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Citation for the original published paper (version of record):
Pettersson, K., Axelsson, E., Eriksson, L. et al (2020). Holistic methodological framework for assessing the benefits of delivering industrial excess
heat to a district heating network. International Journal of Energy Research, 44(4): 2634-2651.
http://dx.doi.org/10.1002/er.5005

(article starts on next page)

Received: 10 June 2019 | Revised: 23 October 2019 | Accepted: 7 November 2019

DOI: 10.1002/er.5005

RESEARCH ARTICLE

INTERNATIONAL JOURNAL OF ENERGY RESEARCH WILEY

Holistic methodological framework for assessing the benefits of delivering industrial excess heat to a district heating network

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Funding information
Swedish Energy Agency, Grant/Award Number: P42222-1

Summary

In Sweden, over 50% of building heating requirements are covered by district heating. Approximately 8% of the heat supply to district heating systems comes from excess heat from industrial processes. Many studies indicate that there is a potential to substantially increase this share, and policies promoting energy efficiency and greenhouse gas emissions reduction provide incentives to do this. Quantifying the medium and long-term economic and carbon footprint benefits of such investments is difficult because the background energy system against which new investments should be assessed is also expected to undergo significant change as a result of the aforementioned policies. Furthermore, in many cases, the district heating system has already invested or is planning to invest in non-fossil heat sources such as biomass-fueled boilers or CHP units. This paper proposes a holistic methodological framework based on energy market scenarios for assessing the long-term carbon footprint and economic benefits of recovering excess heat from industrial processes for use in district heating systems. In many studies of industrial excess heat, it is assumed that all emissions from the process plant are allocated to the main products, and none to the excess heat. The proposed methodology makes a distinction between unavoidable excess heat and excess heat that could be avoided by increased heat recovery at the plant site, in which case it is assumed that a fraction of the plant emissions should be allocated to the exported heat. The methodology is illustrated through a case study of a chemical complex located approximately 50 km from the city of Gothenburg on the West coast of Sweden, from which substantial amounts of excess heat could be recovered and delivered to heat to the city's district heating network which aims to be completely fossil-free by 2030.

KEYWORDS

carbon footprint, district heating, energy market scenarios, GHG emissions, industrial excess heat

1 | INTRODUCTION

The EU accounts for 10% of global greenhouse gas (GHG) emissions. In 2018, a long-term strategy was announced for achieving a climate-neutral economy by 2050.[1] In 2017, the Swedish Parliament enacted a new climate policy framework including a climate goal whereby the country should have net zero GHG emissions by 2045, and thereafter negative emissions.[2]

According to data published by IEA for 2016, industry accounted for 29% of global energy use and 36% of energy-related GHG emissions.[3] Energy-intensive industrial process plants often release large amounts of excess thermal energy to the environment during their operation. This heat can be recovered and used to provide energy services, often in the form of district heating, thereby saving primary energy and generating additional revenue. The EU's Energy Efficiency Directive has highlighted utilization of industrial excess heat as an important factor for reaching the target of increasing energy efficiency by 20% by 2020.[4] The potential to increase excess heat utilization is considered to be substantial.[5] Utilization of industrial excess heat decreases the overall use of energy resources and is thus fully aligned with the principles of circular economy which calls for minimization of the energy used to manufacture products and services within the circular system boundary, as described online.[6] Resource-efficient energy use refers to improving the efficiency of processes in order to minimize the amount of energy used as well as re-using energy elsewhere.

Heating accounts for almost half of total global energy use, divided equally between heat for industrial processes and heat for use in buildings. Despite the large energy use for heating purposes, the transition to renewable energy sources continues to lag behind the power sector, as discussed in REN21.[7] In 2016, the EU proposed a strategy to meet the challenges of the heating and cooling sector, which accounts for half of its overall energy use with only 18% coming from renewables.[8] The strategy includes reducing the amount of heat wasted from industrial processes. The heat currently discharged from industry into air and water is sufficient to meet the EU's entire heating demand in the residential and service sectors.[9] In the Energy Roadmap 2050, the European Commission proposed strategies to reduce annual GHG emissions by 80% to 95% by the year 2050, compared with 1990 levels.[10] Future expansion of district heating is estimated to reduce the cost for this emission reduction and industrial excess heat is assumed to be one of the strategic heat sources.[11]

The potential for increased usage of industrial excess heat in different countries, regions, or industrial sectors has been investigated in many studies.[12-26] Most focus primarily on the potential usage of excess heat for district heating.[12,14-16,18,19,25] Other opportunities for utilizing industrial excess heat include delivery to other industrial plants, electricity production in combined heat and power (CHP) plants, and low temperature applications such as greenhouses and fish farming. Examples of possible future uses include drying of biomass, or supply of heat to integrated biorefineries and carbon capture plants. An overview of possible uses of excess heat is presented in Broberg Viklund and Johansson and Ammar et al.[18,27]

Other studies have investigated factors that affect industrial excess heat collaboration.[28-34] The implications for interorganisational collaborations and strategic planning are discussed in detail in Päivärinne.[35] A major obstacle in Sweden is competition for the available heat sinks with municipal waste-to-energy plants and biomass-fueled CHP plants. Both technologies benefit from strong policy support in the form of the landfill ban for municipal solid waste and the Swedish electricity certificate system promoting production of electricity from renewable sources, including biomass.[30]

The heat discharged from an industrial process is referred to in different studies as residual heat, excess heat, surplus heat, or waste heat. *Industrial Excess Heat (IEH)* is used consistently throughout this work. As discussed in Bendig et al,[36] IEH that could be re-used internally within the process is denoted as *avoidable excess heat*, whereas *unavoidable excess heat* refers to excess heat that cannot be avoided and cannot reduce the use of primary energy at the industrial plant. Different perspectives can be adopted when defining whether excess heat is avoidable or unavoidable. In this paper, we adopt a pragmatic techno-economic perspective whereby avoidable excess heat refers to heat that could be reused internally within the process through heat recovery measures that meet the plant owner's investment performance criteria.

This paper focuses on the recovery of IEH for delivery to district heating (DH) networks. A holistic methodological framework is proposed for evaluating the impact on net GHG emissions as well as economic performance. The methodology focuses on evaluation under different future energy market conditions. The paper also demonstrates the importance of characterizing the IEH (unavoidable or avoidable) when performing analysis of the net impact on GHG emissions of recovering and re-using this heat.

1.1 | Related work

Many previous studies have established the benefits of recovering IEH for supplying heat to DH systems (sometimes in combination with other potential uses) from an economic and/or carbon footprint perspective[15,37-44]). Li et al[15] showed that replacing coal-fired boilers in DH systems in China could lead to significant economic gains as well as reduced emissions of GHG and other pollutants. Similar conclusions were reached by Kim et al [38] who investigated industrial and urban symbiosis concepts for South Korea involving new DH networks as a means to reduce fossil fuel usage in urban areas and industry. Similarly, Popovski et al[40] investigated IEH recovery for usage in heating and cooling systems in southern European municipalities, replacing individual natural gas boilers. All such studies focused on systems where IEH replaces mainly fossil-based heat production.

Assessing the long-term benefits of IEH recovery and usage in DH systems is difficult given that energy and climate policy aims at achieving net-zero GHG emissions in many sectors simultaneously. One expected consequence of such policies is that the use of biomass fuel will increase significantly in DH systems. This could lead to biomass becoming a truly limited resource, which must be considered when assessing the impact on GHG emissions associated with export of IEH to DH systems (see, eg,[45]). Another aspect that increases the complexity of the assessment is the widespread presence of CHP plants in DH systems. Import of IEH to such systems can reduce the output of cogenerated power, which will in turn lead to change in electricity generation elsewhere in the grid, (see, eg,[45,46]).

Harvey et al[47] reviewed methodologies for assessing the long-term economic and carbon footprint performance of future large-scale biorefinery concepts. They concluded that such investments require a prospective assessment approach accounting for possible future conditions and related uncertainties, and that assessment using today's conditions can be heavily misleading.

Arvidsson et al[48] provide recommendations for conducting prospective life cycle assessment (LCA) studies. When evaluating technologies to be implemented in the future (foreground), the selected background systems must be relevant for the point in time at which the system is modeled, and changes in the background systems over time must be considered. Furthermore, it is important to avoid a temporal mismatch between the foreground and background systems. In order to define relevant background system data, predictive scenarios can be used if a given development path is more likely than others. Otherwise, scenario ranges are more relevant.

Several studies have evaluated the use of IEH for DH and other purposes, considering different future scenarios for the background energy system, including energy systems that are carbon-lean.[45,46,49-51] Weinberger et al[45] investigated the use of IEH from a steel mill for deliveries of DH, process steam, and cogeneration of electricity, and concluded that the reduction of GHG emissions varies significantly depending on assumptions regarding the background energy system. Maximum reduction was achieved assuming biomass to be a limited resource and coal-based electricity production. However, this potential reduction decreased by 90% if the average Nordic mix was considered for electricity generation and the use of biomass was assumed to be CO_2-neutral.

Broberg Viklund and Karlsson[49] and Ivner and Broberg Viklund[46] studied the GHG consequences of using IEH in DH by applying different energy market conditions with different system boundaries in time and space. The evaluation was conducted for different energy market scenarios for 2030, with the aim to reduce total system costs. Biomass was assumed to be a limited resoure in all scenarios, and IEH was assumed to be CO_2neutral. The resulting GHG emissions from using IEH were found to depend mainly on two factors: (a) whether heat is supplied by CHP plants or heat only boilers (HOB); (b) the definition of the system boundary used to analyse CHP-based systems.

Olsson et al[52] investigated how methodological choices influence the estimation of GHG emissions from DH systems including CHP plants and deliveries of IEH. The paper focused on unavoidable IEH and did not regard biomass as a limited resource. However, the authors suggested that in order to evaluate IEH and heat from CHP plants on equal terms, both should be considered a byproduct, without allocated emissions.

None of the aforementioned studies considered possible internal usage of the IEH, i.e., IEH was considered to be unavoidable with no allocated emissions. Morandin et al,[50] however, studied DH delivery using IEH from the large chemical complex site considered in this study and considered possible allocation of GHG emissions to the avoidable IEH. The allocation was based on an estimation of the amount of avoidable fuel firing at the site identified through total site analysis.[53] The study concluded that export of IEH leads to larger reductions of regional GHG emissions than increased heat recovery at the site only if the DH system's heat production technologies are similar to that of the industrial plants (e.g., natural gas boilers). However, if the production technologies in nearby DH systems are more efficient and CO_2lean, the region would benefit more from improved energy efficiency at the site. The effect of biomass becoming a limited resource was not considered in the study.

Jönsson et al[51] used a similar approach as that adopted by Morandin et al[50] to investigate the trade-off between internal and external use of IEH from a kraft pulp mill. The results showed that the trade-off depends on energy market prices, the DH demand, and the type of existing heat production. With respect to profitability, external use of the IEH was shown to be preferable for all investigated scenarios if the mill delivers IEH to a small district heating system (biomass heat only boilers). For medium or large systems (including CHP plants fired with biomass and/or waste fuels), the optimal use of IEH was shown to vary with the energy market price scenarios. However, from a GHG emissions perspective, external use was shown to be advantageous, achieving the largest reduction of overall emissions in most cases. Biomass was regarded a limited resource in all scenarios.

1.2 | Objective

The main aim of this work is to propose a new holistic methodological framework for assessing recovery and usage of IEH in DH networks, accounting in a consistent and transparent manner for the following aspects:

- Impact of future energy market conditions on net GHG emissions reduction and economic performance. A scenario tool is used to establish future energy market scenarios that include energy prices and GHG emissions for relevant energy carriers. The tool captures the major changes that are taking place in the electricity system as well as proposing different approaches for quantifying the impact of increased use of biomass on net GHG emissions in the energy system.
- Differentiation between avoidable and unavoidable IEH and how this affects the net GHG emissions related to its capture and use.
- Significant differences between different types of stakeholders regarding the required return on investment for the equipment and infrastructure required to capture and use IEH.

The proposed methodology is illustrated through a case study of export of IEH from a chemical complex to a large DH network.

1.3 | Description of the case study

DH accounts for a large share of heating of the buildings in Gothenburg, Sweden. The existing heat supply mix includes substantial amounts of IEH recovered from industrial plants nearby. Additional IEH is available at the chemical complex site in Stenungsund located approximately 50 km north of the city. Using IEH from Stenungsund for delivery of DH would be well aligned with Gothenburg's energy company's goal of fossil-free production by 2030. Thus, investment in a DH pipeline between Stenungsund and Gothenburg could be an interesting option to compare with alternative investments required to achieve this goal.

The Stenungsund chemical complex site consists of six plants run by five companies producing a variety of products such as amines, surfactants, polyolefins, and other specialty chemicals. It is the largest site of its kind in Sweden (in terms of production volume) and is a major fossil resource consumer and emitter of fossil CO_2 (approximately 1 Mt/y). The companies at the site have formulated a common vision for 2030, whereby their businesses should be based on renewable and recycled raw materials, and contribute to a transition to a sustainable society.[54] Delivering excess heat from the site to a regional DH network could contribute to achieving this vision.

In a previous project (see, eg,[55,56]), future opportunities for regional DH were investigated for Western Sweden, including several municipalities and industries. One conclusion was that the cost of long pipelines leads to major uncertainty for profitability of increased use of IEH, at least with the energy prices and forecasted price developments considered in the study. However, energy prices (including costs associated with emitting GHG) could increase significantly in the future if there is a global consensus on reducing GHG emissions.

2 | METHODOLOGY, INPUT DATA, AND ASSUMPTIONS

2.1 | Methodology overview

This work proposes a holistic methodological framework for assessing the net impact on GHG emissions and economic performance of delivering IEH to a DH system. The methodology builds upon detailed knowledge about the energy system of the industrial plant as well as the DH system's production mix. An important distinction is made between avoidable and unavoidable IEH. The significant impact of the background energy system and its change over time is also highlighted. Two different time horizons were considered: (a) a near-term situation in which the delivery of IEH is assumed to start operation between 2025 and 2035; (b) a long-term perspective reflecting delayed investment in the IEH delivery infrastructure until 2035 to 2045.

2.2 | Calculation of economic performance

The value of IEH in the DH system can be related to the decreased cost of heat production in the system. It was assumed that the energy company needs to invest in new capacity, and investment in a new heat pipeline to the chemical complex site is a possible investment option. Under these conditions, the value of the IEH can be related to the investment cost, fixed costs, and variable costs for a selected alternative technology, in this case assumed to be a biomass-fired CHP plant.

The costs associated with collecting and piping IEH from an industrial site to a DH system are as follows:

- Investment costs
  - Heat exchanger network to collect the IEH at the industrial site and deliver it to the heat pipeline
  - Pipeline between the industrial site and the DH system
  - Connection of the pipeline to the DH system
- Costs for operation and maintenance (O&M) of the components listed above

Capital costs were annualized assuming an economic lifetime of 20 years and a risk-free discount rate of 4%. Sensitivity analysis was performed by increasing the discount rate to 7%. In addition, a sensitivity analysis was conducted in which it was assumed that the economic lifetime of the investments required for collecting the IEH within the chemical complex site is 5 years. In practice, this would require a business model by which the district heating company or a third party intervenes to mitigate the investment risk for the industrial decision makers. All calculations were performed in Swedish Kronor (SEK) and 2017 money value.

2.3 | Calculation of avoided GHG emissions

2.3.1 | Base case

System expansion was considered when calculating the avoided GHG emissions associated with exporting IEH to the DH system. The studied system includes the alternative options for supplying DH (i.e., IEH and a bio-CHP plant). Increased export of IEH from the industrial site reduces the heat produced in the DH system's bio-CHP plant, thereby reducing the electricity generated by the plant as well as its usage of biomass fuel. These changes were in turn assumed to cause changes in the expanded system, see Figure 1. Different possible alternative uses for biomass and grid electricity generation technologies were considered for the background system by using different future energy market scenarios.

In the base case, all IEH delivered from the industrial site to the DH network was assumed to be *unavoidable* and without allocated emissions. In this case, the heat supply technology used at the industrial site is not relevant. However, if the IEH is completely or partially *avoidable*, export of this heat affects the potential for on-site heat recovery at the industrial site, and some or all of the emissions associated with operation of the process boiler plant should be allocated to the IEH.

2.3.2 | Cases in which emissions are associated with delivery of industrial excess heat

In the Base case, it was assumed that all IEH recovered and exported to the DH system is unavoidable in the sense that it is not technically and economically feasible to recover it for saving fuel and reducing emissions at the industrial site. However, the techno-economic feasibility for on-site utilization of IEH is dependent on a number of factors that may be site-specific, such as plant layout,

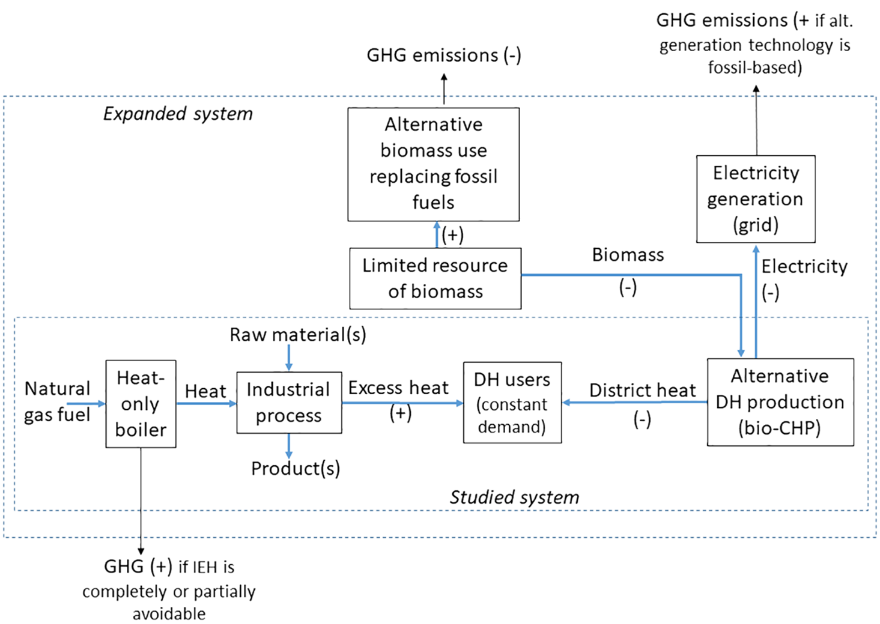

FIGURE 1 Schematic representation of changes to energy and material flows as a result of increased delivery of IEH to the district heating (DH) system. (+) indicates an increase; (−) indicates a decrease [Color figure can be viewed at wileyonlinelibrary.com]

safety considerations and age structure of equipment, and factors that vary over time, such as fuel prices, heat recovery investment costs, plant operating margin, etc. Furthermore, estimations of IEH availability are frequently based upon questionnaires filled in by plant staff, in which case there is not even information available about the thermodynamic potential for heat recovery for internal usage. It is thus often assumed that IEH is unavoidable with no associated emissions. However, in most cases, it is reasonable to assume that some of the IEH could be used internally, in which case emissions should be allocated to the part of the IEH that is used for DH delivery but which could have been recovered within the process for fuel savings on-site. To analyse how sensitive the results are to the base case assumption of unavoidable IEH, two additional cases were considered in which it was assumed that some or all of the IEH is avoidable and could be recovered for use on-site:

- *Case—part of the heat delivered is avoidable excess heat*
- *Case—all heat delivered is avoidable excess heat*

Note that for most industrial processes there will always be unavoidable excess heat, even after thermodynamically maximized heat recovery within the process. Consequently, Case 2 can be regarded as highly unrealistic. However, it has been added here to represent an extreme limiting case to be able to evaluate the whole range of possible emissions associated with delivery of IEH: from zero associated emissions in the base case to maximum associated emissions in Case 2. The emissions associated with utilization of avoidable IEH (Cases 1 and 2) were estimated based on how on-site usage of the excess heat would affect operation of the plant's natural gas-fired process heat boiler (assuming a boiler efficiency of 90% [LHV basis] and a GHG emission factor for natural gas of 248 kg $CO2_{eq}$/MWh). This approach is similar to that adopted by Morandin et al.[50] Figure 2 illustrates the concepts of avoidable and unavoidable excess heat.

2.4 | Estimation of excess heat available at the chemical complex site

The amounts of IEH available at the chemical complex site and the associated investment costs for heat collection and delivery to the DH pipeline were estimated based on previous studies[50,56-58] in which a site-wide circulating water-based heat collection system was considered for heat recovery within the complex.

The circulating hot water circuit temperatures were set based on the future requirements of Gothenburg's DH network, ie, a return temperature of 45°C and a supply temperature of 80°C. The latter temperature is sufficient for most days of the year, and it was assumed that boosting this temperature during peak demand periods is performed by the DH operator when required. To account for heat losses in the pipeline, the DH supply temperature from the chemical complex was set to 82°C. The on-site hot water circuit was therefore set to operate between 86°C and 49°C, considering a 4°C temperature difference for heat exchange between the on-site water circuit and the DH pipeline. An inventory of IEH availability within the complex indicated that approximately 180 MW of heat was available at temperature levels sufficient to deliver heat to the circulating hot water system, assuming a minimum temperature difference of 10°C for heat exchange between process streams and the circulating hot water flow. This is a conservative value that is typical for the tube-and-shell heat exchangers used in industry.

A recent study of the chemical complex investigated economic performance of all possible combinations of

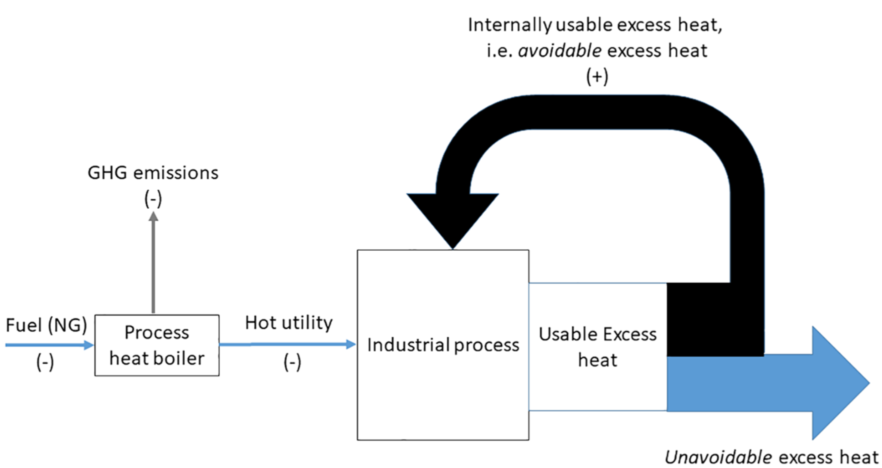

FIGURE 2 Internally usable excess heat, ie, avoidable excess heat, and unavoidable excess heat. The (+) and (−) indicate the consequences of increased usage of excess heat at the plant site [Color figure can be viewed at wileyonlinelibrary.com]

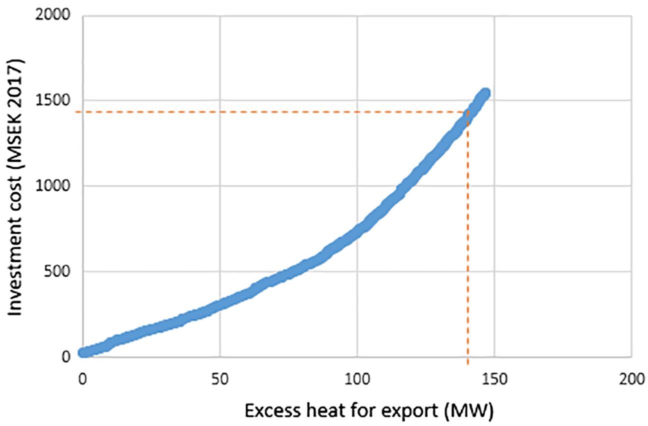

FIGURE 3 The cost of a heat collection system for the IEH and heat exchangers to transfer it to DH pipeline [Color figure can be viewed at wileyonlinelibrary.com]

increased IEH recovery and export to a DH network.[57] Based on the findings of that study and a previous evaluation of possible cost-effective systems for internal heat recovery,[59] it was estimated that 40 MW of the 180 MW of heat could be recovered in a cost-effective manner within the site, i.e., this amount of IEH is avoidable. In the base case, it was therefore assumed that 140 MW of unavoidable IEH was available for delivery to the DH pipeline. According to Hackl et al,[53] an additional 20 MW could be recovered and used at the site, although this would require significant investments. In Case 1, therefore, it was assumed that 20 MW of the 140 MW delivered is avoidable IEH. In Case 2, it was assumed that all IEH delivered is avoidable.

Estimates of investment costs for collection of IEH within the chemical complex were based on area targeting calculations using pinch analysis methods.[60] Optimal levels of heat contribution from individual plants within the complex were evaluated in Eriksson et al[56] and further developed to include a larger variety of combinations of process streams in the plants in Morandin and Eriksson.[58] The resulting initial cost estimates for the heat collection and distribution system were thereafter increased by 50% based on the site's energy managers' previous experience of heat exchanger cost estimates. The resulting cost curve for the heat collection system is shown in Figure 3. The cost increases exponentially with increasing amount of recovered IEH due to increased heat exchanger area and increased heat exchanger network complexity. Note that this curve does not include the costs for recovering the 40 MW of IEH assumed to be used for internal recovery. The cost includes the equipment needed to collect the IEH and to transfer it to the DH pipeline. As shown in the figure, the estimated investment costs required to collect and deliver 140 MW of heat to the DH pipeline is 1420 MSEK. The annual operating and maintenance cost for the heat collection system was assumed to be 1.5% of the investment cost.

A 50-km-long pipeline is required to transfer the recovered IEH to the DH system. The investment costs were estimated to 1350 MSEK, based on a review of a construction costs for built and planned heating water pipelines in Sweden, as discussed in Axelsson et al.[61] This cost is consistent with the review of pipeline costs published by Swedenergy.[62] The annual operating and maintenance costs for the heat pipeline (including pump stations) were assumed to be 1.0% of the investment cost. The cost to connect the pipeline to the DH network was estimated at approximately 380 MSEK, according to information provided by the DH network operator.

The total capital costs for collecting and delivering the IEH to the Gothenburg DH network were thus estimated at 3150 MSEK.

2.5 | Alternative district heating production

DH systems in Europe include systems in which heat is a minor by-product of a large electric power plant, and costranked systems.[63] All Swedish DH systems are costranked, implying that IEH must often compete with biomass or natural gas CHP or heat only boiler (HOB) plants. The DH network in Gothenburg plans to completely phase out firing of fossil fuels by 2030. This will involve decommissioning an existing gas-fired CHP plant. Most large DH systems in Sweden run bio-CHP plants to cover base-load heat production. This is therefore the most relevant technology with which to compare delivery of IEH. Table 1 presents representative data for a state-of-the-art bio-CHP plant.[64] Note that the total efficiency of the plant exceeds 100% on an LHV basis since the plant is assumed to be equipped with a flue gas condenser unit for recovery of the latent heat of the flue gases. The operating costs listed in Table 1 do not include the cost for the biomass fuel and the revenue associated with sold electricity, which depend on energy market conditions, see Section 2.6.

If it is assumed that the bio-CHP plant and the IEH occupy the same position in the heat production dispatch order, both heat supply options can be assumed to have the same annual operating time. It is therefore primarily the costs and emissions associated with operation of the bio-CHP plant that should be compared with delivery of IEH. The other heat production units in the district heating system can be assumed to be unaffected.

Figure 4 presents the future district heating production mix in which the energy company has invested in either a new bio-CHP plant or a pipeline for delivery of IEH from the chemical complex site. As can be seen in the figure, the base load heat is covered by a waste-to-energy CHP plant and existing deliveries of IEH. A new bio-CHP plant or delivery of IEH from the chemical complex site is assumed to be ranked immediately after these existing units in the dispatch order, resulting in an operating time of 5000 h/y. The Gothenburg DH system is very large compared with most district heating systems in Sweden. As a result, it is reasonable to assume that the system can accommodate substantial amounts of additional IEH, although the system currently includes IEH, waste-fired CHP, and an existing bio-CHP plant. As mentioned in the introduction, in many DH systems, IEH is unable to compete with existing waste-fired and/or biomass-fired CHP plants.

2.6 | Energy market scenarios for evaluating investment options

Future energy market conditions are subject to significant uncertainty, and it is appropriate to evaluate candidate investments using different scenarios that include possible future prices for fuels and energy carriers as well as energy taxes and other policy instruments. Such scenarios should also include GHG emission factors associated with energy flows. By assessing economic performance and GHG emissions for different future scenarios, it is possible to identify investment decisions that perform acceptably (in terms of both costs and GHG emissions) for a variety of different scenarios.

2.6.1 | Scenario construction using the Energy Price and Carbon Balance Scenarios (ENPAC) tool

The Energy Price and Carbon Balance Scenarios tool (ENPAC) was developed at Chalmers for assessing the long-term performance of energy projects in industrial process systems.[65,66] The tool calculates energy prices for large-volume users located in Northern Europe, based on possible future regional market fossil fuel prices and relevant policy instruments (eg, costs associated with emitting GHGs, as well as incentives for increased production of electricity and transportation fuels from renewable sources), and key characteristics of energy conversion technologies in the electric power and biofuel production sectors. The purpose and use of the ENPAC tool are illustrated in Figure 5.

2.6.2 | Scenarios used in this study

The energy market scenarios used in this study (see Table 2) include energy prices and GHG emission factors for years 2030 and 2040. Two different scenarios were considered, based on the IEA's World Energy Outlook 2017[67]: New Policy (NewPol) and Sustainable Development (SustDev). The NewPol scenario reflects possible future development of the energy sector based on a

TABLE 1 Key data for the bio-CHP plant

η_{el} (LHV)	29	%
η_{tot} (LHV)	113	%
Heat output capacity	140	MW
Operating time	5000	h/y
Investment cost	2100	MSEK
O&M fixed	200	SEK/kW installed heat capacity
O&M variable	21	SEK/MWh fuel

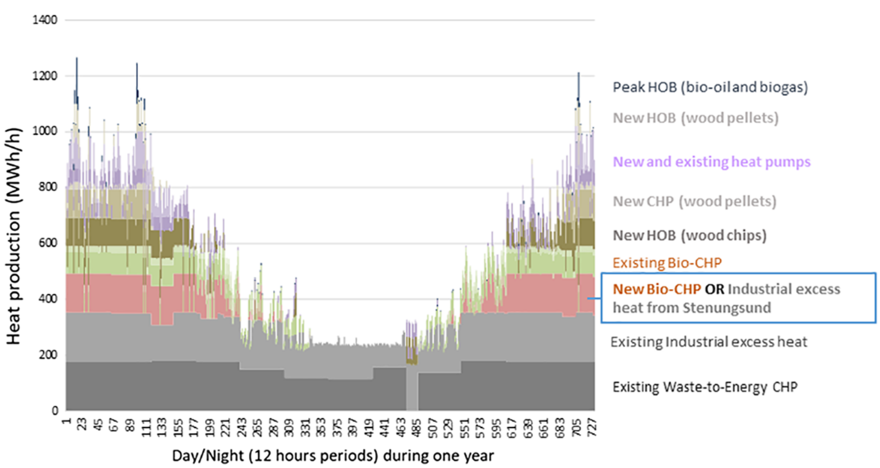

FIGURE 4 Future DH production mix in Gothenburg showing the possible placement of a new bio-CHP plant or delivery of IEH from the chemical complex site [Color figure can be viewed at wileyonlinelibrary.com]

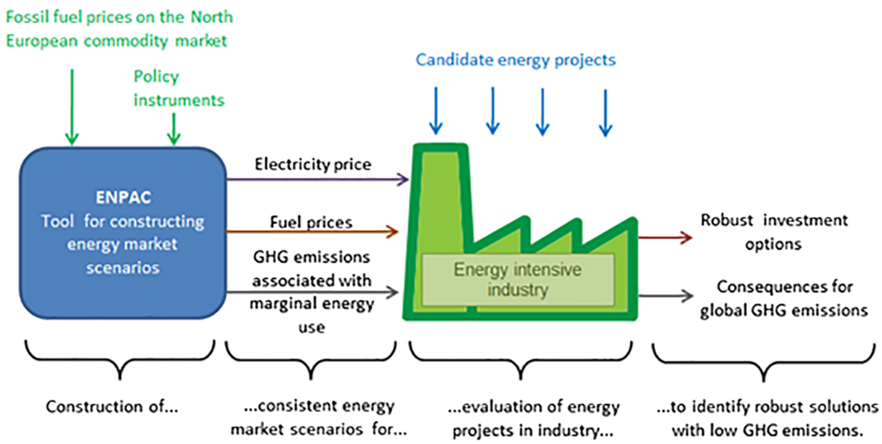

FIGURE 5 Overview of the purpose of the ENPAC tool for construction of energy market scenarios for evaluation of energy efficiency investments in energy intensive industry [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Energy market scenarios for years 2030 and 2040

Scenario Input	NewPol 2030	NewPol 2040	SustDev 2030	SustDev 2040
Oil price [USD/barrel]	94	111	69	64
OECD steam coal import price [USD/t]	80	82	66	64
CO_2 emission charge (general) [SEK/t_CO_2]	282	415	766	1209
CO_2 emission charge (transportation) [SEK/t_CO_2]	1127	1127	1127	1127
Green electricity premium [SEK/MWh]	51	0	51	0
Biofuel premium [SEK/MWh]	365	0	365	0
Carbon capture and storage (CCS) commercially available	No	Yes	No	Yes
Nuclear power allowed as build margin technology in power sector	No	Yes	Yes	Yes
Wind power allowed as build margin technology in power sector	Yes	Yes	Yes	No
Biomass considered as limited resource	No	No	Yes	Yes
Resulting values of end-user prices and GHG emission factors Biomass				
Price [SEK/MWh]	225	335	275	404
GHG emission factor [kg_CO_{2eq}/MWh]	8	8	405	405
Marginal user	FT	FT CCS	Pellets	Pellets
(FT = production of Fischer-Tropsch fuel; FT CCS = production of FT fuels in combination with CCS; Pellets = production of pellets as a substitute for coal)				
Electricity				
Price [SEK/MWh]	482	533	482	577
GHG emission factor [kg_CO_{2eq}/MWh]	0	0	0	0
Build margin power generation technology	Wind	Wind	Wind	Nuclear

detailed review of announced policy plans, assumed to lead to relatively moderate increases of energy prices. The SustDev scenario indicates substantially higher increases, reflecting a world that is united in a common commitment to achieving the energy-related goals in the United Nations' sustainable development plan, requiring high costs associated with emitting GHGs. Fossil fuel prices (ie, oil and coal prices) and the CO_2 emission charge were taken directly from World Energy Outlook 2017. The SustDev scenario has the lowest fossil fuel prices, resulting from the high CO_2 emission charge which leads to a low demand for fossil fuels. The main policy instrument considered is the CO_2 emission charge. Other inputs for the tool were taken from other sources and are discussed further in coming sections.

2.6.3 | Wood fuel market

In a global context, increased usage of bioenergy is crucial for sustainable development as pointed out in IEA's recent technology report.[68] Access to biomass is therefore likely to be limited in the future if the world's economies no longer rely on fossil fuels, as in the SustDev scenario. In the NewPol scenario, biomass might also be a limited resource, but probably in a time-frame beyond that considered in the scenarios used in this study. Biomass was therefore only assumed to be a limited resource in the SustDev scenario (see Table 2).

The wood fuel market price is calculated based on the willingness to pay (WTP) for a specified marginal wood fuel user category. The GHG emissions consequences associated with marginal use of biomass can thus also be determined.

Marginal users of wood fuel

It is important that the appropriate marginal user of biomass is considered when generating scenarios using the ENPAC tool, i.e., the user that operates at the intersection of the supply and demand curves. Two possible price setting categories considered in ENPAC are substitution of coal by industrial pellets and production of biofuel for the transportation sector. Industrial pellets are increasingly traded and transported on a global basis and can substitute fossil fuels in many parts of the stationary sector, e.g., for substitution of coal in large boilers in the power generation sector.[69] The transportation sector is also expected to require liquid fuels for the foreseeable future, and many studies indicate a growing demand for advanced biofuels during the period 2030 to 2050.[68,70]

Willingness to pay (WTP) for wood fuel to produce industrial pellets

Users of industrial pellets price are assumed to be willing to pay a price that can be directly related to the price of steam coal, including the general CO_2 emissions charge. In addition, the price premium paid to generators of green electricity in Sweden and many other countries was also assumed to affect the WTP for pellets. Costs considered to estimate the WTP for low-grade biomass for production of industrial pellets consider the whole value chain for production and use as a substitute for coal fuel for electricity production. The WTP also accounts for revenue from sales of green electricity certificates according to forecasted levels for Sweden.[71]

Willingness to pay (WTP) for wood fuel to produce biofuels for the transportation sector

Gasification-based production of Fischer-Tropsch (FT) biofuels for the transportation sector is an example of a possible future large-volume user of biomass. Biomass-based production of FT fuels was therefore considered as a possible alternative marginal user of biomass in ENPAC. In this case, the WTP for biomass can be assumed to depend on the production costs for FT fuels and the market price for fossil transport fuels (i.e., petrol and diesel, including the CO_2 charge applicable in the transportation sector) and possible revenue from premiums supporting production of renewable transport fuels. The CO_2 charge for fossil transportation fuels, and the level of premium supporting production of biofuels, were both set in accordance with current levels in Sweden.[72]

GHG emissions associated with wood fuel usage

If biomass is not a limited resource, it is only necessary to consider upstream GHG emissions related to harvesting, transport, and pretreatment of the biomass. If, on the other hand, biomass is assumed to be a limited resource, increased use of biomass in one sector must be compensated by an increased use of fossil fuels elsewhere in the energy system, assuming that no other carbon neutral options are available. For example, if industrial pellet production for use as a substitute fuel for coal in the power generation sector, and biomass is considered to be a limited resource, the GHG emissions associated with additional biomass usage are the GHG emissions for coal.

Prices and GHG emissions related to wood fuel in the NewPol and SustDev scenarios

The assumed marginal use of biomass is production of industrial pellets in the SustDev scenario (both 2030 and 2040), and production of FT fuels in the NewPol scenario, see Table 2. For the NewPol scenario in 2040, FT fuel production plants are assumed to adopt carbon capture and storage (CCS) technology, which is assumed to be available in 2040. It is important to note the substantial difference in GHG emissions factor associated with biomass usage in the scenarios where biomass is not considered a limited resource (NewPol) compared with the scenarios where it is considered to be limited (SustDev). Note also that the biomass prices are higher in the SustDev scenarios than in the NewPol scenarios for a given year.

2.6.4 | Electricity market

The ENPAC tool identifies the technology with the lowest levelized cost of electricity generation (including power plant investment cost) in the base-load power market (build margin). The build margin technology is assumed to determine the long-term future electricity wholesale price together with GHG emissions associated with marginal use of electricity.

New base-load capacity additions in the power generation sector are met by a mix of technologies which evolves over time as a result of continuously changing investment costs, primary energy prices and policy instruments. Elforsk[73] conducted an in-depth study of possible future capacity additions in the North European electricity system. Their results indicate that the fraction of fossil-based production decreases over time and is gradually replaced by renewable electricity and to a certain extent nuclear power. The exact mix of technologies and fuels is highly dependent on assumptions regarding energy prices, policy decisions, and willingness to invest in nuclear power. When critical tipping points are reached, the most attractive technology can shift very rapidly from technologies with high emissions to technologies with very low emissions. Therefore, when investigating the GHG balances of new investments, it is important to understand how a range of build margin technologies affects the outcome.

Candidate build margin power plant technologies considered in ENPAC include coal, natural gas combined cycle, wind power, and nuclear power. Nuclear power is assumed to be an option in both scenarios in 2040, but in 2030 it is considered only in the SustDev scenario. Wind power is assumed to be available for widespread deployment in both scenarios for 2030. However, in the SustDev scenario, it is assumed that the attractive locations for wind power are fully exploited by 2040 and it is thus not a candidate build margin technology. Power plants with CCS are assumed to be available as build margin candidates from 2040. As can be seen in Table 2, wind power is the build margin technology in all scenarios except the SustDev scenario for 2040. Thus, all scenarios have build margin technologies which are essentially free of GHG emissions.

3 | RESULTS

3.1 | Economic performance

Figure 6 presents the total cost for supplying heat to the DH system for the IEH and bio-CHP plant options, based on investment costs and operating and maintenance (O&M) costs presented in Section 2.4. The annualized capital cost for IEH heat supply is 231 MSEK/y, with O&M costs amounting to 59 MSEK/y, resulting in a total cost of SEK 290 MSEK/y. Note that the variable O&M costs (pumping costs) for IEH vary slightly between the scenarios and an average value was considered for the results presented in the figure.

For the bio-CHP plant, the total cost of heat production varies significantly between the different scenarios. The capital cost is 155 MSEK/y. Accounting for O&M costs, a total annual cost in the range of 236 to 354 MSEK/y is obtained. In both scenarios, the cost for the bio-CHP plant is lower than for IEH in 2030, and higher in 2040. In the SustDev 2040 scenario for example, the cost for IEH is 82% of the cost for the bio-CHP plant. The price of biomass is significantly higher than in the NewPol 2030 scenario (404 SEK/MWh compared with 225 SEK/MWh), which leads to higher fuel costs for the bio-CHP plant. The electricity price is also higher in the SustDev 2040 scenario (577 SEK/MWh compared with 533 SEK/MWh (including green certificates) in the NewPol 2040 scenario), leading to increased revenues for electricity sales. However, the influence of the electricity

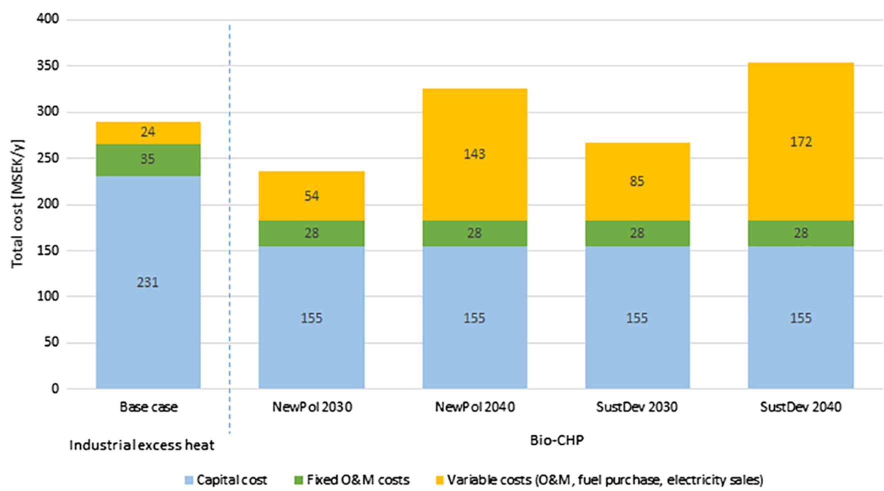

FIGURE 6 Total annual costs for heat supply based on IEH and a bio-CHP plant. Capital costs annualized assuming 20-year plant lifetime and 4% discount rate [Color figure can be viewed at wileyonlinelibrary.com]

price is less than that of the biomass price and the difference in electricity price is significantly smaller than the difference in biomass prices within these scenarios.

3.2 | Economic performance sensitivity analyses

Figure 7 presents the results for the economic performance sensitivity analyses. The results clearly show that if the owners of the chemical plants that supply the IEH require a pay-back period of 5 years or less, the initial minimum acceptable sales price for the heat is very high and not competitive compared with the Bio-CHP plant. As discussed in Section 2.2, this calculation reflects a business model by which the district heating company or a third party intervenes to mitigate the investment risk for the industrial decision makers. The figure shows that the cost for the industrial excess heat calculated based on a pay-back period of 5 years is almost 70% higher than for the bio-CHP plant in the SustDev 2040 scenario, in which the total cost for the bio-CHP plant is highest.

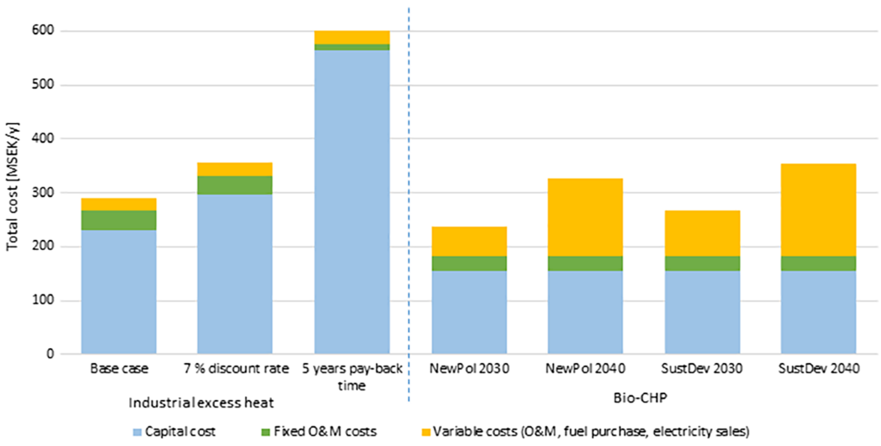

FIGURE 7 Total heat production costs for industrial excess heat and a bio-CHP plant. Sensitivity analysis with respect to discount rate and economic lifetime applied for the heat collection system within the chemical complex [Color figure can be viewed at wileyonlinelibrary.com]

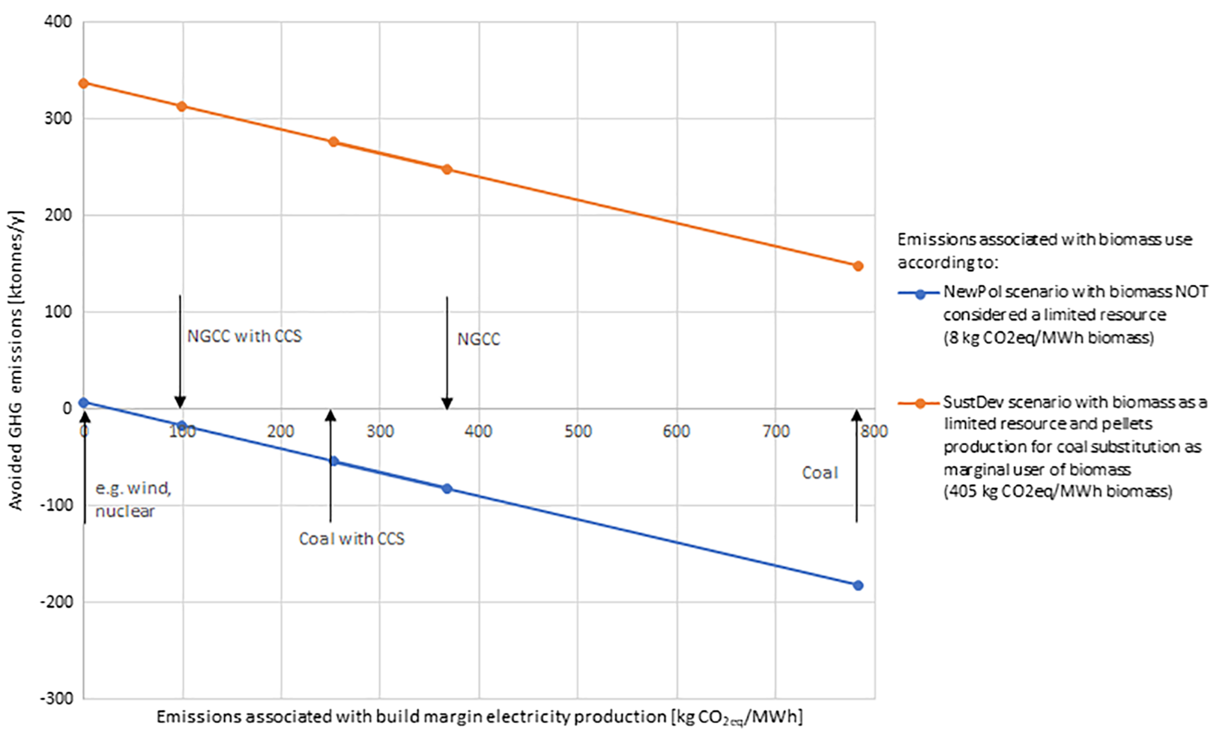

FIGURE 8 Avoided GHG emissions if IEH supplies heat instead of a new bio-CHP plant, for different assumptions regarding build margin electricity production and marginal use of biomass. Indicative levels of emissions for typical reference power generation technologies are indicated in the figure. NGCC = Natural Gas Combined Cycle; CCS = Carbon Capture and Storage [Color figure can be viewed at wileyonlinelibrary.com]

If a discount rate of 7% is applied for all capital costs for the IEH investment, the total cost is higher than that of the bio-CHP plant for all but the SustDev 2040 scenario (compared with the base case). In the SustDev 2040 scenario, however, the total costs for IEH and the bio-CHP plant are very similar. The total cost level for IEH with a discount rate of 7% is similar to that achieved by increasing the investment cost by 25% to 30%.

3.3 | Avoided GHG emissions

3.3.1 | Base case

Figure 8 shows the avoided GHG emissions when supplying IEH instead of building a new Bio-CHP plant. Note that in NewPol as well as SustDev scenarios, the build margin power generation technologies are assumed to be wind or nuclear, which are associated with zero GHG emissions. The effect of assuming higher GHG emissions for build margin electricity production is illustrated in the figure.

In the NewPol scenario with wind as the build margin technology (in both 2030 and 2040), the avoided emissions are low. This is because the emissions reduction related to avoided usage of biomass in the bio-CHP plant is small, and the avoided GHG emissions associated with the electric power co-generated by the Bio-CHP plant are very small since emissions associated with build margin electricity generation are close to zero. If the emissions associated with build margin electricity generation increase slightly compared with carbon-free generation, using IEH instead of investing in a bio-CHP plant increases the GHG emissions. This mirrors the current situation with marginal electricity production based on fossil technologies fired with coal or natural gas. From Figure 8, it can be seen that these technologies are associated with GHG emissions significantly higher than the threshold value for GHG emissions from build margin electricity generation at which the avoided GHG emissions related to excess heat usage become negative. Assuming such fossil-based electricity generation as build margin technology would result in a significant increase of global GHG emissions.

In the SustDev scenario, the situation is different, resulting in substantial GHG emissions reduction. In this scenario, it was assumed that biomass is a limited resource. By recovering IEH, biomass that would be used

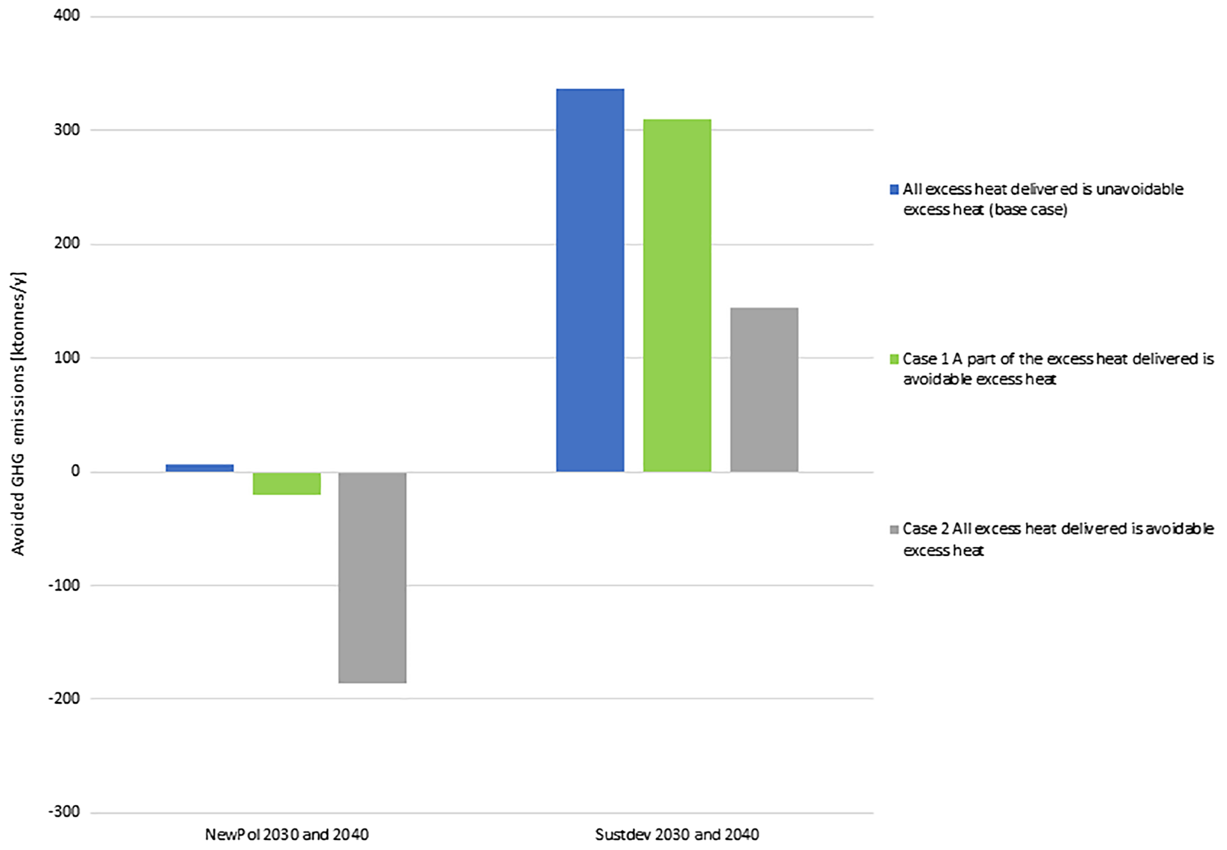

FIGURE 9 Avoided GHG emissions associated with industrial excess heat utilization for different scenarios, including different cases where emissions have been allocated to the excess heat [Color figure can be viewed at wileyonlinelibrary.com]

in the bio-CHP plant can be used instead to replace fossil fuels elsewhere (in the SustDev scenario, it is assumed to replace coal), thereby decreasing GHG emissions. The resulting GHG emissions reduction is substantial, even if the build margin electricity generation technology has significantly higher emissions than wind or nuclear. However, in this scenario, it is likely that build margin electricity production will be essentially free from GHG emissions.

3.3.2 | Emissions reduction sensitivity analysis: Unavoidable or avoidable excess heat

In the base case results presented in the previous section, no on-site emissions were allocated to IEH (all IEH was assumed to be unavoidable). Figure 9 shows the avoided GHG emissions for using IEH in the different scenarios, under different assumptions about the extent to which it is unavoidable.

For Case 1, in which part of the IEH is avoidable, there is a slight increase of GHG emissions compared with the base case. In the NewPol scenario, the GHG emissions increase for Case 1, since the GHG emissions reduction was low in the base case in which all IEH was assumed to be avoidable.

For Case 2, in which all IEH is assumed avoidable, the impact on GHG emissions changes substantially. In the NewPol scenario, emissions increase significantly. Emissions still decrease in the SustDev scenario, although significantly less than in the base case, because biomass is assumed to be a limited resource. As a result, although the IEH is burdened with emissions (from natural gas), the emissions reduction resulting from the release of biomass for usage elsewhere is greater.

4 | DISCUSSION

4.1 | Economic performance

The biomass price is decisive for the profitability of recovering IEH compared with investing in a bio-CHP plant. In the SustDev 2040 scenario, in which the total cost for IEH is significantly lower than the heat production cost for the bio-CHP plant, the biomass price is very high (404 SEK/MWh) due to high expected CO_2 emission charges (1209 SEK/t_CO_2 in 2040). The marginal user of wood fuel in this scenario is production of industrial pellets for substitution of coal in the power sector. The WTP for wood fuel in this scenario is naturally very high for industrial pellets, since the GHG emission factor for coal is very high.

The cost for IEH is also lower than the heat production cost for the bio-CHP plant in the NewPol 2040 scenario, in which the price for biomass is also relatively high (335 SEK/MWh). In this scenario, the biomass price is driven by the demand for biofuel in the transportation sector. The CO_2 emission charge assumed for the transport sector (in all scenarios) is based on the current level in Sweden (1127 SEK/t_CO_2). This level is significantly higher than the general CO_2 emission charge applicable for other sectors in all scenarios except SustDev 2040 in which similar levels are used. It should be noted that despite the (relatively) high level of CO_2 charge in the Swedish transportation sector (and with additional support for biofuels), production of biofuels has only increased moderately in Sweden [74]. This is the main reason why it was assumed in this study that the current differentiated level of CO_2 emission charge will not change significantly within the foreseeable future. However, the additional premium for biofuels is assumed to be discontinued after 2030. The assumed widespread availability of CCS technology as of year 2040 is expected to increase the WTP for biomass for biofuel production (FT fuels), given that a relatively pure stream of CO_2 is separated as part of the process, generating additional revenue corresponding to the CO_2 emission charge.

In the NewPol 2030 scenario, the cost for the industrial excess heat is significantly higher than the heat production cost for the bio-CHP plant. In this scenario, the biomass price (225 SEK/MWh) is much lower than in the 2040 scenarios. Still, the price is somewhat higher than the current level of wood fuel prices in Sweden (approximately 190 SEK/MWh for forest residues [75]). Thus, for current biomass price levels, the IEH recovery is not profitable. However, it is a long-term investment that must be evaluated for future conditions.

In addition to future energy market conditions and related prices, the capital costs are associated with significant uncertainties. The annualized capital cost is affected by the discount rate, the economic lifetime of the investment, and the total investment cost. The annuity factor considered in the base case was consistent with the hurdle rates used by energy companies for assessing this type of investment. However, industrial stakeholders usually have significantly higher requirements for return on investment. If the economic lifetime for the heat collection investments within the chemical complex site are reduced to 5 years, IEH recovery is no longer attractive, while the project could still be acceptable for a higher discount rate provided that the biomass price is very high.

4.2 | Reduction of GHG emissions

Assuming that the energy system makes a rapid transition to climate neutrality, the avoided GHG emissions related with IEH delivery to a DH network are not easy to quantify. During the period of transition, various measures and components will be more or less critical, and in this work we argue that the supply of biomass could be such a limitation, which should be considered when quantifying reduction of GHG emissions. Such limitations are primarily economic with clear implications for achieving transition to a climate-neutral energy system at the lowest cost. In this work, we have assumed that this translates to the assumption that if biomass is released from the studied system, more fossil fuels and feedstocks can be replaced elsewhere.

IEH recovery has no direct impact on the GHG emissions from the industrial plant site. The impact on emissions may instead be sought in the surrounding energy system as a result of reduced use of biomass and reduced electricity production in bio-CHP plants. Assuming a future with essentially fossil-free electricity production, the impact on GHG emissions of changed electricity production will also be small.

In the NewPol scenario (both 2030 and 2040), the avoided GHG emissions related with using IEH are very small (7 kt/y). In this scenario, biomass is not assumed to be a limited resource. Consequently, the GHG emissions that can be related to the use of biomass are relatively low and due to harvest, transport, and handling of the biomass. In the NewPol scenario, biomass might also be a limited resource, but probably within a time-frame beyond that considered in this study.

The SustDev scenario assumes a rapid transition to a climate-neutral energy system. Biomass is assumed to be a limited resource. Consequently, the impact on net GHG emissions of using IEH is very large (337 kt/y) because the biomass that would have been fired in a new bio-CHP plant can instead be used to replace coal with a very high GHG emission factor. It should be pointed out that biomass is not a limited resource today and that base-load electricity generation is still to a certain extent fossil-based. At present, it is therefore better from a climate perspective to produce heat and electricity in a bio-CHP plant than to use industrial excess heat from the chemical complex site. Thus, radical changes of the energy system are required in order for IEH to have a positive and significant impact on GHG emissions reduction.

The results show that there is a significant difference in avoided GHG emissions between using unavoidable and avoidable IEH. In the NewPol scenario, the GHG emissions can be expected to increase significantly if the IEH is avoidable, assuming that fossil feedstocks and fuels still dominate at the industrial process site. In the SustDev scenario, emissions reduction can still be achieved in this case, but at a significantly lower level than if the IEH is unavoidable. The energy and climate policies required to achieve the SustDev scenario are likely to lead to rapid transition to renewable and recycled feedstocks and fuels at the chemical complex site. However, this does not mean that avoidable IEH has no allocated emissions. Since biomass is considered to be a limited resource, emissions related to increased biomass usage are allocated to the avoidable excess heat. Consequently, the reduced level of avoided GHG emissions is similar in the SustDev and NewPol scenarios regardless of whether the IEH is avoidable or unavoidable. To achieve significant reduction of GHG emissions from IEH recovery, it is important that a significant portion of the IEH is unavoidable.

5 | CONCLUSIONS

This paper focused on recovery of IEH for delivery to DH systems. A holistic methodological framework was proposed for evaluating the impact on net GHG emissions as well as economic performance accounting in a consistent manner for key aspects that have been shown to be highly significant in previous work. The methodology focused on evaluation under different future energy market scenarios, i.e., consistent sets of possible future energy market prices and GHG emission factors for relevant energy carriers. Two scenarios were presented: (a) the NewPol scenario that reflects expected development of energy markets in accordance with implemented and planned policies; (b) the SustDev scenario that reflects the energy market development that is necessary to meet the energy-related targets in the United Nations' Sustainable Development goals. The proposed methodology was illustrated through a case study of export of IEH from an industrial site to a large DH network. Heat supply from IEH was compared with investment in a new biomass-fired CHP plant.

The biomass price was shown to be a decisive factor and is significantly higher in the SustDev scenario. In a short-term 2030 NewPol 2030 scenario, the cost for collecting and piping the IEH to a DH system is significantly higher than the cost for producing the same amount of heat in a bio-CHP plant. In a more long-term perspective (2040) and considering the SustDev scenario, substantial energy price increases lead to significantly higher alternative DH production costs, which favours recovery of IEH.

With respect to impact on GHG emissions reduction, the key factors identified were whether biomass is a limited resource or not and the GHG emissions associated with the build margin power generation technology. In the SustDev scenario, the GHG emissions reduction potential of IEH usage is very large. In this scenario, biomass is assumed to be a limited resource. As a result, the biomass released if IEH is used instead of operating a bio-CHP plant can be used to replace fossil fuels elsewhere, resulting in significant GHG emission reductions. Conversely, in the NewPol scenario where biomass is not a limited resource and the build margin electricity production is associated with fossil GHG emissions, the recovery and use of IEH leads to increased GHG emissions.

The proposed methodology also emphasized the importance of differentiating between avoidable and unavoidable IEH and how this affects the net GHG emissions related to its capture and use. The potential level of net GHG emissions reduction associated with using unavoidable IEH is significantly higher than the level that can be achieved if the excess heat is mainly avoidable, for all scenarios.

Finally, the proposed methodology also emphasized the importance of considering the significant differences between different types of stakeholders regarding the required return on investment for the equipment and infrastructure required to capture and use IEH. In order for IEH to have a lower heat supply cost than the alternative district heating production technology it has to be seen as a strategic investment with low discount rate and long economic lifetime. However, a somewhat higher discount rate could be acceptable in scenarios with very high biomass prices.

ACKNOWLEDGEMENTS

Funding for this work was provided by the Swedish Energy Agency (grant number P42222-1).

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How to cite this article: Pettersson K, Axelsson E, Eriksson L, Svensson E, Berntsson T, Harvey S. Holistic methodological framework for assessing the benefits of delivering industrial excess heat to a district heating network. *Int J Energy Res*. 2020;44:2634–2651. https://doi.org/10.1002/er.5005