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A combined heat and green hydrogen (CHH) generator integrated with a heat network

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ABSTRACT

Combined heat and power (CHP) systems offer high energy efficiencies as they utilise both the electricity generated and any excess heat by co-suppling to local consumers. This work presents the potential of a combined heat and hydrogen (CHH) system, a solution where Proton exchange membrane (PEM) electrolysis systems producing hydrogen at 60–70% efficiency also co-supply the excess heat to local heat networks. This work investigates the method of capture and utilisation of the excess heat from electrolysis. The analysed system was able to capture 312 kW of thermal energy per MW of electricity and can deliver it as heated water at either 75 °C or 45 °C this appropriate for existing district heat networks and lower temperature heat networks respectively. This yields an overall CHH system efficiency of 94.6%. An economic analysis was conducted based on income generated through revenue sales of both hydrogen and heat, which resulted in a significant reduction in the Levelized Cost of Hydrogen.

1. Introduction

To meet net-zero emissions targets [1], the UK aims to increase the utilization of Renewable Energy Sources (RES). Although the cost of renewable energy has seen rapid reductions in recent years [2], the intermittent nature of RES remains a significant barrier to further growth. There is a growing opportunity around Power-to-Gas (PtG) technology, a solution which utilises the transformation of intermittent electricity into hydrogen gas (H_2) and thus as an energy store [3]. Fundamentally, when renewable electricity generation is abundant, excess electricity is converted to hydrogen. Hydrogen can be utilised across transport, industry, or heat, however, should electricity demand transcend supply, hydrogen can be converted back to electricity. Current figures estimate an excess renewable electricity generation of over 45GWh per year [4] equating to roughly £67million of lost revenue but also useful energy [5]. The UK is one of the largest wind markets with offshore wind meeting up to 40% of electricity demand [6]. The estimated installed wind capacity of 40GW by 2040 [7] and further deployment of other RES presents intermittency challenges and hence periods of imbalanced electricity supply and demand.

Proton Exchange Membrane (PEM) electrolysis is one of the most promising technologies for PtG [8] and with water as the only feedstock, PEM electrolysis is able to transform renewable electricity into hydrogen without direct carbon emissions. System efficiencies range from 60 to 80% with the remaining energy being converted to heat and vented to the environment.

Whilst the value of hydrogen is often presented in terms of its wider energy system benefits at a national or regional scale, this article focuses on its potential wider value and opportunities at a local scale. Local sources of hydrogen from electrolysis are of interest as they can avoid the need for gas distribution by utilising off-peak electricity network capacity. Locally hydrogen can be used for transport fuels, industrial processes, heat or energy storage etc. Thus, this article analyses the potential opportunity of generating hydrogen through PEM electrolysis whilst harnessing excess heat produced and integrating it into district heating networks (DHNs) for domestic use. It brings forward the concept of a combined heat and green hydrogen (CHH) generator system – analogous with the widely deployed combined heat and power (CHP) generator system. It explores a comprehensive thermodynamic model of a PEM electrolyser with a cooling system to extract excess heat. The

Abbreviations: CAPEX, Capital Expenditure; CHH, Combined Heat and Hydrogen; CHP, Combined heat and power; DHN, District Heat Network; kWh, Kilo Watt Hour; LCOH, Levelized Cost of Hydrogen; MWh, Mega Watt Hour; OPEX, Operating Expenditure; PEM, Proton Exchange Membrane; PtG, Power-to-Gas; RES, Renewable Energy Source.

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developed model is used to estimate the quantity of heat and hydrogen generated by PEM electrolysis along with the accompanying revenue streams. Finally, the model was scaled to provide an assessment on the deployment of CHH generators for real-world applications. Fig. 1 presents a visual representation of the proposed symbiotic CHH system as part of a net-zero energy system.

2. Hydrogen as an energy vector

Hydrogen, the most abundant element in the universe has the highest gravimetric energy density of all known substances [9] and produces zero carbon emissions at the point of end use. With natural gas reserves likely to be depleted within the next 60 years, a hydrogen economy could provide a clean and flexible solution to many growing world problems [10].

2.1. Hydrogen production methods

Several hydrogen production methods currently exist with auto-thermal reforming of natural gas being by far the predominant method for large scale generation [8]. This method, coupled with Carbon Capture, Use and Storage (CCUS) is likely to make up most of the 'blue' hydrogen production in the near future. However, steam reforming of methane is dependent on natural gas and even with CCUS reducing carbon emissions, the depleting fossil fuel supply and increasing cost of natural gas means that this method of hydrogen production is unsustainable for long term use.

Water electrolysis is the leading method of producing 'green' hydrogen with zero carbon emissions. Electrolysis is forecast to be instrumental in the conversion of excess electrical energy from RES into hydrogen. With the drive for renewable energy, hydrogen production by electrolysis is likely to rise above 22% by 2050 [11]. Although this technology has huge future potential, as a result of a high CAPEX (Capital expenditure) electrolysers, only 4% of global hydrogen is currently produced from splitting water [12].

2.2. Proton exchange membrane electrolysis

There are several methods of electrolysis currently in active research, the three most significant being: Proton Exchange Membrane (PEM), Alkaline (AEL) and Solid Oxide (SOEC) electrolysis. This project focuses on PEM electrolysis as it is widely considered the most promising method for the future of PtG [8]. Also, notable advantages of PEM electrolysis include: a compact design, fast cold start time (3x faster than AEL and SOEC), fast system response (ms), wide operating range (0–200%), high current density (greater than $2Acm^{-2}$), high proton conductivity ($0.1 \pm 0.02Scm^{-1}$), the ability to operate at low temperature (60–80 °C) and high output pressure (approximately 80 bar) [12].

Existing PEM electrolyser designs see up to 40% of input energy vented to the atmosphere as heat [12]. With as much as 700 GW of electrolysis installed by 2030 or 1700 GW by 2050 [13], the capture and use of this excess heat presents a significant opportunity. A schematic containing a PEM electrolyser with a representative cooling system is presented in Fig. 2.

2.3. Heat delivery

2.3.1. Heat networks

District heating networks (DHNs) are a possible sink for the heat produced by PEM electrolysis. Heat networks typically move hot water or steam and would be considered as fuel agnostic [14] and can therefore be adapted to switch to operate with different primary energy sources. As more electrolysers are deployed, PEM electrolyser excess heat is a potential heat source for current and future DHNs. Ambitious estimates suggest that heat networks could supply as much as 43% of the UK's heat demand by 2050 [15] and low temperature heat networks operating at 15–25 °C mark the future of this technology [16].

2.3.2. Hydrogen for heat

Currently, 85% of UK domestic heat is provided through the

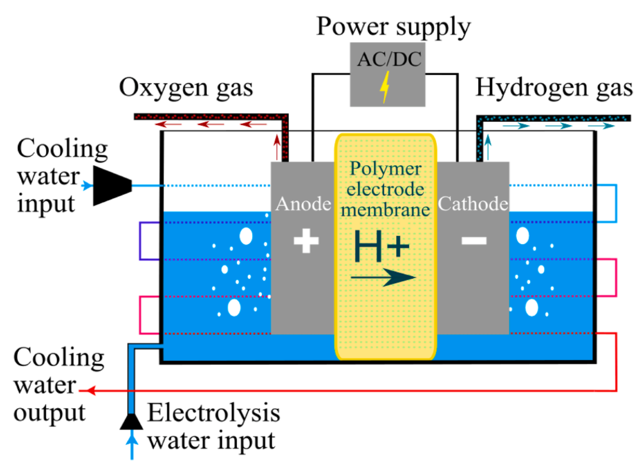

Fig. 2. PEM electrolyser with representative cooling circuit.

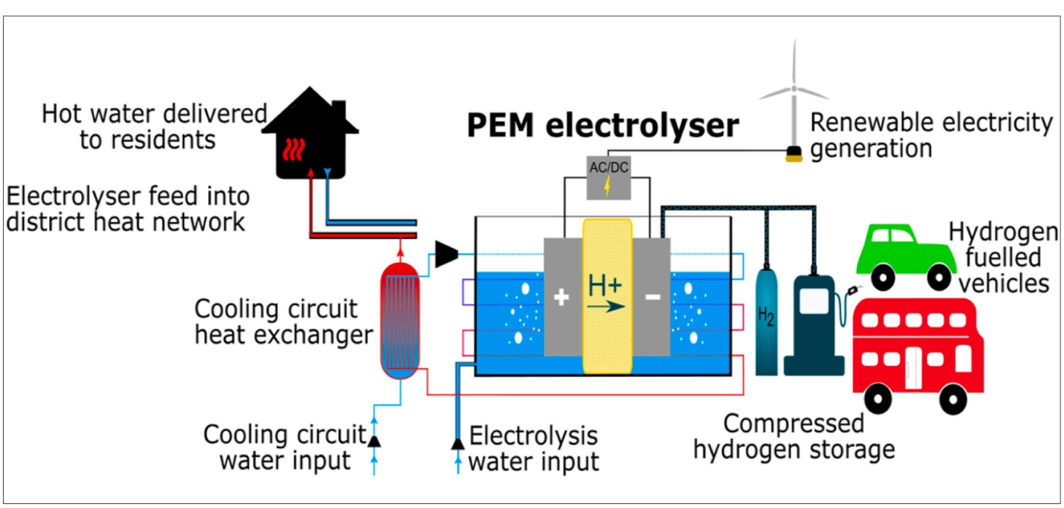

Fig. 1. Complete combined heat and hydrogen (CHH) system embedded into a net-zero compliant energy system.

combustion of methane delivered through the natural gas network [7]. The replacement of natural gas with hydrogen is an active area of research and it is expected that there will be more than 16million hydrogen boilers in operation by 2050 [17]. HyDeploy [18] successfully blends hydrogen with natural gas at concentrations of 20% within the Keele University grid network and aims to replicate this at a larger scale in Winlaton. The h21 Leeds City Gate Report [19] concluded that the conversion of the natural gas grid to hydrogen is feasible and would require minimal infrastructure compared to other future heating options. Leeds will begin the conversion of 3.7million homes to hydrogen gas in 2028.

The use of hydrogen for heat has been thoroughly investigated before and therefore, the focus of this research is on the more novel concept of integrating electrolyser excess heat into district heat networks.

3. Summary of relevant literature

A study on *Heat management of PEM Electrolysis* [20] provides insight into the heat produced by a 290 kW electrolyser and models a dedicated cooling system to extract excess heat. The model was developed in MATLAB and found that 92% of all the heat produced from the stack could be extracted through the cooling circuit. The resulting efficiency was 14% higher than the default electrolyser. The researchers at TU Delft postulated uses for this excess heat however, no further analysis was conducted into these applications.

The Power to Hydrogen and Heat (P2HH) analysis conducted by Li [21] explores the use of electrolysers to deliver both hydrogen and heat. A cooling system increased electrolyser efficiency by 15% and produced 60–80 °C output water. Li notes the ability to utilize this heat in district heat networks. A manufacturing cost analysis for PEM electrolysers [22] explores how mass manufacturing of PEM systems can reduce capital costs. A key finding was the reduction in full system costs from £400/kW to as little as £190/kW based on production volumes increasing from 10 to 1,000 units per year.

Studies on the use of Aspen Plus for electrolyser development enabled validation of results. Both Botsis [23] and Sanchez [24] developed models of small electrolysers, however, use of electrolyser excess heat was not of interest in their work.

An important challenge for PtG technology is optimizing the duration of time that electrolysers operate for. Simonis and Newborough [4] investigated the conversion of excess electricity into hydrogen, with the produced hydrogen being mixed into natural gas distribution networks. Building on these ideas, the present work analyses how any heat produced during operation can be utilised.

4. Novelty of this work

It is clear from literature that exploring the valorisation of heat produced by PEM electrolysis is often overlooked. Although some research has been conducted into the use of this heat to drive the hydrogen compression process [25], the possible integration of excess heat into DHNs has not been considered in detail previously. This work presents both a technical and economic assessment of capturing and distributing the excess heat that current electrolysers would normally vent to the environment. It explores a novel concept and establishes an opportunity for a combined heat and hydrogen (CHH) generator.

The developed model provides mass flows and output streams consistent with literature whilst also capturing excess heat in a cooling circuit. This model paired with technical and economic data has yielded encouraging results which may help to ease the transition to a fully renewable energy system and decarbonized heating.

5. Methods

5.1. Electrolyser model

The Aspen Plus software was used to transform the representation of the electrolyser (Fig. 2) into a tangible model. The primary purpose of the model was to provide sufficient data on the operating parameters of a PEM electrolyser with a specific focus on the excess heat available for extraction. As PEM electrolysers can be linearly scaled [26], the model can be easily configured to simulate the operation of any sized electrolyser.

5.1.1. Simulation data

The simulation of the electrolyser was based on Eq. (1). Water flow rates are specified, along with the electricity input and it then carries out the simulation of electrolysis and the resulting energy and mass balance. The results are then interpreted and recorded to form conclusions. The model uses the standard value of just under 300 kJ/mol to split water (different at different temperatures and pressures) to produce the simulation results.

$$2H_2O \rightarrow 2H_2 + O_2 \tag{1}$$

5.2. Technical analysis

The model aimed to validate the technical feasibility of extracting heat from a PEM electrolyser during operation. The technical analysis set out to investigate supplying excess heat from the electrolyser to district heat networks. This included the temperature of heat available from the electrolyser and subsequently the percentage of heat network demand that an electrolyser could provide.

5.3. Economic analysis

The next step was to determine electrolyser investment and running costs as well as possible revenue streams. For simplicity and ease of communication, the Levelized Cost of Hydrogen (LCOH) was computed for the proposed model, and this was compared against the LCOH of a standard electrolyser. The aim of this analysis was to ascertain what revenue could be generated from capturing and selling excess heat and whether the LCOH could be reduced by doing so.

6. CHH generator model development

6.1. Preliminary model

The first step was to develop a working model of a PEM electrolyser. To ensure performance was consistent with the state-of-the-art, operational parameters were chosen that matched the model from TU Delft [20] and were verified against industry leading electrolysers such as those from Nel hydrogen [27] and ITM power [28]. Fig. 3 shows the components of the preliminary model; water and electricity are fed to the PEM stack, water is converted and separated into hydrogen and oxygen gas and unreacted water is recycled. It is important to note that the conversion rate of water in a PEM electrolyser is very low. Therefore, any water that is not converted is directed back to the stack, ensuring that no heated water is wasted. The water input stream can be reduced to only replenish the water used up in the electrolyser.

The operating conditions were set to a pressure of 30 bar and a temperature of 80 °C, and in this preliminary model, excess heat is vented instead of utilized. This model produces over 5 kg of hydrogen per hour and in excess of 85 kW of heat per 270 kW of input electricity, resulting in a system efficiency of just over 60%. Around 82 kW of this excess heat comes from the stack, with the remaining heat contained in the gas streams. From this initial analysis, it was immediately clear that a significant portion of the input energy is lost as excess heat. Therefore,

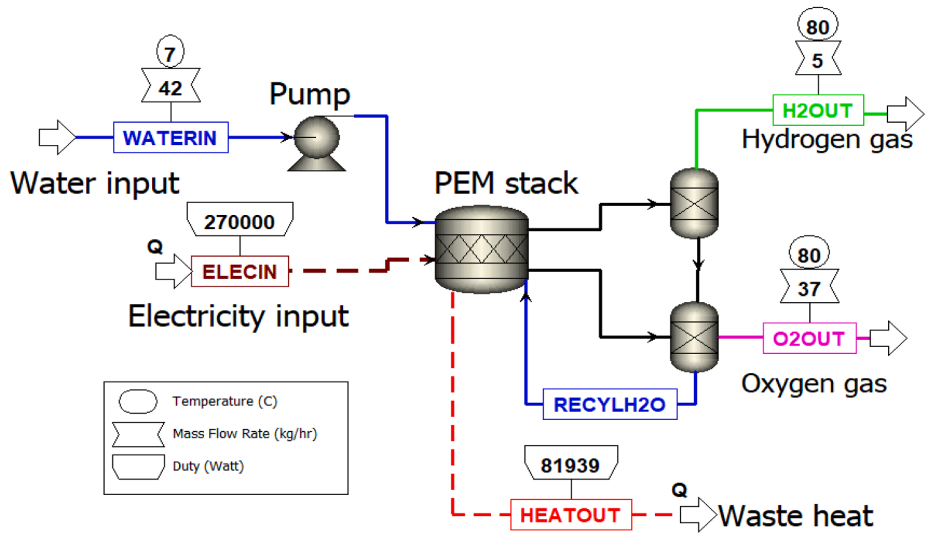

Fig. 3. Model of the electrolyser system.

the logical next step was to develop the model was to implement a cooling system capable of extracting this heat.

6.2. *Cooling system integration*

6.2.1. *Heat exchangers to cool gas streams*

As a result of the large thermal mass of the electrolyser, the hydrogen and oxygen gas streams leave the stack at 80 °C. Both gas streams contain the excess heat which can make hydrogen compression and storage more difficult [29].

To extract this heat, an independent cooling system was developed utilizing a heat exchanger for each gas stream. The configuration of the gas cooling system is presented in Fig. 4. Heat is transferred from the hot gas streams to cold water streams through heat exchangers until the gas streams reach a temperature of 7 °C. A total of 3.3 kW of heat is transferred to the cooling stream from the gases.

6.2.2. *Capturing stack heat*

The majority of excess heat comes from the stack, as shown by the heat stream in Fig. 3. To make use of this heat, it was channelled into a cooling stream carrying water at 7 °C, resulting in an outlet stream containing just under 82 kW of heat. The stack cooling stream is then mixed with the stream cooling the gases, resulting in a single heated water output. The stack cooling schematic is again displayed in Fig. 4.

6.3. *Complete CHH generator system*

The full CHH generator model containing the electrolyser and cooling stream is presented in Fig. 4. The design is the same as in Fig. 3 with the added components attributed to the cooling system. The cooling streams are configured to output water at the same temperature and are mixed to form the final 75 °C cooling system output stream. This system is able to capture 85% of all excess heat and the use of the cooling system does not affect the output hydrogen flow.

Fig. 5 shows the three useful output streams from the CHH generator:

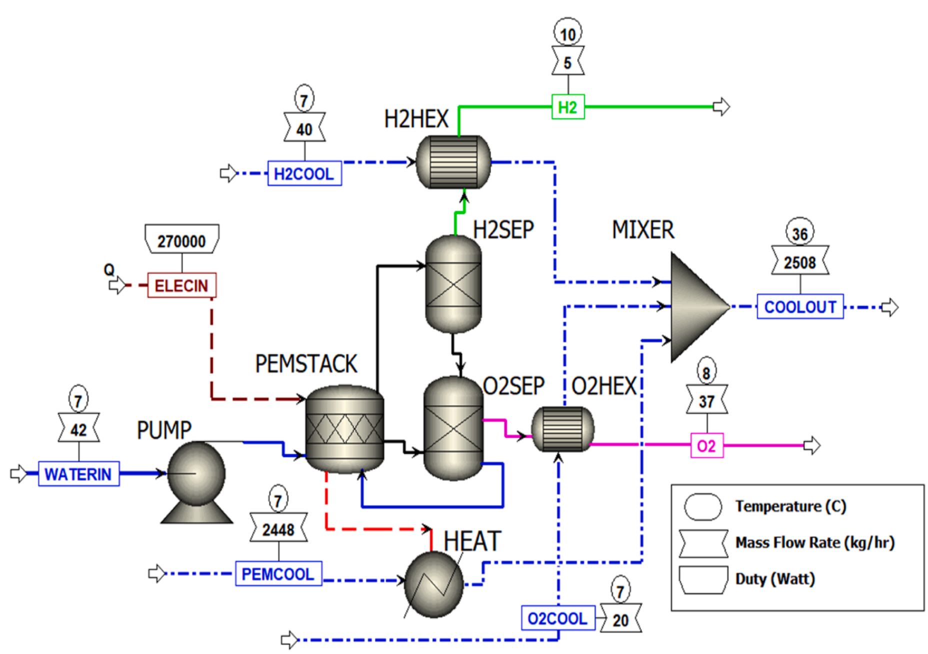

Fig. 4. CHH generator model with electrolyser and cooling system.

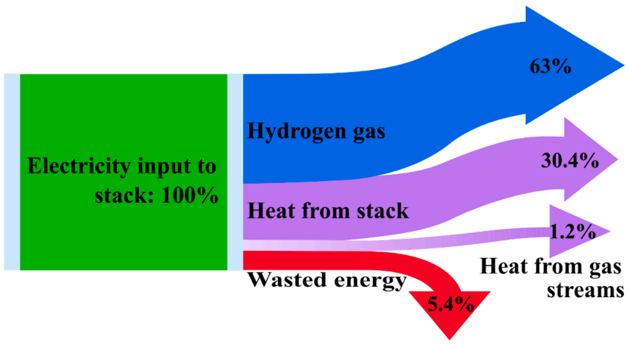

Fig. 5. Energy flow within the system.

hydrogen gas, heat from the electrolyser stack and heat from the gas streams. The energy contained within the hydrogen stream makes up most of the system output and the electrochemical efficiency is therefore 63%. The cooling system enables the capture of an additional 31.6% of input energy from the stack and gas stream heat. This would result in an overall system efficiency of 94.6%. Similar efficiency gains were observed by TU Delft [20] and Li [21], with electrolyser efficiencies being increased above 90% as a result of cooling systems capturing excess heat.

6.4. Standardized model

Although the model was developed to operate at 270 kW, it is likely that much larger electrolysers will be commonplace in the near future, therefore the model was standardized to operate as a 1 MW system. Table 1 summarizes the outputs of the system for each MW of input electricity and can be linearly scaled to suit any sized system.

Fig. 6 shows the algorithm used when developing the system model. Once the size of the electrolyser has been determined, the operational parameters (water and electricity input) are calculated using Table 1 and entered into the simulation. The model then carries out the simulation to determine the quantity of hot water and hydrogen produced by that electrolyser size.

6.4.1. Model validation

The values obtained from the model were cross referenced with existing electrolyser technology and other PEM models from literature. A 1 MW electrolyser from Nel hydrogen [27] is capable of producing just under 20 kg of hydrogen per hour; an ITM power [28] 1 MW PEM electrolyser produces around 17.46 kg of hydrogen per hour; and the TU Delft model scaled to 1 MW produces 18.21 kg of hydrogen per hour. The system presented here produces 18.7 kg of hydrogen per hour and is therefore in line with current technology and research.

To represent the use of the modelled CHH generator system, a ‘standard’ operational mode has been configured. This entails a 1 MW CHH generator running for 5 h per day correlating to the times of lowest electricity costs. This operational mode is considered multiple times in the subsequent technical and economic analysis.

6.5. Cooling circuit optimization

The model shows the ability to capture the excess heat from an electrolyser. However, to be used for domestic heating, the heated cooling water must be available at the correct temperature.

Table 1
Operating parameters of 1 MW system.

Hydrogen production (kg/h)	18.7
Oxygen production (kg/h)	137.3
Heat extracted in cooling circuit (kW)	312

6.5.1. High temperature cooling circuit

District heat networks typically deliver heat in the temperature region of 70–80 °C [30]. The first cooling system proposed restricts the flow rate of cold water through the heat exchangers to ensure the output temperature is 75 °C. At this temperature, excess heat from the CHH generator can be integrated into existing networks. From Table 2, the high temperature cooling circuit produces 312 kW of heat per MW of electricity in the form of 3,933 kg/h of 75 °C water.

6.5.2. Neutral temperature cooling circuit

The neutral temperature cooling circuit was configured to operate at 45 °C to enable heat integration into lower temperature heat networks. This was achieved by increasing the flow rate of water in the cooling system to reduce the temperature rise for the same heat transfer. The hydrogen and oxygen flow rates are independent of the cooling system; however, the neutral temperature system extracts 3 kW less heat per MW than the high temperature circuit as presented in Table 2. The ability to provide heat at different temperatures shows the current and future potential of this technology. The next step of the project determined the contribution that the CHH generator system could have to the heat demand of real-world district heat networks.

7. Integrating heat into district heat networks

District heat networks currently provide roughly 2% of the UK’s heat demand and government research indicates that this share could be significantly increased to as much as 43% by 2050 [15]. Progress has been made in diversifying heat sources for DHNs with notable contributions coming from biomass (10%) and excess heat from heat pumps, however 88% of heat is still supplied by non-renewable sources [15]. The heat demand of different sized networks is shown in Table 3 and given the drive to integrate low carbon heat sources into DHNs, it was of interest to investigate the proportion of heat that could be supplied by the CHH generator system.

The ability of CHH generators to contribute heat is dependent on the time that the system is operational. For this analysis, it is assumed that all the heat produced by the CHH generator can be either stored or integrated into a DHN.

7.1. A 1 MW CHH generator system scale

Table 4 tabulates the heat contributions that the modelled 1 MW CHH generator system could make to different sized heat networks. It is clear that different operational times result in varying heat contributions to the network. For as long as the CHH generator is operating, heat can be extracted and integrated into heat networks. This table also gives the percentage of heat demand supplied per MWh of CHH generator operation which can be scaled to any sized system operating for any number of hours.

Considering the standard operational mode, a 1 MW CHH generator would provide almost enough heat to supply the demand of an entire small heat network, or the equivalent heat demand of 35 homes.

7.2. CHH system size required to supply entire network

The CHH generator system size required to meet the heat demands of an entire heat network is shown in Table 5. These values were obtained by scaling the 1 MW model to the appropriate size and are based on a CHC system operating for 5 h per day with 312 kW of heat available per 1 MW of input electricity.

This analysis demonstrates the significant contribution that CHH generator excess heat can provide for DHNs. The two different cooling systems modelled enable heat to be added at both neutral and high temperatures illustrating the potential current and future applications of this technology.

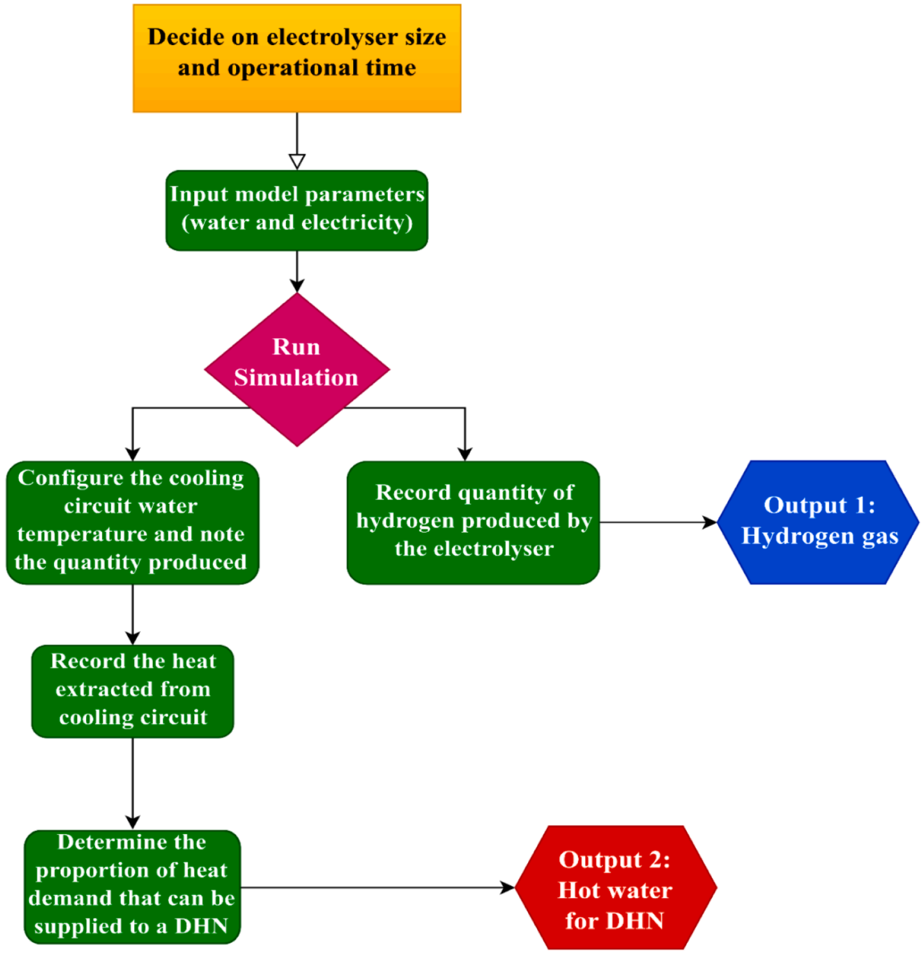

Fig. 6. Model development flowchart.

Table 2
Operating parameters of cooling circuit variations.

Cooling circuit variant	Heat extracted (kW)	Cooling water output (kg/h)
High temperature cooling circuit (75 °C)	312	3,933
Neutral temperature cooling circuit (45 °C)	308.9	6,967

Table 3
Heat demand of different scaled DHNs (reproduced from [31]).

DHN size	Average daily heat demand (MWh/day)	Number of dwellings
Small	1.6	35
Medium	16.8	190
Large	102.4	1,035

7.3. CHH generator location

Currently, heat networks supply hot water from a central source through a piping system. Pipelines may be up to several kilometres long if the heat source is located far away from the end user. This is the case for combined heat and power (CHP) plants which provide 32% of heat network demand [15]. Geometry and length are key factors that determine heat loss from piping and therefore, the further that heat has to travel, the more inefficient the network becomes [32]. In fact, heat losses can range from 544 to 797 kWh/m for bulk and non-bulk district heating schemes respectively [33].

As a result of the compact design of CHH generators, the footprint of a 1 MW system is about the size of a standard shipping container (12.2 m × 2.5 m × 3 m)[27]. As long as there is DC electricity and a water supply, CHH generators can be located almost anywhere. Positioning a CHH generator close to the end user would dramatically shorten heat network length and consequently heat losses. This is a key principle in low temperature heat networks that aim to incorporate multiple sources of heat (solar thermal, biomass and PV) in close proximity to the end user [16], reiterating the future potential of the neutral temperature cooling circuit proposed earlier.

8. Heat storage

System flexibility can be improved through the use of heat storage. As heat demand and CHH generator operation may not always align temporally, it is important that a thermal storage solution exists to provide heat when required. A hot water tank coupled to the CHH generator system would ensure that the excess heat is available when demanded instead of only whilst the system is operating.

A thermal storage tank was added to the model. Considering the 1 MW CHH generator model with a high temperature cooling circuit, around 3.9m^3 of 75°C water is produced per hour. If this produced heat is not instantaneously required by a DHN it can be efficiently stored in a large hot water tank. For the standard CHH generator operation, a 20m^3 hot water tank would store all the thermal energy until it is required by the heat network. With appropriate insulation, heat losses could be minimized to around $2\text{kW}/\text{hr}$ [34]. This potential enables for the heat

Table 4
Data on the 1 MW CHH system model for different operational cases.

Operating parameter For a 1 MW CHH system	Heat extracted in cooling circuit (MWh)	Percentage of the demanded heat for small network	Percentage of the demanded heat for medium network	Percentage of the demanded heat for large network	Estimated number of homes that could be heated per year
1 h	0.312	0.05%	0.005%	0.0008%	0
1 h per day for a year (365 h)	113.88	19.8%	1.85%	0.3%	4
5 h per day for a year (1,825 h)	569.4	99.03%	9.3%	1.52%	20
24 h per day for a year (8,760 h)	2733.12	475.33%	44.5%	7.32%	96

Table 5
CHH generator systems required to heat entire networks.

DHN size	CHH generator sized to heat entire network
Small (35 buildings)	1.01 MW
Medium (190 buildings)	11 MW
Large (1,035 buildings)	66 MW

produced by the CHH generators during the night to meet heat demand of the DHN several hours later.

For CHH generators that supply a large proportion of DHN demand (usually small DHNs) a thermal storage tank is required so that heat is always available. In this case, heat may come directly from the CHH generator if demand corresponds to low-cost renewable electricity, or from the hot water tank should the CHH system not be in use.

The thermal storage tank size required is dependent on the size of the CHH generator as well as the size of the DHN that it feeds. Large heat networks that supply over a thousand buildings have an extremely large thermal mass and inherently act as a heat store [15]. Therefore, CHH generators that integrate heat into these networks may not require hot water tanks as the heat contributed by the CHH system is small in comparison to the thermal mass of the network.

Whilst the use of hot water tanks reduces the intermittency of excess CHH generator heat production, the CHH generator operation is largely influenced by energy from RES. A combination of heat from electrolysis and other sources (such as biomass and other sources of waste heat) would ensure security of heat supply whilst aiding the decarbonisation of heat.

9. Economic analysis

9.1. Entire system investment costs

9.1.1. Capital expenditure (CAPEX)

Mayyas [22] showed that PEM system costs are largely dependent on economies of scale, manufacturing technologies and the relative size of the PEM system. This includes stack cost, the balance of plant, installation, and mark-up costs. As production volumes increase from 10 to 1,000 units a year, a 1 MW system could reduce in cost from £400/kW to as little as £190/kW [22]. By 2030, future technology could result in systems costs being as low as £170/kW [35].

Fig. 7 shows the projected cost of manufacturing 200 kW and 1 MW CHH generators. Given that this project focuses on a 1 MW sized CHH system and is based on current technology, the full system cost is taken to be £400,000. This represents the Capital Expenditure (CAPEX) required to purchase an ‘off the shelf’ 1 MW electrolyser and is the required investment cost for this analysis. The curves in Fig. 7 exhibit the same trend as a result of the same improvements in technology for both 200 kW and 1 MW electrolysers. The difference between the rate of decrease is down to the scale which the electrolysers are produced, the cost reduction is greater for the 1 MW electrolyser because of economies of scale. This is supported by the work of McKinsey [35] and Mayyas [22] who explored the economics of PEM electrolysers and how the prices change with improvements of technology towards 2030.

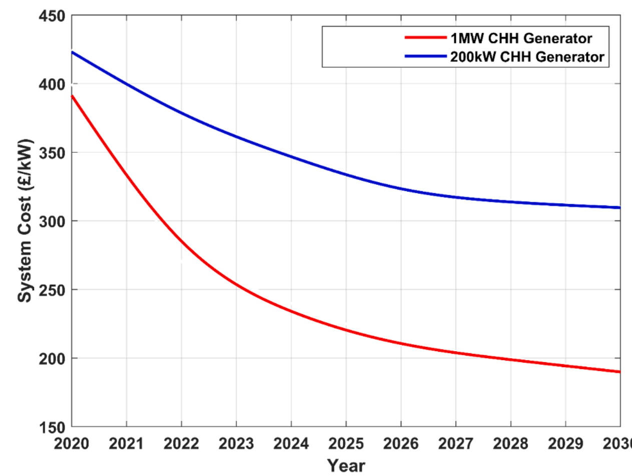

Fig. 7. Complete CHH system investment cost.

9.1.2. Annual investment cost

The annual investment cost breaks down the CAPEX financial model to give the annual investment required for the entire CHH system. The expected lifetime of a current electrolyser stack is estimated to be 60,000 h which could increase to 90,000 h with 2030 technology [8]. This equates to a lifetime of almost 7 years should the system be operating continuously throughout the year. For the standard case, with the CHH generator operating for 5 h per day, the stack lifetime is extended to almost 33 years. This estimated ‘on’ time represents the generator capacity factor which is taken to be 21% for this economic model.

Applying a 3% discount rate to the investment, spread over the lifetime of the CHH system enables the annual investment cost to be calculated. This model computes a full system investment cost of £31,300 per year.

9.2. Operational expenditure (OPEX)

The operational costs of a CHH system are dominated by the cost of electricity. The cost of water is almost negligible and can therefore be left out of the analysis. Several scenarios have been investigated to determine the likely electricity costs for the generator operation.

9.2.1. Operating using excess energy only

Over the next three decades, the installed onshore wind capacity is estimated to increase four fold, with offshore capacity increasing by as much as ten times [36]. Although an increase in wind energy is associated with the issue of intermittency, the opportunity of negative electricity prices is also created. The lowest electricity price measured in 2020 was -£38.80/MWh and negative electricity prices are four times as common now as they were in 2015 [5]. ***Carrying out electrolysis whilst electricity prices are low or negative could dramatically reduce***

operating costs.

It is during these times that PtG becomes attractive and with excess renewable electricity exceeding 45GWh per year [4], there are likely to be significant periods throughout the year where electricity costs become negligible. This is explored further in ***Case Study 10.2***.

Unfortunately, the inability to accurately predict periods of excess renewable electricity render this operational mode challenging. Carrying out electrolysis only when there is excess electricity would result in unsteady streams of hydrogen and heat production which in turn may fail to meet demands.

9.2.2. Hourly electricity prices

To take advantage of varying electricity prices, the CHH generator can be tailored to operate during the cheapest hours of electricity in the day. Fig. 8 shows the hourly electricity prices of a day taken at random in 2020 [37]. The variability of electricity throughout the day is evident and although the daily average price is £34.75/MWh, there are significant periods in which electricity prices are far below this value.

Similar trends can be seen for the majority of days within the year. Electricity prices in the period 01:00–06:00 are consistently cheaper than the remainder of the day and are almost always lower than the yearly average price. Operating CHH generators daily in this time frame would result in 5 h of generator 'on' time per day and a cost-effective means to produce a reliable and steady stream of hydrogen and heat.

9.2.3. Operating using average electricity prices

The average electricity price in 2020 was £35.26/MWh [37], which is considerably lower than in previous years. Fig. 9 shows the estimated yearly average electricity prices based on historical data [37] and future predictions.

As PtG systems aim to harness excess renewable energy, electrolysis is unlikely to be carried out whilst electricity demand is high. The average electricity price can therefore be treated as a maximum given that CHH generators are expected to operate at times when electricity prices are below this value.

Taking the standard modelled 1 MW CHH generation system as an example at an electricity price of £35.36/MWh, a maximum estimate of the electricity costs would be £64,350 annually.

9.3. Revenue streams

Current solutions typically see excess heat vented from electrolysers hence revenue is only available from selling hydrogen. This paper investigates a second possible revenue stream in selling the excess heat captured in the cooling system.

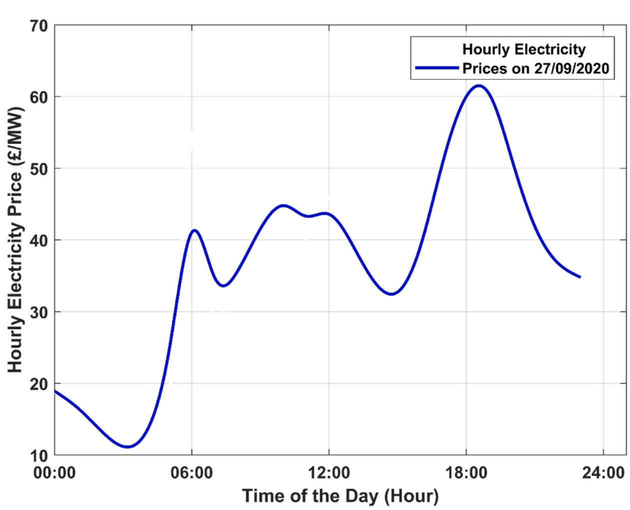

Fig. 8. Hourly electricity prices.

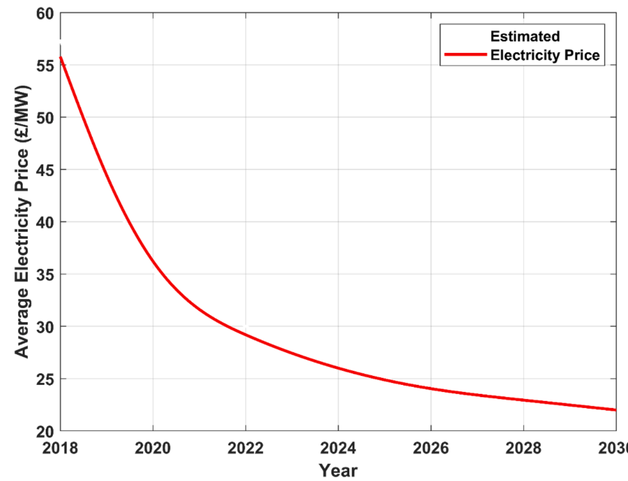

Fig. 9. Estimated yearly average electricity prices.

9.3.1. Selling hydrogen

As per Table 1, 18.7 **kg**/h of hydrogen is produced per MW of inputted electricity. So, for the standard case of 5 operational hours per day, the CHH generator produces 34,128 kg of hydrogen per year. Hydrogen produced by electrolysis is 99.9995% pure and can be directly used in applications such as combustion systems, fuel cells and chemical feedstocks [27].

The cost of hydrogen production ranges between £1-3/kg depending on the method used [38] and the sale price of hydrogen varies depending on use. For example, UK hydrogen refuelling stations sell hydrogen in the region of £10-15/kg [39]. For the case studies in ***Section 10***, a hydrogen retail price of £10/kg was assumed, which ensures competitiveness with the global retail price at refuelling stations.

9.3.2. Selling heat

The other available revenue stream from CHH generator operation is selling heat extracted by the cooling system. As per the flow sheet model, for every 1 MW of input electricity, a maximum of 312 kW of heat is available in the form of 75 °C water. As proposed earlier, this heat can be stored in hot water tanks or directly integrated into district heat networks for domestic use.

Typically the average domicile connected to a heat network pays around £102.30/MWh for heat [40] although this is dependent on a number of factors including specification, size of network *etc.* as well as the primary source of energy used to generate the heat. However, the vast majority of the cost (around 73%) is from the capital, maintenance and operational costs associated with the heat network infrastructure [41]. Thus, in this context, the remainder *i.e.* £27.62/MWh was the value used to estimate the potential income from selling CHH generator excess heat into such a network.

As an example, operating the 1 MW CHH generator for 5 h per day and assuming that all the excess heat can be effectively stored or integrated into DHNs, the yearly income could be as much as £15,727. This quantity of heat (569.4MWh) equates to the annual heat demand of a small district heat network.

9.4. Levelized cost of hydrogen (LCOH)

9.4.1. Without revenue from heat

The levelized cost of hydrogen is a metric that assesses how much it costs to produce hydrogen based on CAPEX and OPEX. It is calculated by standardizing the total annualized cost of the CHH system against the quantity of hydrogen that is generated per year, as in Eq. (2).

$$LCOH = \frac{C_{annual}}{E_{h_2}} \tag{2}$$

The annualized cost of the system C_{annual}, is obtained by summing the annual investment cost with the annual operational costs. The quantity of hydrogen generated per year E_{h_2} is extracted from the model.

For the standard 1 MW model, the annual investment cost was taken to be £32,150 and the cost to run the CHH generator was modelled at £64,350 per year. This generator operation produces 34,127.5 kg of hydrogen over the course of a year. Substituting these values into Eq. (2) generates an LCOH of £2.83/kg.

Mechanically compressing hydrogen for use at a refuelling station (delivered at 700 bar) is energy intensive. Including the investment required for compressor technology [42] and the additional running costs of suppling hydrogen at a high pressure [43], the LCOH is increased to £3.93/kg. *This value is supported by LCOH values obtained from literature* [44] *and further validates the performance of the model.*

9.4.2. Reduction in LCOH with heat sales

With the cooling system able to capture excess heat, the LCOH can be recalculated given the extra revenue from heat. Using the same operational case as above but factoring in the 569.4MWh of heat sold (generating £15,727 annually), the LCOH is reduced to £2.37/kg (or £3.47/kg if hydrogen compression is required). This marks a significant reduction in LCOH and is comparable to the cost of hydrogen production from steam reforming of methane.

As previously introduced, a thermal storage solution increases the flexibility of the system and allows heat to be distributed when demanded. Based on the hot water production of the 1 MW CHH generator, a 20m^3 on site hot water tank has been included in the model. Standardizing the cost of the water storage tank results in an increase in CAPEX of £10,000/MWh [45]. Following the same methodology as above, the LCOH of hydrogen with a hot water tank is £2.39/kg (or £3.49/kg with hydrogen compression). Fig. 10 compares the LCOH for a CHH generator operating with and without excess heat capture for a 2020 system configuration. The reduction in LCOH is substantial if heat is effectively captured and sold. ***Adding a heat storage solution only marginally increases the LCOH, whilst adding considerable flexibility to the overall system.*** Hydrogen compression increases the LCOH further, and so must be accounted for if the electrolyzer is to be utilized at a refuelling station.

9.4.3. LCOH for 2030 technology

By 2030, CAPEX and electricity prices are likely to have reduced further. A 1 MW system will cost in the region of £200,000 and average electricity prices may drop below £25/MWh [22]. Using the same analysis as above, the LCOH was recalculated accounting for 2030 technology and Fig. 11 presents the results for comparison. The estimated technological improvements made by 2030 lower the LCOH significantly, and including hydrogen compression and heat storage, the LCOH could be as low as £2.22/kg.

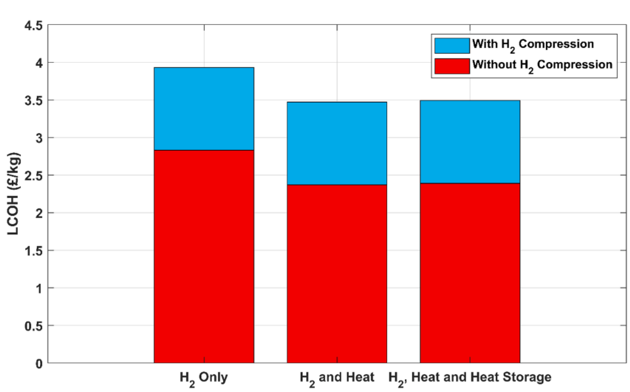

Fig. 10. LCOH comparison for 2020.

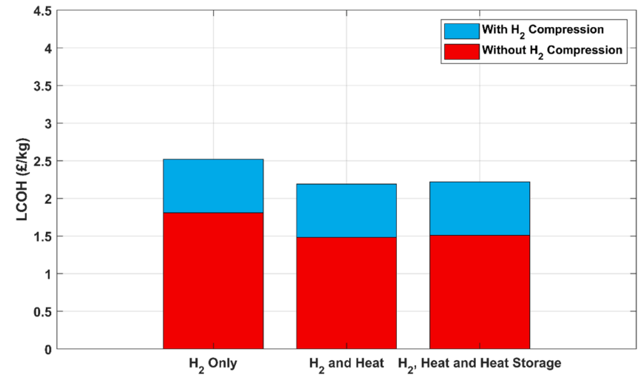

Fig. 11. LCOH comparison for 2030.

10. Case studies

10.1. Scaling a CHH generator for a hydrogen filling station

10.1.1. A 2020 hydrogen refuelling station

The 13 hydrogen refuelling stations in the UK are equipped to deliver around 60 kg of hydrogen per day [46]. 60 kg of hydrogen is enough to fill around 10 hydrogen fuel cell cars and although there are only around 2,500 registered in the UK, the government predicts that there could be over 1.5million hydrogen powered vehicles on the roads by 2030 [46].

In order to deliver 60 kg of hydrogen per day, the modelled 1 MW generator would have to operate for just over 3 h each day. This small operating time per day would enable the generator to switch on when the price of electricity is low, for example during the hours between 01:00 and 06:00. To produce this quantity of hydrogen, 3MWh of electricity would be required and the integrated cooling system would capture just under 1MWh of heat in the form of 75 °C heated water. Over the course of a year the cooling system would extract around 340MWh of heat. This equates to nearly 60% of the heat demand of a small district heat network, which is enough heat for 20 homes per year.

The ability to store hot water bridges the gap between the heat produced by the CHH generator and the demand of the heat network. This enables all the heat captured by the cooling circuit to be utilized irrespective of instantaneous demand. The compact size of CHH generators makes it feasible to locate them within the fuel station premises and given that fuel stations are usually situated near residential areas, the integration of excess heat into local heat networks is certainly viable. This has the added benefit of minimized heat distribution loss as the distance that heat must travel between source and destination is reduced. Table 6 summarizes the operation of the CHH generator and presents the income that can be generated for a refuelling station selling hydrogen and excess heat.

Fig. 12 depicts a Simple Payback Model (SPB) model applied to this CHH generator (without hydrogen compression and storage) whilst operating at a fuel station. The estimated break-even time for this case is just over 2 years.

10.1.2. A 2030 hydrogen refuelling station

Future filling stations are predicted to deliver over 1,200 kg of

Table 6
Economic summary of 60 kg/day hydrogen fuel station.

Investment cost	
System CAPEX (£410/kW)	£410,000
Daily expenditure	
Electricity (£35.26/MWh)	£105.78
H_2 compression (£20.60/MWh)	£61.80
Daily Income	
H_2 sales (£10/kg)	£600
Heat sales (£27.62/MWh)	£25.78

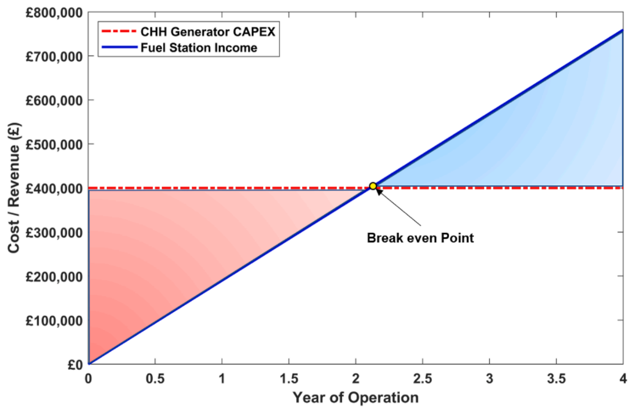

Fig. 12. 1 MW CHH generator operating at a hydrogen refuelling station.

hydrogen per day in order to meet the increased demand of hydrogen for fuel [46]. This would provide enough hydrogen for over 15 fuel cell lorries or around 200 cars.

This hydrogen demand could be met with an amalgamation of 12, 1 MW CHH generators operating for 5 h per day. Considering 2030 technologies, the CAPEX of the generator was reduced to £200/kW (£210/kW including hydrogen storage) as presented in Fig. 7. The cost of electricity, heat and compression were reduced in line with 2030 predictions and the hydrogen sale price was adjusted to £5/kg based on a 50% reduction in hydrogen refuelling retail prices by 2050 [38]. The CHH generator required is summarized in Table 7.

Again, operating in the early hours of the morning would reduce the cost of the 60MWh of electricity required. Under these operating specifications, the cooling system would capture 18.72MWh of heat per day, equivalent to 6.83GWh of heat per year. This is enough heat to supply an entire medium sized heat network which typically serves 190 homes. Alternatively, this heat could be integrated into a large district heating network to supply 20% of the heat demand. As with the previous case, hot water storage tanks have been integrated to store the excess heat if required. *The sale of hydrogen at this price and scale (without hydrogen compression and storage) results in a significant yearly net income of just under £1.8million and therefore an estimated break-even period is under a year and half.*

10.2. Scaling a CHH generator to capture all the excess energy generated by renewable sources

The annual excess renewable energy generation is estimated at 45GWh, with a peak instantaneous value of 40 MW [4]. It is therefore intuitive that a 40 MW CHH generator would be required to maximize the absorption of this excess energy. A system this size would operate for around 1,125 h (3 h daily per year) in order to capture the 45GWh. Table 8 presents the summary of scaling the generator model to this size. Integrating this 14GWh of heat into a district heating network would serve around 400 homes, equating to nearly 40% of the heat demand of a large network.

Fig. 13 exhibits the estimated LCOH of hydrogen should the electrolyzer operate on the excess electricity generated by RES. Without

Table 7
Economic summary for 1200 kg/day operation.

Investment cost	
System CAPEX (£210/kW)	£2.52 million
Daily expenditure	
Electricity (£25/MWh)	£1,500
H_2 compression (£13.3/MWh)	£798
Daily Income	
H_2 sales (£5kg)	£6,000
Heat sales (£19.5/MWh)	£365

Table 8
40 MW CHH generator summary.

CHH generator summary	
Electricity consumed	45GWh
Operational time	1,125 h
Hydrogen produced	841,500 kg
Heat produced	14GWh

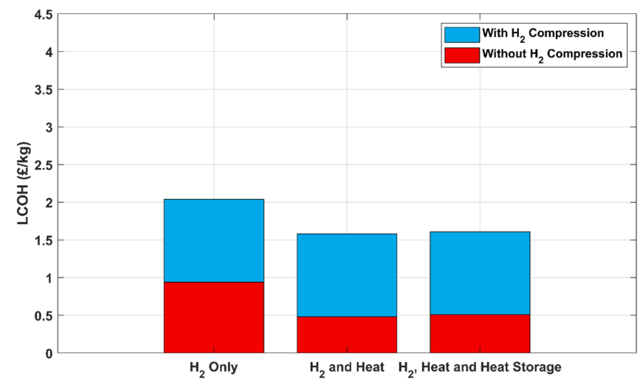

Fig. 13. LCOH calculated for negligible electricity costs.

accounting for excess heat sales, the LCOH (without hydrogen compression) is under £1/kg. With heat sales included, and even with hydrogen compression, the LCOH is significantly lower if the generator operates on only excess, free electricity.

This application of CHH generators would be a large step forward in the PtG initiative, and the heat produced and utilized by a large heat network further demonstrates it's potential.

11. Conclusions

This study has demonstrated the possibility of modelling CHH generator systems. The developed model is consistent with current commercial designs and provides the ability to scale the CHH generator to different sizes for a range of different applications. The modelled cooling system allows the separation of thermal and electrochemical models enabling heat to be extracted in the form of heated water.

The cooling circuit increases the efficiency of the generator by transforming excess heat into hot water. Considering both electrochemical and thermal efficiencies, the overall generator efficiency was increased to 94.6%. The cooling system can be configured to deliver heat between 75 °C and 45 °C, marking the ability to integrate heat into both current and future heat networks and the difference in extractable heat between the two circuits is almost negligible. An example covered thoroughly in the present work is the entire heat demand of a small heat network being met through the operation of a 1 MW CHH generator system for 5 h per day, highlighting the contribution of generator excess heat.

In addition, the economic analysis shows the further potential of operating CHH generators with the capture of excess heat. It was found that operating costs were dominated by electricity prices and by running the generator at times when electricity is cheap, income from heat and hydrogen sales can be maximized. The LCOH was calculated for CHH generators operating with and without heat capture, and the economic model showed a significant reduction in the LCOH through the sale of generator excess heat.

The model was then scaled to real-world applications. A 1 MW CHH generator comfortably provides enough hydrogen for use at current refuelling stations, and the heat generated as a result could supply as much as 60% of a small heat networks demand. Future refuelling stations would require a 12 MW CHH generator system and could heat up to 200 homes with excess heat. Finally, a 40 MW CHH generator was proposed in order to capture the 45GWh annual excess electricity generated. This CHH generator, operating without any charge for electricity has huge economic potential as well as the ability to provide heat for more than 400 homes.

CRediT authorship contribution statement

Dominic Burrin: Methodology, Software, Investigation, Writing – original draft. **Sumit Roy:** Conceptualization, Writing - review & editing. **Anthony Paul Roskilly:** Funding acquisition, Writing - review & editing. **Andrew Smallbone:** Supervision, Resources, Writing - review & editing.

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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