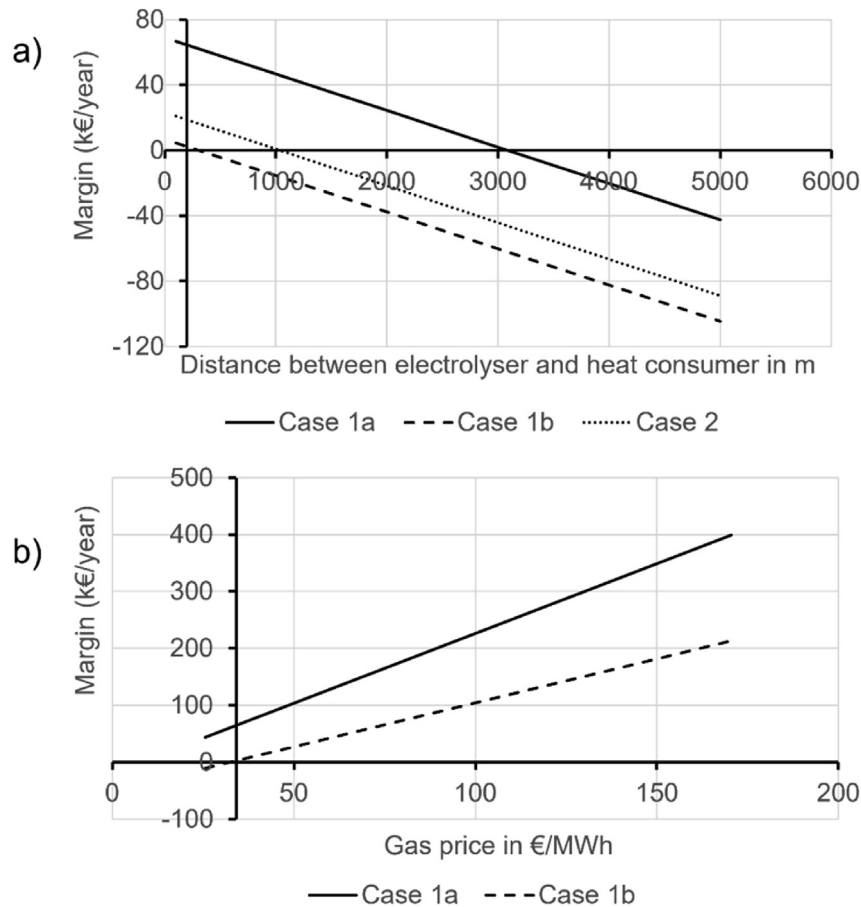


Fig. 9 – Sensitivity of a) distance between electrolyser and heat consumer and b) gas price on the margin between costs and saved costs at the heat consumer. The y-axis crossing shows the currently chosen value in the analysis. In b) the gas price is shown on the x-axis, but in this analysis, the electricity price is changed simultaneously with the same percentage for a fair comparison.

propose gives both possibilities to reuse heat within the electrolyser as well as supply heat to an external consumer, and could thus be helpful as a starting point for other studies. Regarding the economics, we should note that we have worked with a stable hydrogen production rate for over ten years. New electrolyser projects are not likely to start producing at full capacity from year one. Over time the production capacity will increase, building up to full capacity, thus in the first circa five years probably less heat will be delivered (and less CO₂ reduced). More precise calculations for specific cases should be done to determine the exact effect on the business case. For the cases presented in this paper, it means that the LCOE and margins presented should be seen as a first-order approximation. A highly feasible case (1a) will probably stay feasible even with these start-up effects taken into account. Furthermore, the decision for a heat consumer to replace natural gas with waste heat does not have to be of a purely economic nature, or more indirectly. A ‘green’ profile can enhance the reputation of a company, leading to a better position in the market and eventually to higher financial performance [54].

Furthermore, in this study, we only considered the costs to extract and deliver waste heat, independent from the hydrogen production costs. Eventually, both ‘products’

(hydrogen and heat) are connected for the owner of the electrolyser, and thus the hydrogen production costs could play a role in the business case of the waste heat. For example, in the results (see 3.5), we have shown that high gas prices will increase the margin between the costs of waste heat delivery and saved costs for the consumer. But, high gas and (therefore) electricity prices will affect the business case for green hydrogen and may lead to the hydrogen producer asking a higher price for the waste heat to compensate for higher electricity costs. This is even the case for green hydrogen produced with a solar or wind-based power purchase agreement (PPA), as those PPA prices are affected by the wholesale market including fossil-based electricity sources [55].

Ancillary services and hot standby mode

Electrolysers can fulfil ancillary services [56,57]. This would mean that the electrolyser would quickly (within seconds) reduce or increase its capacity [58]. We have not considered the impact of this mode of operation in this study. Yet, although the ancillary services can have a positive impact on the business case of the electrolyser [59], the total amount of hydrogen (and thus heat) produced will not vary significantly when production targets have to be met. We thus expect that

the influence on the amount of heat produced will not deviate more than a few per cent.

When ancillary services are part of the business case for an electrolyser, it either has to operate at the time when it is bidding in for the balancing markets, or it has to stay in hot standby mode so it can react quickly [58]. In the hot standby mode, the electrolyser will consume electricity, about 3% of its nominal power [58,60]. Part of the electricity consumption for the hot standby mode is used to keep the electrolyser warm and could maybe be supplied by its own waste heat. With the assumption of 50% of the hot standby energy use being fulfilled by waste heat, we calculated that about 28 MWh/year of heat could be used within the electrolyser itself (for case 1a). This is a small potential but could be interesting in combination with other waste heat uses, so the costs for a heat buffer could be shared.

Efficiency raise of electrolyser stack

We have seen an efficiency raise of the total PEM electrolyser stack from 76% to 90/91% (HHV based) when the electrolyser heat is taken into account, thus a 14–15% efficiency increase in total. Bilbao mentions a 13% potential efficiency increase for an alkaline electrolyser if heat would be recovered [21]. In Buttler & Spliethoff two projects are mentioned that increase their efficiency including heat utilisation to 95% and 86%. Frank et al. [23] show a range of options for a 1 MW Power-to-Gas plant with an alkaline electrolyser including different parts of the electrolyser design to recover heat from. With the stack, electrolyte circuit, product gas treatment and water supply taken into account, they calculated an efficiency gain of external heat use from circa 78% to 97% with a 60 °C operating temperature. For the overall electrolysis system, the efficiency gain would be 17.6% (from 72.8 to 90.4%). Jonsson & Miljanovic found an overall system efficiency for a PEM electrolyser including heat recovery of 94.7%, an 18% increase from their reference scenario if all waste heat can be utilised (at 80 °C working temperature) [61]. So although most available data are for alkaline electrolysis, our findings for the efficiency raise are comparable with the literature. Moreover, we have not yet considered the possible reduction in energy use of the dry coolers of the electrolyser system, which could lead to lower energy use of the electrolysis process. The heat utilisation from the electrolyser can thus clearly increase the overall system efficiency of the electrolysis process. When applied, the electrolyser will be a hydrogen as well as heat producer and will help to make even better use of available renewable energy.

Comparison to other (waste) heat costs

We have calculated the LCOE of waste heat from the electrolyser for different temperature levels and applications. We have concluded that there is a high possibility for a positive business case for direct heat delivery to a heat consumer and heat delivery to a low-temperature DHN (40–60 °C). Moreover, it is relevant to compare our results with other sources of (waste) heat, especially for district heating networks. Table 11 shows a comparison of heat production costs per MWh, without the distribution costs. For low-temperature waste-

Table 11 – Heat source cost (LCOE) comparison.

Heat source	Costs (LCOE) in €/MWh _{heat}
Waste heat electrolyser to DHN – this publication without heat pump (54 °C)	8.4–8.9
Waste heat electrolyser to DHN – this publication with heat pump (100 °C)	36.9
Heat from surface water with a heat pump (45 °C)	55.4–73.4
Industrial waste heat sources (<35 °C, with heat pump to 75 °C) [62]	36–46
Industrial waste heat sources (75–100 °C) [62]	6–10
Geothermal energy at low temperature (50 °C, depth 500–1000 m, including heat pump) [63]	54–65

heat sources below 40 °C, a heat pump is necessary to increase the temperature, which is reflected in the LCOE. The LCOE of electrolyser heat without a heat pump including a short transport distance (8.4–8.9 €/MWh_{heat}) is well below this range (36–73.4 €/MWh_{heat}). Even with a heat pump to increase the temperature, the costs for electrolyser heat are at the lower end of the range with 36.9 €/MWh_{heat}, while the temperature is higher (100 °C). Electrolyser heat could compete as well with higher temperature waste heat sources, but only at a lower temperature level (at 54 °C), so without a heat pump. Overall, these data show that the waste heat from the electrolyser may compete with other industrial waste heat sources depending on the necessary temperature level, and is likely to be cheaper than lower-temperature heat sources.

Other sources that specifically discuss the business case of heat from electrolysers are scarce. Jonsson & Miljanovic found costs of 20 €/MWh_{th} for waste heat utilisation from a PEM electrolyser of 100 MW, with a heat pump raising the temperature to 120 °C [61]. Without the heat pump (so only a heat exchanger), they calculated 1.65 €/MWh_{th}, yet costs for a tie-in and controls have not been taken into account here so these values seem to be an underestimation. Our results show higher costs because more cost components have been taken into account, but Jonsson & Miljanovic [61] show that with larger electrolyser installations, the costs will probably decrease.

Theoretical potential of electrolyser heat

In our case study, we have considered a 2.5 MW electrolyser that could part of a local hydrogen cluster. Local green hydrogen production is expected to grow exponentially in the coming years and decades, within the current plans of for example the EU and its RePowerEU programme [5]. The waste heat from the electrolyser could thus potentially become a waste heat source for district heating. Yet, there are many other possible waste heat sources available, so what would be the share of heat from hydrogen production compared to the total available waste heat potential? We will focus on Europe to answer this question. Fleiter et al. [64] calculated that there

is a potential of 425 PJ (118 TWh_{th}) of heat at 95 °C available within Europe, 503 PJ (140 TWh_{th}) at 55 °C and 960 PJ (267 TWh_{th}) with a temperature of 25 °C. Of this 425 PJ at 95 °C, 151 PJ could be utilised within a 10 km range from the heat source in existing district heating grids and almost all of the heat (415 PJ – 115 TWh_{th}) would be useable considering the expected increase of district heating grids.

How does the amount of heat from electrolyser installations relate to this? The EU target is 10 million tonnes of domestic hydrogen production in 2030 [5]. According to van Wijk et al. [65], about 5% of this hydrogen production capacity will be decentral capacity, and 15% will be produced directly at the industry/point of use itself (captive market). The other 80% of green hydrogen production will be large centralized production, at places with good solar and wind resources, probably further away from (heat) consumers. For the captive market and decentral capacity, it is most likely that there is a useful purpose for the waste heat. Thus, if we assume that about 20% of the expected hydrogen production capacity could lead to useful heat production, this corresponds to 2 million tonnes of hydrogen production. With 80% efficiency of the electrolysis (HHV based), this amounts to 98.5 TWh of electricity input. We have calculated that 14% of the electricity input will be used as heat (see section 3.2), so around 13.8 TWh_{th} of electrolyser heat could be added to the total waste heat potential within the EU. This is about 10% of the waste heat potential at 55 °C, a modest, but not insignificant amount of heat. Böhm et al. calculated a 56–84 TWh_{th} (theoretical) potential of thermal energy from hydrogen supply based on the European hydrogen strategy [26], but haven't corrected for hydrogen production in proximity of heat demand. Our calculations are thus probably closer to the technical potential of hydrogen waste heat.

Recommendations for future research

We have obtained insights on how heat from electrolysers could (technically) be recovered as well as an energetic, environmental (CO₂-reduction) and economic potential. Yet, the adoption of heat utilisation from electrolysers is still small so there is a lack of real data from actual projects. Validation of results is now merely done with other theoretical studies, so for future research, validation with practical data would be very valuable. These data could also give more insight into a stepwise increasing hydrogen (and thus heat) production pattern during the first period of operation. Furthermore, other use cases can be evaluated. Some interesting other use cases could be a wastewater treatment plant with local hydrogen production (where oxygen could be utilised in aeration) or a hydrogen fuelling station with local hydrogen production and use of the waste heat for car washing. Another possibility is to use the waste heat for thermal desalination, thereby producing deionized water at lower costs than with reversed osmosis technology [66].

If a heat pump is necessary to increase the waste heat temperature, more research could be done on how local renewable capacity would influence the business case in terms of electricity prices. Lastly, the results could be further refined by taking into account the business case of hydrogen

as well, including different modes of operation of the electrolyser as well as ancillary services. Furthermore, there is the possibility to use part of the waste heat for the hot standby mode of the electrolyser, combined with another heat consumer.

Conclusions

We have shown that it is possible to make a redundant system design to utilise heat from an electrolyser without compromising on the hydrogen production process. The utilisation and valorisation of heat from electrolysers could lead to.

- *Higher system efficiency* - An increase in combined electrolyser system (stack + waste heat) efficiency from 76% to 90–91%, based on HHV. Furthermore, 14–15% of the electricity input to the electrolyser stack can be utilised as heat by a heat consumer, depending on the use case. For the district heating system (case 2), we have shown that the electrolyser (waste) heat can fulfil around 16% of the total heat demand of the neighbourhood.
- *CO₂ savings* - Direct heat use (case 1a) leads to 0.28 tonne CO₂/MWh_{heat, used}. With a heat pump (case 1b) to increase the heat temperature, the savings would be 0.18 tonne CO₂/MWh_{heat, used} if the heat pump works on an average electricity grid mix. Delivery of heat to a low-temperature DHN leads to 0.08 tonne CO₂/MWh_{heat, used}, compared to heat produced directly by a heat pump working on an average electricity grid mix.
- *Economic feasibility* - When a heat pump is necessary to increase the waste heat temperature, it will be harder to realise a business case (LCOE 36.9 €/MWh_{heat, used}) than without a heat pump (8.9 €/MWh_{heat, used}). If CO₂-pricing of 60 €/tonne would be taken into account, the business case is likely to be positive in all cases (LCOE of –7.9 - 26 €/MWh_{heat, used}). The sensitivity analysis has shown that the transport distance of heat is an important factor in determining the feasibility of electrolyser heat utilisation. The feasible distance varies per use case between 1 and 3 km. Compared to other waste heat sources, the LCOE of the electrolyser heat (8.4–36.9 €/MWh_{heat, used}) falls within or below the range of lower-temperature heat sources. Without a heat pump, the LCOE (8.4–8.9 €/MWh_{heat, used}) also falls within the range of other high-temperature industrial heat sources.

Overall, we show that electrolyser heat can both from an environmental and economic point of view be a valuable addition to a local integrated energy system, and further enhance local system optimisation by integrating both hydrogen and heat production.

Data

Raw data of the modelling results from the cases described in the publication can be accessed via DOI: <https://doi.org/10.4121/21666152>.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2023.03.374>.

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