Waste heat availability from hydrogen-based industries in district heating systems – A Swedish case study

(article starts on next page)

Energy Reports 14 (2025) 432–444

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Waste heat availability from hydrogen-based industries in district heating systems – A Swedish case study

Sofia Rosén [a,*], Parvathy Sobha [b], Cecilia Wallmark [c]

[a] Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden
[b] Department of Engineering Science and Mathematics, Luleå University of Technology, Luleå, Sweden
[c] Centre for Hydrogen Energy Systems Sweden, CH2ESS, Department of Engineering Science and Mathematics, Luleå University of Technology, Luleå, Sweden

ARTICLE INFO

Keywords:
Waste heat
Hydrogen-based industries
District heating
Energy system optimization model

ABSTRACT

This study examines the changes in waste heat (WH) potential from existing and emerging hydrogen-based industries and their impact on district heating (DH) systems. Gällivare and Gothenburg, two Swedish municipalities with differing demographics, industries, energy needs, renewable potential, and climates, are assessed for their common role in the ongoing hydrogen-based industrial transition. Gällivare and Gothenburg are modelled using energy system optimization models, TIMES-City and the in-house City model respectively, and are assessed for 2050. In Gällivare, integrating WH from emerging hydrogen-based industries into DH could reduce electricity demand for heating by around 20 times, thereby freeing up power for the decarbonization of industry and transport. In the maximum WH scenario, DH's share in heat supply reaches almost 100 %, reducing marginal heating costs by 22 % compared to the current level. In Gothenburg, recovered heat from electrolysis could meet up to 20 % of the annual heating demand. In general, Power-to-Heat technologies are preferred when WH availability is low. However, large-scale hydrogen production via electrolysis increases electricity grid congestion, leading to investments in combined heat and power plants to meet the demand for electricity locally.

1. Introduction

Sweden has set forth ambitious plans for utilizing hydrogen extensively in various sectors to aid climate mitigation (IEA, 2023). Although no national hydrogen strategy has yet been formalized, several proposals have been made (Fossil Free Sweden, 2021; Swedish Energy Agency, 2022). A common theme in the proposals is the focus on enhancing domestic competitiveness through green hydrogen production, infrastructure development and business engagement (Swedish Environmental Research Institute, 2024; Ćetkovićoch and Stockburger, 2023). Key sectors identified in the proposed hydrogen strategies includes steel industry and petroleum oil refineries and are expected to contribute to meeting Sweden's climate targets (Fossil Free Sweden, 2021; Swedish Energy Agency, 2022). This focus is justified as the iron and steel industry is responsible for the highest emissions in the industrial sector (34 %), followed by the minerals industry (19 %), and refineries (18 %) (Ministry of the Environment, 2020).

In conventional steelmaking, iron is extracted from iron ore, typically hematite (Fe_2O_3) or magnetite (Fe_3O_4) using one of three primary methods: blast furnace, direct reduction, or smelting reduction typically using coke or natural gas as the reducing agent (i.e., the substance that removes oxygen from the iron ore) (Hasanbeigi et al., 2014). However, the iron and steel industry in Sweden is transitioning away from fossil fuels toward hydrogen based processes. In these emerging approaches, hydrogen is used as the reducing agent in the direct reduction process, replacing carbon-based fuels like coke or natural gas to remove oxygen from iron ore. The subsequent steelmaking and casting stages are them powered primarily by electricity (Karakaya et al., 2018).

A key shift is in the production of sponge iron, also known as direct reduced iron (DRI). This is achieved by reducing iron ore in the solid state using hydrogen gas, without melting the iron. In this process, hydrogen reacts with the oxygen in the ore, producing water vapor and leaving behind a porous, metallic material known as sponge iron, which is fossil free. This high-quality feedstock can then be used in electric arc furnaces for steel production, significantly lowering carbon dioxide (CO_2) emissions compared to traditional blast furnace–basic oxygen furnace routes (Hasanbeigi et al., 2014; Balat, 2009). The hydrogen used in this process can be produced from fossil fuels, biomass, or through the electrolysis of water (Balat, 2009), preferably low-carbon electricity. Sweden's, access to renewable and low-carbon electricity from hydropower, nuclear, and wind energy is a key enabler of this transition

* Corresponding author.
E-mail addresses: sofia.rosen@chalmers.se (S. Rosén), parvathy.sobha@ltu.se (P. Sobha), cecilia.wallmark@ltu.se (C. Wallmark).

https://doi.org/10.1016/j.egyr.2025.06.028
Received 19 November 2024; Received in revised form 31 May 2025; Accepted 15 June 2025
Available online 20 June 2025

Nomenclature

CHP	Combined heat and power
COM	Commercial sector
COP	Coefficient of performance
DH	District heating
DRI	Direct reduced iron
EB	Electric boiler
EFOM	Energy flow optimization model
ESOM	Energy system optimization model
HOB	Heat only boiler
HP	Heat pump
IK	Industries as we know them
IND	Industrial sector
MC	Marginal cost
MUN	Municipal sector
NZ	Industries net-zero pledge
O&M	Operation and maintenance
PtH	Power-to-heat
PV	photovoltaic
RSD	Residential sector
SC	Sector coupling
TIMES	The Integrated MARKAL EFOM System
MARKAL	Market Allocation
TRA	Transportation sector
WH	Waste heat

(Ćetkovićoch and Stockburger, 2023). Notably, Hybrit Development AB (HYBRIT, 2024a), having produced the world's first fossil-free steel, and Stegra AB (Stegra, 2025), building the world's first green steel production plant, are pioneering hydrogen-based steelmaking technologies in northern Sweden, setting a global example for fossil-free steel production.

In oil refining industries, hydrogen is currently used to remove impurities from the feedstock and break down hydrocarbon chains. To decarbonize the value chain, refineries could switch to biofuels and/or electrofuels, both of which also require hydrogen for purification (for biofuels) and production (of electrofuels) processes (Energimyndigheten, 2019; Grahn et al., 2016). The purification of biofuels typically requires a larger amount of hydrogen, as compared to fossil fuels (Edvall et al., 2022). Electrofuels such as methanol (CH_3OH) and methane (CH_4), are synthetic hydrocarbons, produced from CO_2 and hydrogen (H_2) from electrolysis (Grahn et al., 2016), offering an alternative to traditional fuels. Today, oil refineries such as St1 and Preem, located on the west coast of Sweden, produce hydrogen through steam methane reforming (SMR) of natural gas. Even if the production shifts from fossil fuels to biofuels and/or electrofuels, the demand for hydrogen will remain. To reduce fossil fuel dependence in hydrogen production, alternatives like SMR of biogas or water electrolysis are being considered. However, producing hydrogen via electrolysis increases electricity demand, reducing the availability of cheap electricity for other sectors such as transport and heating (Rosén et al., 2024). In the south of Sweden, Preem refinery is expanding biofuel production units with hydrogen as a key feedstock (Mark-och miljödomstolen, 2017).

Sweden, home to a large energy-intensive industrial sector, has for long integrated waste heat into district heating (DH) networks (Lygnerud and Werner, 2017). WH refers to excess thermal energy such as high-temperature exhaust gases or residual steam released during different industrial or other processes, which would otherwise go unused. In the case of iron and steel plants, this heat can be captured from blast furnaces, or exhaust gases and used in the DH network to provide space heating or hot water to buildings. In 2020, 4.6 TWh (8 %) of input used in DH in Sweden was from waste heat (WH) (Swedish Energy Agency, 2024) and the estimated WH potential from existing industries ranges from 10 – 25 TWh (Miró et al., 2015). This practice of reusing WH aligns with the EU strategy for 'smart, sustainable, and inclusive growth', promoting efficient resources and energy use, thereby reducing primary energy consumption (European Comission, 2010). Integrating industrial WH into DH grids can also lead to reductions in CO_2 emissions, and overall system costs (Dominković et al., 2017).

The ongoing industrial transition towards hydrogen-based processes is expected to significantly alter the availability of industrial WH, thereby affecting DH systems and the broader energy system. For instance, shifting to hydrogen-based reduction in ironmaking, improves thermal efficiency compared to conventional fossil-fuel-based processes, resulting in lower WH generation (Trinca et al., 2023). On the other hand, the hydrogen production process itself, particularly through electrolysis, generates substantial amounts of low-grade WH, which can potentially be recovered and integrated into DH systems (Danish Energy Agency, 2024). While conventional industrial processes produce high-temperature WH that may already be utilized, electrolysis generates primarily low-grade heat, significantly affecting the quantity, quality, and usability of WH within local energy networks. As a result, the overall impact of the hydrogen transition on WH availability is complex and highly location-specific.

The potential of industrial WH in DH has been extensively studied in literature. Researchers have assessed the technical feasibility of integrating industrial WH into DH systems (Pelda et al., 2020), identified various measures that facilitate this integration (Fang et al., 2013), including political, social, and environmental factors (Ziemeleoch and Dace, 2022). Additionally, studies have explored the economic feasibility limits of integrating low-grade industrial WH into DH networks (Santin et al., 2020), developed optimized WH recovery systems to improve energy efficiency (Fitó et al., 2020). Several studies have focused on the iron and steel industry, analyzing and optimizing the processes for recovering industrial WH (Yang et al., 2024; Inayat, 2023)) and suggesting improved WH recovery methods (Jafari et al., 2023). However, there is a lack of studies examining the systemic impact of changes in WH potential, particularly concerning the emerging hydrogen-based iron and steel industries. These industries affect both the demand and supply sectors due to their high electricity demand (HYBRIT, 2024b) and changing WH potential. Consequently, a holistic assessment approach is necessary to capture the full scope of these changes.

Similarly, research on refineries has evaluated how WH potential changes with the adoption of new technologies such as electrolysis to reduce carbon emissions. Svensson et. al (Svensson et al., 2022) found that the use of electrolyzers could potentially increase the excess heat usable in DH network. However, the study was based on conventional processes rather than bio- and electrofuel production and did not address connections to the rest of the energy system. The electrification of Preems oil refinery using electrolysis has been studied for different scenarios, including both production of biofuels and electrofuels (Ahlström and Hult, 2023; Stenberg et al., 2024). In a study performed by Stenberg et al (Stenberg et al., 2024) on the Preem refinery in Lysekil, it was found that producing hydrogen through electrolysis resulted in significant volumes of WH (1–4 TWh depending on scenario). However, the study did not include the integration of WH in the district heating system. An alternative to producing sustainable bio- and/or electrofuels within the refineries is to shut down. This could be the case if oil refineries fail to follow policy development and/or remain competitive on the market (Samadi et al., 2016). In Gothenburg, WH from the two refineries Preem and St1 contributed with approximately one-third of the annual district heating demand in 2023 (Preem, 2023; St1, 2023;

Göteborg Energi AB, 2023). Since WH from the refineries contribute substantially to the annual DH supply in cities such as Gothenburg, their absence could significantly impact the DH system configuration. These uncertainties in oil refinery development pathways, combined with their critical role in urban DH systems, further underline the need for a comprehensive, system-level evaluation of future scenarios.

In summary, previous studies have provided valuable insights into technical feasibility, facilitating measures, economic limits, and sector-specific opportunities for integrating industrial WH into DH systems. However, a holistic view that considers the interdependencies between components such as energy supply, demand, resource potential, regulatory constraints, technological advancements, costs, and environmental impacts is still lacking. Hence this study aims to address this research gap by conducting system analysis on the energy system of municipalities undergoing hydrogen transition. Here, energy system optimization models (ESOM) are used to mathematically represent the structure and dynamics of these systems. The analysis focuses on understanding how changes in the availability of industrial WH from hydrogen-based industries affect DH networks and the broader municipal energy system.

To explore these impacts, two municipalities in Sweden are selected as separate case studies: Gällivare in the north and Gothenburg in the south, chosen for their contrasting industrial contexts. These municipalities are not physically connected, and their DH systems are completely independent. They are studied in parallel to allow for a comparative analysis of WH opportunities under differing industrial and regional contexts. Gällivare represents an emerging industrial hub centered on fossil-free sponge iron production, while Gothenburg hosts long-established oil refineries transitioning toward bio- and electrofuel production. This comparison enables a comprehensive analysis of WH recovery opportunities from both traditional and emerging industrial processes, reflecting broader trends in Sweden's energy and environmental strategies. Furthermore, differences in climate conditions and population dynamics between the two regions add additional depth to the assessment. Scenario analysis is employed to explore different future pathways by varying the availability of industrial waste heat, the development of hydrogen-based industries, and the future operational status of refineries.

The rest of the paper is organized as follows: **Section 2** provides background information about the municipalities; **Section 3** presents the models used; **Section 4** outlines the model results; **Section 5** discusses the results and **Section 6** concludes the paper.

2. Background

This section provides a brief comparison of the two case study municipalities (Refer Table 1). Fig. 1 provides a graphical representation of the DH network distributed across the two municipalities and their geographical location in Sweden.

Table 1
Comparison of Gothenburg and Gällivare specific to the research context.

	Gällivare	Gothenburg
Area (km^2) (SCB, 2024a)	16,800	1025
Population (SCB, 2024b)	17,540	579,000
Energy utility (Electricity and District Heating - ELC&DH)	610 MW hydropower 121 MW wind power 0.16 MW solar power 40 MW CHP plant*	600 MW CHP plants¤ 935 MW HOB plants 160 MW Large-scale HP 145 MW WH
Energy demand (ELC&DH)	1.8 & 0.16 TWh (SCB, 2024b)	4.6 & 3.3 TWh (Göteborg Energi AB, 2019)
Share of industrial ELC demand (Länsstyrelserna, 2024)+	82 %	13 %
Hydrogen based industries	Sponge Iron production (LKAB/ HYBRIT)	Refineries (St1, Preem, Nynas)

Values for model base year (2019) are provided; *Fuels- wood fuels, forest residues and peat; ¤Fuels – waste incineration, wood chips, natural gas; +2017

2.1. Gällivare

Gällivare is a municipality in northern Sweden. The local economy is heavily dependent on the mining industry (both copper and iron ore), which provides the majority of the employment opportunities for the local population. The expansion of iron ore mines necessitated the demolition or relocation of several houses and buildings, leading to the construction of new buildings in other areas of the municipality. Currently, the area is experiencing a profound green transition, primarily driven by green industries. For instance, HYBRIT, the world's first fossil-free sponge iron production plant is under construction by LKAB in Gällivare with an aim to reduce Sweden's CO_2 emissions by 10 % (SSAB, 2024; LKAB, 2024). The HYBRIT plant will employ green hydrogen produced to reduce iron ore to iron. It is well placed in Gällivare due to the availability of iron ore, cheap renewable electricity and water for hydrogen production. The plant is expected to provide new job opportunities and attract other companies in the renewable energy industry to the area. Additionally, the municipality is actively working to enhance Gällivare's social sustainability and overall quality of life (Gällivare Municipality, 2024) to benefit the current population and attract new residents. While the extent of these industrial and social changes is unknown, they are expected to influence the municipality's energy system, resulting in increased demand for energy services and products.

2.1.1. Gällivare's DH system

Gällivare's DH system, operated by the municipal utility Gällivare Energi AB provide heating to its residents, businesses, and public facilities. The main DH plant is a combined heat and power (CHP) plant equipped with flue-gas condensation technology, allowing it to recover additional heat from exhaust gases. It is primarily fueled by biomass including wood pellets, forest residues, and sawdust, sourced locally. Additionally, peat is used as a supplementary fuel to stabilize combustion, while oil serves as an emergency backup during extreme cold spells. The system produces approximately 170 GWh of heat in 2024, though this varies depending on winter severity. Technical investigations and discussions are going on in collaboration with LKAB, Gällivare Energi and the municipality for using the low-grade WH from reduction process in HYBRIT into the existing DH system (Gällivare Energi).

2.2. Gothenburg

Gothenburg is the second largest city in Sweden located in the southern part of the country. The city hosts several industries which are facing challenges as emissions are phased out. Electrification is stated as an important measure to reduce emission within the industry and road transportation sectors and stated as the potentially largest additional contributors to increasing the peak capacity of electricity (Göteborgs Stad, 2023). Historically, most electricity consumed within the city has been imported from the regional and national transmission grid (Göteborg Energi AB, 2023), but as the electricity demand increases, the risk of congestion in the electricity grid rises. The municipality's Environment and Climate Program states that only renewable energy sources shall be used from 2030 (Göteborgs Stad, 2023).

Three refineries, St1, Preem and Nynas are located in Gothenburg. In 2023, Preem and St1 were responsible for approximately half of the territorial emissions in Gothenburg due to their dependency on oil and natural gas (Miljöförvaltningen Göteborgs Stad, 2023). Preem aims to achieve a climate neutral value chain by 2035 by investing in units producing bio- and electrofuels (Preem, 2023). The current plan is to produce a total of 5 million m^3 of bio- and electrofuels annually by 2035,

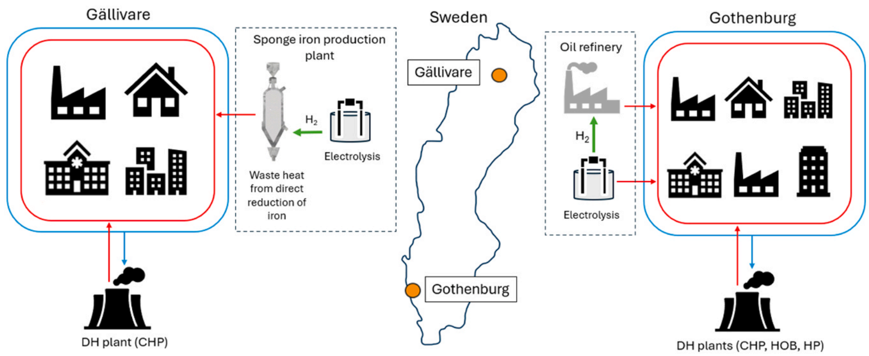

Fig. 1. Graphical representation of the DH network, red and blue represents supply and return lines respectively.

as compared to today's production of 18 million m^3 fossil and renewable fuels from the two refineries operated by Preem in Sweden (Preem, 2023). St1 is planning to set up a biorefinery, focusing on the production of sustainable aviation fuel (St1, 2023). The switch to bio- and/or electrofuels involves change in feedstock from crude oil to biomass and transition from fossil based to fossil-free hydrogen production. These changes could impact both the availability of WH in the local DH network and the industrial electricity demand.

2.2.1. Gothenburg's DH system

The DH system in Gothenburg was built in 1955–1960 and from 2006, close to 90 % of Gothenburg's heating demands are met through DH (Göteborg Energi AB, 2025). Göteborg Energi AB, the DH supplier in Gothenburg, has announced that by 2025, the DH must be sourced from either recycled (i.e., WH from industries and waste incineration) or renewable energy (Göteborg Energi AB, 2023). In 2023, approximately 3.5 TWh of DH was consumed in Gothenburg, with 67 % being sourced from WH from refineries and waste incineration (Göteborg Energi AB, 2023). Additionally, DH was sourced from CHP units fueled by wood chips and natural gas, heat-only-boiler (HOB) units and industrial scale heat pumps (HP). Uncertainties remain regarding future WH availability from refineries as their processes change. Except for the waste incineration plant (CHP waste) presented in Table 1, no existing technologies are included in the model runs.

3. Method

In this paper, we employ system analysis to study the energy system of the case study municipalities. System analysis aids to have a holistic view, allowing to identify the objectives, performance measures, constraints, resources, components and their interactions within a system. It offers a basis for developing ESOM which serve as the tools for analyzing and optimizing complex energy systems. These models are computational frameworks integrating diverse data, techno-economic parameters, and environmental considerations to simulate the behavior of the energy system under different scenarios (Meier, 1984). By leveraging these models, insights can be gained into strategies, measures, potential pathways and their trade-offs in achieving the climate and sustainability goals. Two different ESOMs are used to represent the two municipalities, TIMES-City model and an in-house City model. The rest of the section briefly introduces the models and Table 2 provides their comparison.

3.1. Model descriptions

3.1.1. TIMES-City Model

The TIMES-City-GÄL model is an ESOM based on TIMES-City (The Integrated MARKAL EFOM System) tailored to suit Gällivare's energy system (Refer Fig. 2). TIMES-City, developed within the Surecity (Sustainable and Resource Efficient Cities) project, consists a modelling structure to support cities in achieving their sustainability targets

Table 2
Comparing TIMES-City-GÄL and City models.

	TIMES-City-GÄL Model	City Model
Objective	Long-term energy planning	Investment & dispatch in a year
Type	Techno-economic ESOM of local energy system	
Methodology	Optimization (linear programming, cost minimization, dynamic)	
Structure	Demand of energy-intensive services: provided exogenously Supply: modeled endogenously	
Sectors considered*	Supply: ELC&DH, Fuel & ELC imports; Demand: RSD, MUN, COM, TRA, IND (HYBRIT - ELC Demand & WH)	Supply: ELC&DH, H2, Fuel & ELC imports; Demand: RSD, MUN, COM, TRA, IND (Refineries:– ELC&H2 Demand & WH)
Temporal resolution	12 per year	8760 per year
Time horizon	2018–2050	1 year, 2050
Cost inclusion	Import prices, investment & operational costs, energy & emission taxes	Import prices, investment & operational costs
Data source	Danish Energy Agency (Danish Energy Agency, 2024) (for techno-economic data)	

*RSD- residential, MUN- municipal, COM- commercial, TRA- transportation, IND- industrial sectors.

(Pardo-García et al., 2019). The TIMES-City model comprises two energy supply sectors and six demand sectors. The supply side includes one sector for current and potential energy resource extraction, imports, and exports (supply sector), and another for electricity generation and district heating systems (ELC&DH). On the demand side, the six sectors are: residential buildings (residential sector), private commercial buildings (commercial sector), municipality-managed buildings (municipal sector), the transport sector (divided into municipal and other demand), public lighting managed by the municipality (public lighting), and the industrial sector (Krook-Riekkola et al., 2018). The industrial sector is treated as a "black box" in TIMES-City since it lies beyond the city's discretion. However, in TIMES-City-Gal, we have incorporated a simplified representation of new green industrial facilities being built in Gällivare to account for shifts in electricity demand and potential integration with the local DH system (see (Sobha, 2023), for model details). The model also allows for electricity exchange with the national grid. While Gällivare currently exports significant amounts of electricity, this dynamic may shift as new green industries emerge.

The model input includes available energy resources, import limits, import prices, energy and emissions taxes, subsidies, climate targets, techno-economic parameters of current and future technologies, and energy demand among others (Refer Appendix A for key model inputs). Demand is seen as useful energy or as useful energy service, e.g. person-kilometers travelled in cars, or space heating in residential houses. Emission factors are defined either as tailpipe or upstream for greenhouses gases and air pollutants but are not discussed in the study as the primary focus is on WH utilization. The time frame in which the model operates spans from 2018 to 2050, with each year being divided into 12

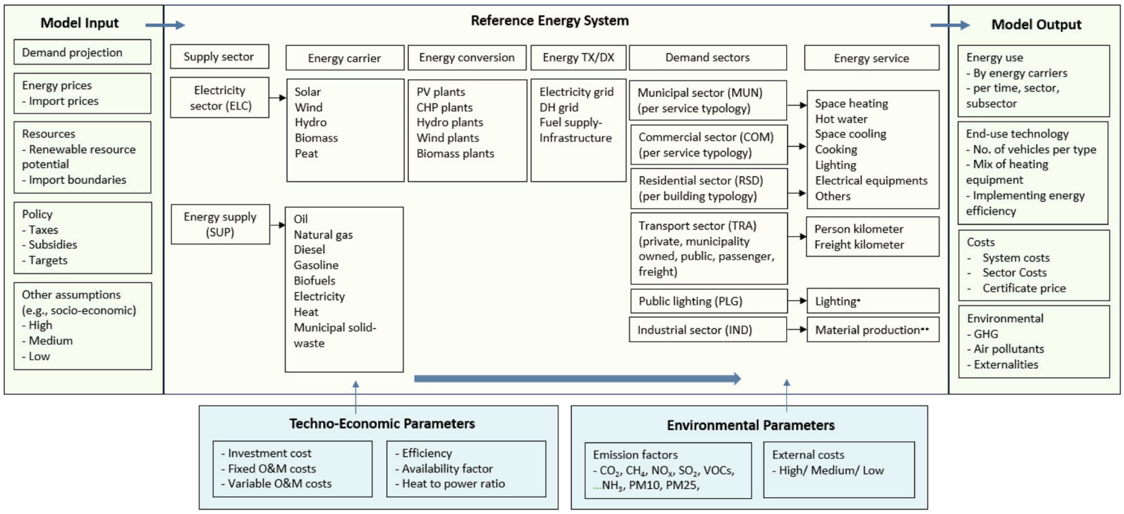

Fig. 2. Representation of TIMES-City-GAL model.

time-slices. Though the base year of the model is 2018, the model has been calibrated for years 2019 and 2020. The model optimizes net system cost to meet the given demand using available resources, technologies, and within the given constraints using Eq. 1 over the entire modelling horizon (Loulou et al., 2016) (Refer Appendix B for further equations). The model output includes energy use per sector and per fuel type, the choice of end-use technologies, emissions and various costs involved such as service costs (heating and electricity costs), investment cost, import costs and taxes among others.

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r,y) \quad (1)$$

where *NPV* is the net present value of the total cost for all regions; *ANNCOST(r,y)* is the annual cost in region *r* and for year *y*; $d_{r,y}$ is the general discount rate; *REFYR* is the reference year for discounting; *YEARS* is the set of years for which there are costs, including all years in the horizon, plus past years and *R* is the set of regions in the study area.

3.1.2. City Model

The city model developed at Chalmers University of Technology, Sweden, used to study the energy system of Gothenburg was first introduced in 2019 by Heinisch et al (Heinisch et al., 2019). where the sector-coupling of the electricity and DH sectors was studied. The study included demands from the residential and commercial sectors. The model was further developed to include private electric vehicles, buses and trucks (Heinisch et al., 2021). Subsequently, Rosén et al (Rosén et al., 2024). included hydrogen as an energy carrier in the model and studied the impact of hydrogen production on the urban energy system, although without considering WH from electrolyzers. The model input includes hourly electricity, heat, and hydrogen demands, techno-economic data for the available technologies, import capacity of electricity from the regional grid as well as approximate future electricity prices, as visualized in Fig. 3. The full set of equations describing the model is found in Appendix C and key model assumptions in Appendix D.

The objective function of the model presented in Eq. 2 aims to minimize the total system cost (C^{tot}) over one single year, including annualized investment cost (C_p^{inv}) and fixed operational and management costs ($C_p^{OM_{fix}}$) in relation to the installed capacity (i_p) of technology *p*, operational costs ($C_p^{OM_{var}}$) related to the hourly production ($g_{p,t}$) at timestep *t*, and lastly the cost of imported electricity from the regional grid (C_t^{el}) multiplied with the electricity imported (w_t).

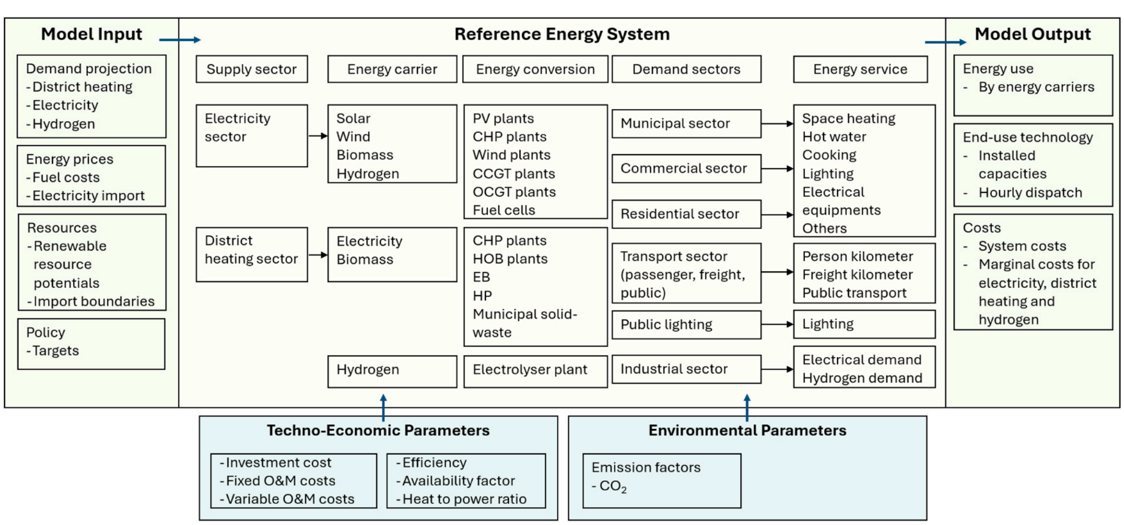

Fig. 3. Representation of the City model.

$$MINC^{tot} = \sum_{p \in P}\left(\left(C_p^{inv} + C_p^{OM_{fix}}\right) * s_p + \sum_{t \in T}\left(C_p^{OM_{var}} * g_{p,t} + c_{p,t}^{start} + c_{p,t}^{partload}\right)\right) + \sum_{t \in T} C_t^{el} * w_t \quad (2)$$

Three demand and supply balances are in the model: electricity, DH and hydrogen. The DH balance is presented in Eq. 3 where the hourly demand for heat, D_t^{heat}, and charging of heat storages, $z_{p,t}^{ch}$, need to be less than or equal to the generation from heating technologies, $g_{p,t}$, discharge of thermal energy storage, $z_{p,t}^{dch}$, and heat from the refineries and existing waste incineration plant, $y_{p,t}$.

$$D_t^{heat} + \sum_{p \in P_{HSt}} z_{p,t}^{ch} \leq \sum_{p \in P_H} g_{p,t} + \sum_{p \in P_{CHP}} \frac{g_{p,t}}{\alpha} + \sum_{p \in P_{HSt}} z_{p,t}^{dch} + \sum_{p \in P_{Ex}} y_{p,t} \quad (3)$$

The model is restricted through constraints on offshore wind farm availability, available roof and land area for solar PV investments, and limitation on fossil CO_2 emissions among others. The electricity and heat demand are derived from the demand profiles for the year 2019. As for the electricity demand, it is adjusted to follow the expected increase in population by 2050 (Göteborgs Stad, 2024b, 2024a) as well as including fully electrified private vehicles, trucks and buses. The only existing technology implemented to the model is a waste incineration plant (CHP waste) with possibility for an annual heat contribution of 1380 GWh (Renova, 2023) and a supply capacity of 185 MW (Romanchenko et al., 2017). To make use of the WH produced from the electrolyzer, an HP with a coefficient of performance (COP) value of 5.4 is included as an investment option as compared to the Large-scale HP that has a COP value of 3.6 (Danish Energy Agency, 2024). Eq. 4 describes the relation between the electrolyzer and Electrolyzer HP, with η_{heat} being the share of the input energy to the electrolyzer that can be used for DH purposes and with a value of 16.9 % (Danish Energy Agency, 2024).

$$g_{Electrolyzer\ HP,t} * \left(1 - 1/COP_{Eectrolyzer\ HP}\right) \leq \eta_{heat} * g_{Electrolyzer,t} \quad (4)$$

Import of electricity is limited to a capacity of 1.5 GWh/h derived from plans for the national transmission grid (SvK, 2023) and an offshore wind farm of 1 GW is assumed to be available for investment (Eolus, 2021). In a report by Edvall et al (Edvall et al., 2022), the future demand for hydrogen in three urban areas with hydrogen intense industries along the west coast of Sweden was estimated to be 4.9–14 TWh through interviews with the relevant actors. The highest hydrogen demand scenario for Gothenburg estimates an annual demand of 5 TWh, but since the future hydrogen demand is uncertain, the effect on the DH system configuration depending on hydrogen demand is evaluated through a sensitivity analysis.

3.1.3. Comparison of the models

The TIMES-City-GÄL model and the City model differ fundamentally in their focus, structure, and temporal resolution, reflecting the distinct characteristics and research needs of Gällivare and Gothenburg. TIMES-City-GÄL is built for long-term energy planning, modeling multiple years up to 2050 and dividing each year into 12 time slices, which is suitable for capturing gradual technological, infrastructural, and policy transitions in a fast-developing small municipality like Gällivare. In contrast, the City model focuses on operational analysis within a single year (2050) at an hourly resolution, making it well-suited for representing the real-time dynamics, sector coupling, and electricity grid challenges in a large, diversified urban area like Gothenburg. Another important distinction lies in how heating demand is represented: TIMES-City-GÄL models demand through detailed subsector divisions (e.g., different building types and efficiency levels), allowing flexibility between DH and individual heating solutions, while the City model aggregates the city's total heating demand and focuses only on the DH system, based on historical profiles. While the two models differ significantly in structure and temporal detail, they are each tailored to match the specific context of their municipality. TIMES-City-GÄL provides insights into long-term investment strategies and energy system evolution in a small, rapidly changing city, whereas the City model captures the operational complexity and sector coupling dynamics critical for a large, electricity-intensive city. Thus, although direct quantitative comparisons must be interpreted with care, together the models offer complementary perspectives, enabling a more comprehensive understanding of how hydrogen-based industrial developments impact local energy systems.

Both TIMES-City-GÄL and City models are techno-economic tools focused on system-wide cost-optimization under various energy and policy scenarios. It does not explicitly represent spatial aspects, network topology or asset placement within the municipality for different technologies. Instead, these physical and operational complexities are often reflected through cost parameters and technical constraints. Further the model determines whether a technology is selected as part of a cost-optimal solution. For example, in the case of DH, the model includes cost estimates for integrating WH based on local conditions and resource availability. It then assesses whether this integration is economically optimal. However, the model does not simulate the physical layout or the specific connection costs of pipelines or infrastructure required to utilize that WH. This approach enables the evaluation of the system-level role of technologies like WH integration within the broader context of energy transition. At the same time, it acknowledges that detailed engineering assessments are required to inform spatial planning, implementation and accurate estimation of WH connection costs.

3.2. Scenarios

Below, the three scenarios investigated are presented: *industries as we know them (IK)*, *industries net-zero pledge (NZ)* and *sector coupling (SC)*. In Table 3, the parameters differing between scenarios are summarized for the two municipalities.

Industries as we Know them (IK)

In this scenario, industrial developments proceed with a focus on climate but lack significant ambition resulting in the attainment of net zero target by industries after 2050. Consequently, in Gällivare, the development of HYBRIT progresses slowly, failing to reach the targeted iron production of 5.4 million tons per year (mtpy). Instead, it follows the initial plan, producing 1.3 mtpy starting from 2026 (HYBRIT, 2024c), and maintains this production level through 2050. The fully functional plant will have 4 electrolyzers with a capacity of 700 MW per electrolyzer. The heat from electrolyzers is considered for initiatives other than DH such as food production (Pelda et al., 2020; Fang et al., 2013). The WH potential depends on the stage of HYBRIT's development and varies based on the scenario assumptions. It is calculated during model run using the available data on HYBRIT's operation, WH integration, along with inputs from feasibility studies (Ziemeleoch and

Table 3
Scenario description for respective municipality.

		Industries as we know them (IK)	Industries Net-Zero pledge (NZ)	Sector coupling (SC)
Gällivare	Sponge iron production (mtpy)	1.3	5.4	5.4
	Waste heat considered (Yes/No)	No	No	Yes
Gothenburg	Annual waste heat from St1 and Preem refineries (GWh/yr)	1 120	0	373
	Available waste heat capacity from St1 and Preem refineries (MW)	145	0	48
	Hydrogen demand (TWh/yr)	-	-	5

Dace, 2022) and expert knowledge. All other factors such as fuel supply, fuel costs, taxes, available technologies and their techno-economic specifications remain same across all scenarios. A CO_2 cap has been applied enabling the municipality to take a green path and make no further investments in conventional fossil fuel-based plants. All demands (excluding the industrial electricity demand) are assumed to increase based on the population projection from the municipality and remains same across scenarios and is given in Table 4.

For Gothenburg this scenario represents a future where the refineries continue their processes and provide the same industrial WH as today. The annual WH supplied to the DH network in Gothenburg was 520 GWh (Preem, 2023) and 600 GWh (St1, 2023) for Preem and St1 respectively in 2023 and will act as reference values for WH potential. The supply capacity is 85 MW (St1) and 60 MW (Preem) respectively (Romanchenko et al., 2017). It is not allowed to invest in fossil fuel based technologies in any of the scenarios. The DH demand remains as 3.5 TWh/year in all scenarios.

Industries Net-Zero pledge (NZ)

In this scenario, industries achieve climate targets by 2050. In Gällivare, HYBRIT achieves its target of 5.4 mtpy of iron production by 2050, with 2.8 GW installed capacity from four electrolyzers. However, the scenario focuses solely on climate target and less attention is paid to sustainability such as maximizing resource efficiency. Hence the option of reusing WH and integrating it into DH is not considered. This scenario is still considered to allow comparison with other scenarios that prioritize both climate goals and sustainability.

For Gothenburg this scenario represents a future where the refineries could not find feasibility in new processes and are shut down to avoid emitting CO_2. This results in no available WH from the refineries.

Sector Coupling (SC)

This scenario is similar to NZ scenario, but the municipality is proactive in sustainability action along with climate mitigation. In Gällivare, the WH from HYBRIT is integrated into the DH system, leveraging WH as a sustainability measure to minimize fuel use (or reduce primary energy consumption) and enhance overall energy efficiency.

For Gothenburg this represents a future with reduced WH potential (compared to current availability) and increased electricity demand due to hydrogen production via electrolysis. The reduction in WH is in line with Preem's plans to reduce their fuel production. An annual hydrogen demand of 5 TWh is considered. It is assumed that 1/3 of the WH potential presented in the IK scenario is still available, resulting in 200 GWh/year and 173 GWh/year of WH with maximum supply capacities of 28 MW and 20 MW from St1 and Preem respectively.

4. Results

The TIMES-City-GÄL model results include the energy system behavior from 2018 to 2050, and the in-house city model presents the system status for the year 2050, hence results for the year 2050 are mainly presented in the analysis. The actual values of the parameters examined fall within different ranges due to the different sizes of the municipalities, so, they are represented in percentages rather than in absolute units to facilitate easier comparison (e.g., heat generated from different DH sources is shown in percentage rather than in MWh or GWh).

Table 4
Base year demand and demand projection for future years.

Year	Transport (GWh)	Residential (GWh)	Commercial (GWh)	Municipal (GWh)
2020	83	180	40	57
2030	94	203	45	64
2040	108	222	49	71
2050	121	241	53	76

4.1. DH sources

The share of thermal energy generated from different sources in the DH system includes the heat generated from both existing plants and the new plants invested in to meet the growing demand till 2050 (Refer Fig. 2). For Gällivare, in the IK scenario, around 50 % (54 GWh) of heat in the DH system is sourced from CHP plants utilizing peat and biomass (including wood fuels, forest residues), 40 % (43 GWh) from peat-based CHP and 10 % (7 GWh) from industrial WH. In the NZ scenario, 100 % (65 GWh) of DH generation is sourced from the CHP plants in the absence of WH. In the SC scenario, approximately half of the DH (54 GWh) is sourced from the CHP plant, with the remaining half (50 GWh) from industrial WH. The share of DH meeting the heating demand in the system increases with the WH availability (Refer Fig. 6). This is due to the increased cost efficiency as the scenarios do not include any energy efficiency targets such as reducing primary energy consumption (explained in section- New Investments). The model includes a one-time investment cost for the installation of industrial scale HPs for heat transfer while integrating WH into the system.

Peat is the primary fuel used in new heat generation plants. Currently, both biomass and peat are sourced from within a 300-kilometer radius of Gällivare. Peat is economically advantageous in Sweden due to its abundance, as it covers 15 % of the land area (Geological Survey of Sweden, 2024) and is exempt from carbon taxes and only subjected to a sulfur tax (IEA, 2024). This favorable regulatory status, combined with its local availability, makes peat a cost-effective choice compared to other types of biomass.

For Gothenburg in the IK scenario, approximately 24 % of the annual heat generation in DH stems from industrial WH, 39 % from already the already existing CHP waste plant, and 37 % comes from new investments, primarily Power-to-Heat (PtH) technologies including Large-scale HPs and electric boilers (EB). At hours when high electricity prices correlate with high heating demand, PtH technologies are shut down and the heat-only boiler (HOB) units are operated. In the NZ scenario, the annual share of heat supplied from new investments increases to 61 % primarily through investments in Large-scale HP units when compared to the IK scenario. The remaining 38 % of DH is supplied from the CHP waste plant.

In the SC scenario, the heat supply from Electrolyzer HP is related to the load of the electrolyzer and covers 20 % of the annual heat supply. Together with WH from other refinery processes it reaches 30 %. The Electrolyzer HP has a higher COP value resulting in less electricity being required to generate the same amount of heat compared to the Large-scale HP units. The installed electrolyzer capacity in the SC scenario is 1070 MW and the capacity of the Electrolyzer HP is 145 MW. The capacity of the Electrolyzer HP stays at 80 % of the possible capacity, explained by the number of full load hours needed for the investment to become feasible. In the SC scenario, it becomes cost-efficient to invest in CHP units as they can produce both electricity and heat. The electricity demand for the city is significantly larger for Gothenburg in the SC scenario due to primarily hydrogen production (approximately a total of +7.5 TWh when compared to the annual demand of 4.6 TWh in 2019 (Göteborg Energi AB, 2019)). With increased electricity demand, the connection to the regional grid becomes congested and frequently reaches its maximum capacity. Thus, local electricity production becomes of additional interest, where CHP units can serve both electricity and heating sectors.

4.2. New investments

In the TIMES-City-GÄL model, capacity expansion of the heat generating sources is driven by demand in the respective year. The maximum capacity expansion within the modeling horizon is reached by the year 2050 attributed to the growing demand and a similar trend is observed in investment costs. The heating demand is assumed to increase due to the hydrogen industry and the subsequent industrial, residential (population growth) and commercial (service industries) developments in the region. For Gothenburg, the heating demand is assumed to mainly depend on whether it is a cold or hot year and not population growth. This assumption is based on a tradeoff between better insulated buildings and population rise.

Fig. 3 illustrates the net DH capacity expansion till 2050 as a percentage of the base year capacity (same capacity for 2018–2020). The investment cost for heat generating plants and HPs (for WH) till 2050 is represented as a percentage of the net investment cost for heating systems (including plants, HPs and end-use technologies) till 2050 is shown for Gällivare. The aim is to visualize the demand growth and scaling of investments required to meet this demand.

The DH capacity expansion is highest in the IK scenario with 21 MW from new plants and 3 MW from WH. The capacity expansion is lowest in the NZ scenario with 5 MW from new plants with no WH availability. In the SC scenario, while no investments have been made in plants, there is a 20 MW capacity addition from WH. Across all scenarios, investment costs vary according to the capacity expansion. The results show that the existing CHP plant (based on biomass and peat) operates at maximum capacity, generating approximately 200 GWh in all scenarios throughout the model years. The heat output from new peat-based CHP plants varies with heating demand and operates at its maximum capacity around 2050. It can be observed that investment in DH plants increases with the integration of WH when the available WH is insufficient to meet the demand. This is because integrating WH reduces the cost of heat generation, making DH cost-effective compared to individual heating options. For example, the heat output from the new CHP plant is approximately 150 GWh in the IK scenario, where WH is incorporated, compared to only 40 GWh in the NZ scenario without WH. In the NZ scenario, fewer investments are made in DH and more in individual heating options. This indicates that WH enhances the cost-effectiveness of DH systems, driving investments in DH infrastructure, thereby expanding the DH share within the energy system.

Investment costs vary across scenarios depending on the integrated capacity. In the NZ scenario, investment cost for the new plants & HP (for WH) is reduced to approximately 25 % (1 m€) due to lower investments in DH compared to the IK scenario. Similarly, in the SC scenario, investment cost is reduced significantly (15 k€) due to abundant availability of WH leading to no investment in DH plants.

Fig. 4 illustrates the capacity additions and investments compared to the reference scenario IK for Gothenburg. In Gothenburg, in the NZ scenario, the total heating capacity increases by approximately 11 % (from 1300 MW to 1450 MW) while the investment cost as part of the total cost increases by 51 % when compared to the IK scenario (from 3.9 % to 5.9 %). 145 MW of heat generating capacity is no longer available as WH from the refineries is no longer accessible. Hence investments are made in Large-scale HPs that are operated flexibly with respect to electricity prices and heating demand.

The Large-scale HPs are shut down when availability of cheap electricity is low and HOB biogas units are run instead. As the Large-scale HP investments increase, so do the investments in HOB units to cover the hours with scarcity in cheap electricity, resulting in an overall larger capacity in the DH system. In the SC scenario the total installed capacity (1230 MW) is lower than in the IK scenario, while the investment cost as a part of the total cost is higher (4.2 %). This is because the investments are made in base load heat generation (CHP units), characterized by high investment costs and low running costs, that are run for more full load hours. As CHP units are invested in, the investments in both PtH and HOB units are lowered.

4.3. Marginal cost

In TIMES, marginal cost (MC) serves as an indicator of system-wide cost dynamics rather than the final consumer price. It reflects the cost incurred to produce one additional unit of heat (EUR/kWh), accounting for resource constraints, technology portfolios, and system optimization under perfect foresight assumptions. MC is derived as the shadow price of the heat demand balance constraint for given time period (t) (Eq. 5), representing the system's marginal value of heat (Eq. 6 and eq. 7). It includes annualized investment costs (capital expenditures, CAPEX), fixed and variable operation and maintenance costs (O&M), fuel costs and emission costs. Here, the marginal technology is the last unit dispatched to meet demand, determining MC at a given time. Changes in MC across scenarios (e.g., with waste heat integration or sector coupling) reveal shifts in system competitiveness and cost structures. Since TIMES assumes competitive markets and cost minimization, MC variations also indicate how constraints (e.g., infrastructure limits, fuel prices) affect heat production economics. MC is not the same as the DH consumer price, rather it's an internal system signal, final prices may include margins, taxes, or network costs. Eq. 6 shows the demand balance constraint for heat. MC is the lagrange multiplier **(λ)** associated with this constraint, representing the change in the total system cost when the demand increases by 1 unit (Eq. 7) (Loulou et al., 2016). Similar to the TIMES-City-GAL model, in the City model, the marginal cost comes from the change in total system cost in the objective function (Eq. 2) when producing one more unit of heat in the heat balance (Eq. 3), giving a marginal cost of heat (EUR/kWh) in each hour.

$$\sum_t Heat\ output_t \quad \geq \quad Heat\ demand_t \tag{5}$$

$$MC = \quad \lambda_{Heat\ demand} \tag{6}$$

$$\lambda_{Heat\ demand} = \quad \frac{\partial Total\ system\ cost}{\partial Increase\ in\ heat\ demand} \tag{7}$$

The percentage change in (MC of the heat generation in DH system

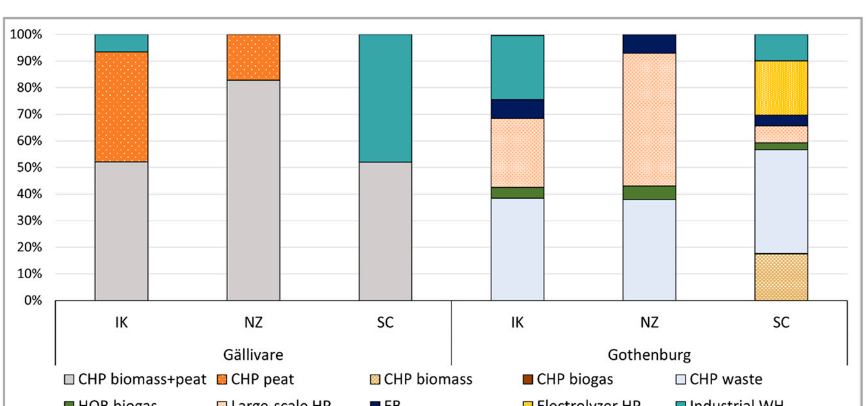

Fig. 4. Share of thermal energy generated from different plants in DH system in 2050.

with respect to the IK scenario is illustrated in Fig. 5. For Gällivare, the marginal cost is highest in the IK scenario. In this scenario, the share of demand met by DH is high, and any further increase in demand would necessitate capacity expansion in the DH system, resulting in higher marginal costs. In the NZ scenario, investments have been made in new CHP plants; however, a significant portion of the demand is met by individual heating technologies, providing room for demand addition without additional capacity expansion. The marginal cost is the lowest in the SC scenario, attributed to the ample availability of WH. There is an excess of WH (unused heat due to low demand) of approximately 35 % in the system, indicating a significant margin for heat utilization. In other words, in both the NZ and IK scenarios, the marginal technology involves new technology investments rather than the industrial WH.

In Gothenburg, the average MC of heat over the year remains similar between the IK and NZ scenarios. Industrial WH together with waste incineration are the cheapest option to supply DH in Gothenburg and as such, the first resources to be used. As the refineries can no longer provide WH in the NZ scenario, due to being shut down, the MC increases slightly as the use of Large-scale HPs, EBs and HOB units take on a larger share of the annual heat generation. In scenarios IK and NZ, the most expensive technology, in terms of operating costs is the HOB units, which are only used when cheap electricity is scarce. In the SC scenario, MC increases (+25 % compared to scenario IK), despite WH from refineries, waste incineration and Electrolyzer HP supplying slightly more annual WH (65 %) compared to the IK scenario (63 %). This can be explained by the investment in more expensive technologies (CHP units) to meet heat and electricity demand, coupled with congestion in the electricity grid, where power for hydrogen production is prioritized over power for heating purposes. Furthermore, investments need to be made in Electrolyzer HP to recover the heat from the electrolysis process.

4.4. City specific analysis

4.4.1. Gällivare

Heating Technologies. DH is not the sole technology used to meet the end-use heating demand in residential, commercial and municipal sectors in Gällivare. In all the scenarios, DH holds more than 90 % of the heating share. Generally, DH prices are high and are increasing in Sweden (Magnusson, 2012). However, with the inclusion of industrial WH the DH prices drop, and it would become economical to invest in new DH plants. Conversely, in the NZ scenario, the absence of WH leads to an increased reliance on other heating methods. Individual HPs are considered the next best option, particularly for non-residential buildings. This preference arises from the higher and more consistent energy demand (Bruck et al., 2022), economies of scale, and centralized management in these buildings contributing to lower costs. Other heating options includes solar thermal and biomass boiler technologies.

Sensitivity Analysis. In Gällivare, peat is the primary fuel used in new heat generation plants. To assess the impact of alternative fuels, a sensitivity analysis was conducted by varying the price of biomass fuels, such as pellets and wood chips, in comparison to peat. The price of biomass alternatives was systematically reduced by up to 50 % relative to the baseline price to evaluate at which point they would become competitive with peat-based heating. Additionally, a separate sensitivity analysis was performed to examine the factors influencing the share of DH within the local energy system. In this case, two parameters were varied: the fuel prices and the fixed O&M costs of DH systems. The results indicate that fuel price variations have the most significant influence on DH competitiveness, while changes in fixed O&M costs have only a minor effect on the overall system dynamics.

Trend in model horizon. Fig. 6 shows the fuel input used for heating services in Gällivare. WH, biomass, and peat are used in the DH system, while electricity is used for individual heating in buildings (in HPs). Other renewable sources, such as ambient heat (for HPs) and solar thermal energy, are also utilized but are not included in the figure, since they are not associated with any import limitations or fuel cost. The municipality has prioritized transitioning from peat to biomass and has established a minimum share of biomass, as seen over the years from 2020 to 2025 and the trend is expected to continue.

4.4.2. Gothenburg

Sensitivity Analysis. Uncertainties remain regarding the WH potential as well as hydrogen demand in future refining processes in Gothenburg. Hence a sensitivity analysis was carried out to study the robustness of the results and is presented in Fig. 7. The hydrogen demand varied between 1 and 5 TWh/yr and the availability of WH from refinery processes (excluding hydrogen production through electrolysis) varied between 0 % and 150 % compared to the IK scenario, as presented in Table 5.

It was found that CHP units were introduced when the demand for hydrogen exceeded 3 TWh. Simultaneously, the installed capacity of Large-scale HPs decreased, leading to a greater proportion of heat being generated from biomass resources rather than electricity. At 4 TWh of hydrogen demand, local offshore wind power and solar PV parks are

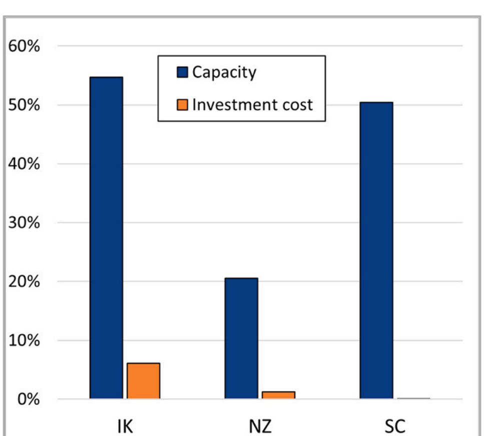

Fig. 5. DH capacity addition as percentage of total capacity and investment cost for this capacity expansion as a percentage of net investment cost including end use technologies for Gällivare for 2050.

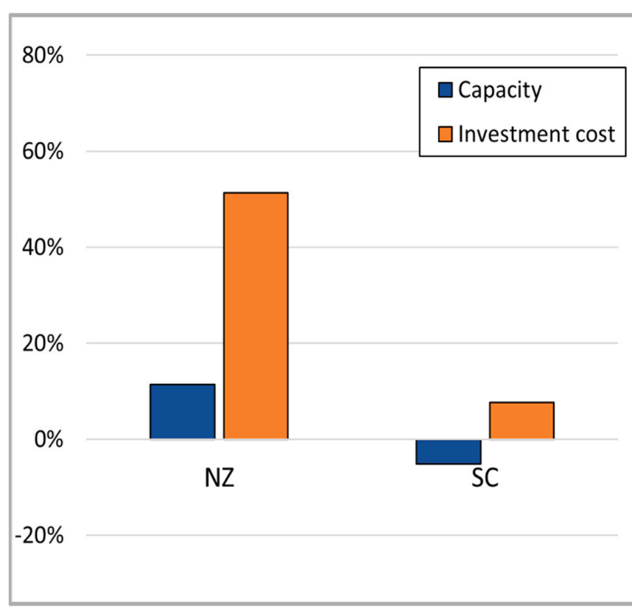

Fig. 6. Change in supply capacity and investment cost for heating technologies as a percentage of total cost, compared to the IK scenario in Gothenburg for 2050.

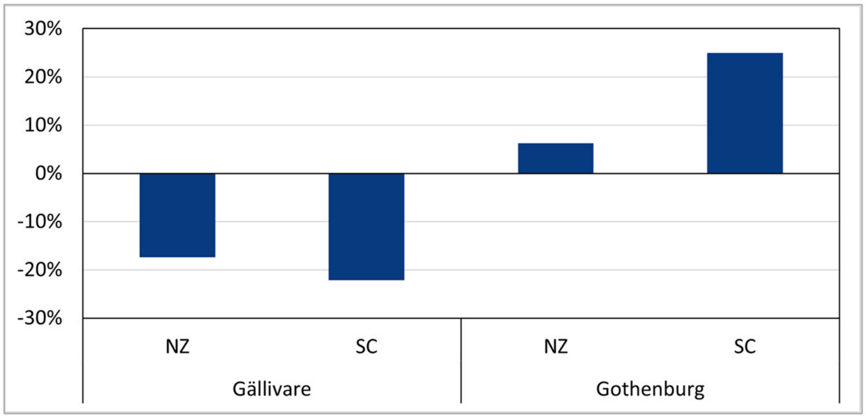

Fig. 7. Percentage change in marginal cost of the heat generation in DH system with respect to IK scenario for 2050.

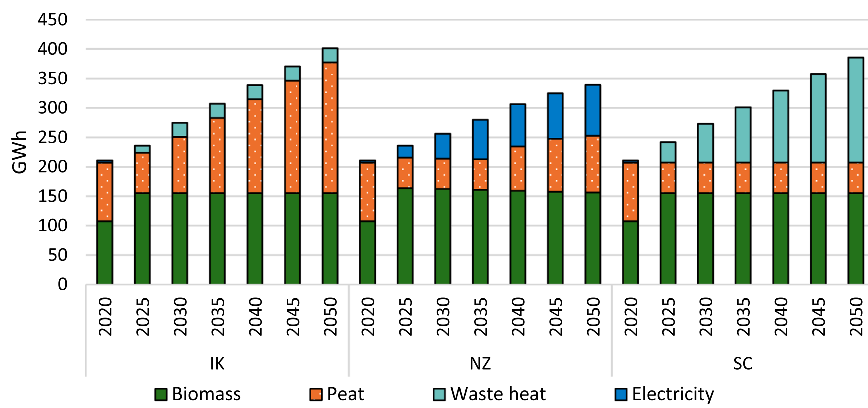

Fig. 8. Fuel input used to meet heating services in residential, municipal and commercial sectors in Gällivare.

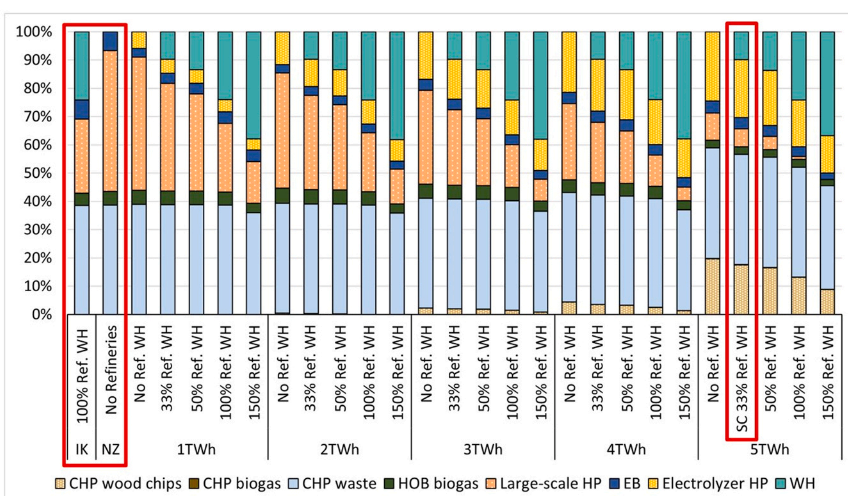

Fig. 9. Share of annual heat supply in 2050 for Gothenburg with varying availability of WH (0–150 %) from refinery processes (excluding hydrogen production), and demand for hydrogen (1–5 TWh/year); Ref- short for refineries.

invested in up to their maximum allowed capacity (1 GW and 0.1 GW respectively). As hydrogen demand reaches 5 TWh, the CHP unit reaches its largest investment.

As expected, the installed electrolyzer capacity varies with changes in hydrogen demand; however, the capacity remains relatively constant (±1 %) independent of refinery WH availability for the studied hydrogen demands. This suggests that the possibility to use WH from the electrolyzer in the DH network does not incentivize larger investments in electrolyzer capacity from a cost-effective perspective.

The full load hours of the electrolyzer remains relatively constant (±3 % compared to the SC scenario) while the full load hours of the Electrolyzer HP varies between −23 % and + 45 % compared to the SC scenario (7100 h electrolyzer; 4060 h Electrolyzer HP) as the demand for hydrogen and availability of WH from the refinery processes are

Table 5
Waste heat potentials from the oil refineries in Gothenburg in the sensitivity analysis.

Waste heat potential from oil refinery processes		0 %	33 %	50 %	100 %	150 %
Gothenburg	Annual waste heat from St1 and Preem (GWh/yr)	0	373	560	1 120	1680
	Capacity (MW)	0	48	73	145	218

changed. The number of full load hours of the Electrolyzer HP increases with smaller availability of WH and a small demand for hydrogen.

The highest number of full load hours for the Electrolyzer HP (5900 h) occurs with 1 TWh of hydrogen demand and with no WH from the remaining refining processes, while the lowest number of full load hours (3100 h) is observed with 5 TWh of hydrogen demand and 150 % WH availability. In a way, the electrolyzer and Electrolyzer HP compete for electricity, and the results show that hydrogen production is prioritized. This can be derived from the fact that while heat can be produced via different technologies, electrolyzers are the only allowed technology for hydrogen production in the study. The capacity of the Electrolyzer HP varies between 71 % and 82 % of the maximum possible capacity depending on WH availability and hydrogen demand, following a similar pattern as the full load hours.

5. Discussion

While the TIMES-City-GÄL model can provide insights into how investments are made over time and more sector specific results, the inhouse City model gives insights into how to operate the technologies invested in. However, the assessment of model results for Gällivare and Gothenburg reveal both similarities and differences in the evolution of hydrogen-based industries.

DH systems aim to meet the local heating demands by utilizing WH and other fuels. In Gällivare, DH sources include CHP plants and WH and in Gothenburg DH includes CHP plants, HOB units, HPs, waste-to-energy facilities and WH to meet the demand. The DH system benefits from economies of scope by integrating diverse heat consumers and suppliers into a wide network, optimizing local resource use. It also achieves economies of scale by reducing the average cost of heat through increased network size, more efficient production and operational efficiencies.

Due to the high technical efficiency and the availability of cheap electricity, HP becomes the most cost-effective option after existing plants and WH in DH in both municipalities. As the demand for heating and electricity rises due to population growth and industrial expansion, investments are made in CHP units that can produce both heat and electricity for both Gällivare and Gothenburg. In Gothenburg, CHP units become a cost-efficient technology mainly due to congestion in the electricity grid, resulting in the need for locally produced electricity. Congestion also limits the availability of cheap electricity for heating purposes. In both municipalities, further investments are made in wind power to meet the electricity demand.

This study focuses mainly on hydrogen produced through water electrolysis. It is possible that other ways to supply hydrogen are used in parallel, such as gasification or import (among other alternatives). This could be of particular interest to assess in Gothenburg where hydrogen production through electrolysis results in higher marginal cost of DH as well as congestion in the electricity grid, leading to more investments in locally produced electricity. In Gällivare, on the other hand, the introduction of hydrogen-based industries results in a lowered marginal cost of DH as more WH becomes available.

In the TIMES-City-GÄL model, the industrial sector is simplified to represent HYBRIT, and subsequent industrial developments are not currently represented. However, developments in other sectors are included. The focus on WH from HYBRIT and its integration in DH means that the results are unlikely to be significantly impacted by the omission of other industries. As for the inhouse city model describing Gothenburg, hydrogen as a fuel for shipping and long-haul transportation is not included and could be of interest for future studies.

Some assumptions and simplifications have been made in the model runs that are worth addressing. In both models, the COP is assumed to be constant although it varies over the year, affecting the electricity demand that risks being underestimated during winter and overestimated during summer. It is assumed that 16.9 % (Danish Energy Agency, 2024) of the electrolyzer load can be used for DH purposes. In general, it can be said that efficiencies typically vary depending on load and temperature, which is not captured in the models. Another assumption regards the heat demand implemented that is in reality dependent on whether it is a cold or warm year. For instance, the heat demand in Gothenburg can differ with 1 TWh between years (Göteborg Energi AB, 2019). The modeled year is relatively warm and for further analysis different years should be modeled.

6. Conclusion

Hydrogen-based industries present both opportunities and challenges for local energy systems, with impacts that are highly context-specific. In Gällivare, the development of hydrogen-based sponge iron production enables sector coupling between industry and the energy supply system. Integrating industrial WH into DH network improves energy efficiency, lowers electricity demand for heating, and reduces marginal costs. It also allows electricity to be redirected toward sectors where decarbonization is more difficult.

In contrast, Gothenburg faces a more complex situation. Although WH from refineries has historically supported its DH system, the shift in refinery operations to meet climate targets introduces uncertainty in heat supply. At the same time, increasing electricity demand for hydrogen production adds pressure on the grid, raising system costs and highlighting trade-offs between hydrogen deployment and DH system stability.

These contrasting cases demonstrate the need for tailored, location-specific energy strategies. Municipalities must assess the role of hydrogen in their broader energy planning, considering factors such as WH availability, grid capacity, fuel prices, and sector interactions. A uniform approach is inadequate; instead, adaptive, integrated planning is essential to ensure hydrogen development supports sustainable and resilient local energy systems.

CRediT authorship contribution statement

Sofia Rosén: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Cecilia Wallmark:** Writing – review & editing, Supervision, Resources. **Parvathy Sobha:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sofia Rosen reports financial support was provided by Göteborg Energi AB. Parvathy Sobha reports financial support was provided by Swedish Energy Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Sofia Rosén acknowledges Göteborg Energi AB for the financial support within the project Modellering av stadens energiomställning

(ES02), and Lisa Göransson and Mariliis Lehtveer for feedback on an early version of the manuscript. Parvathy Sobha acknowledges the financial support received from the Swedish Energy Agency [grant number 49627–2].

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2025.06.028.

Data availability

Data will be made available on request.

References

Ahlström, E., Hult, O., 2023. Hydrogen production for a net zero refinery. Chalmers tekniska högskola, Göteborg.

Balat, M., 2009. "Possible Methods for Hydrogen Production,". Energy Sources Part A 31, 39–50.

Bruck, A., Casamassima, L., Akhatova, A., Kranzl, L., Galanakis, K., 2022. "Creating Comparability among European Neighbourhoods to Enable the Transition of District Energy Infrastructures towards Positive Energy Districts,". Energies 15 (13), 4720.

S. Ćetkovićoch, J. Stockburger, "Hydrogen Strategy of Sweden: Unpacking the Multiple Drivers and Barriers to Hydrogen Development," RIFS Discussion Paper, April 2023, 2023.

Danish Energy Agency, "Technology Data," 2024. [Online]. Available: ⟨https://ens.dk/en/our-services/projections-and-models/technology-data/⟩.

Dominković, D.F., Bačeković, I., Sveinbjörnsson, D., Pedersen, A., Krajačić, G., 2017. "On the way towards smart energy supply in cities: The impact of interconnecting geographically distributed district heating grids on the energy system. Energy 137, 941–960.

Edvall, M., Eriksson, L., Harvey, S., Kjärstad, J., Larfeldt, J., 2022. "Vätgas på Västkusten. RISE Research Institute of, Sweden, Göteborg.

Energimyndigheten, "Industrins processrelaterade utsläpp av väcthusgaser och hur de kan minskas. En nulägesanalys inom regeringsuppdraget Industriklivet," Statens energimyndighet, Eskilstuna, 2019.

Eolus, "Vindkraftpark Västvind - Samrådsunderlag avgränsningssamråd," Eolus, Hässleholm, 2021.

European Comission, "A strategy for smart, sustainable and inclusive growth," European Commission, Brussels, 2010.

Fang, H., Xia, J., Zhu, K., Su, Y., Jiang, Y., 2013. "Industrial waste heat utilization for low temperature district heating,". Energy Policy 62, 236–246.

Fitó, J., Hodencq, S., Ramousse, J., Wurtz, F., Stutz, B., Debray, F., Vincent, B., 2020. "Energy- and exergy-based optimal designs of a low-temperature industrial waste heat recovery system in district heating,". Energy Convers. Manag. 211, 112753.

Fossil Free Sweden, "Strategy for fossil free competitiveness - Hydrogen," Fossil Free Sweden, 2021.

Gällivare Energi, "Preparations to be able to receive fossil-free residual heat," 11 3 2025. [Online]. Available: ⟨https://gallivareenergi.se/4894-2/⟩. [Använd 02 05 2025].

Gällivare Municipality, "News," Gällivare Municipality, 2024. [Online]. Available: ⟨https://gallivare.se/bygga-bo-och-miljo/arkiv/nyheter⟩. [Accessed 18 07 2024].

Geological Survey of Sweden, "Peat," [Online]. Available: ⟨https://www.sgu.se/en/physical-planning/energy/peat/⟩. [Accessed 19 07 2024].

Göteborg Energi AB, "Års- och hållbarhetsredovisning," Göteborg Energi AB, Gothenburg, 2019.

Göteborg Energi AB, "Års- och hållbarhetsredovisning 2023," Göteborg Energi AB, Göteborg, 2023.

Göteborg Energi AB, "Fjärrvärmens historia - en klimatsmart resa," Göteborg Energi AB, 2025. [Online]. Available: ⟨https://www.goteborgenergi.se/i-var-stad/artikelbank/fjarrvarmens-historia⟩. [Använd 05 05 2025].

Göteborgs Stad, "Göteborgs Stads energiplan 2022-2030," Göteborgs Stad, Göteborg, 2023.

Göteborgs Stad, Folkmängd 1984-2022 (SCB), Statistikdatabas Göteborgs Stad, 2024a.

Göteborgs Stad, "Demografisk analys: Befolkningsprognos 2024-2050," Göteborgs Stad, Stadsledningskontoret, Statistik och analys, Göteborg, 2024b.

M. Grahn, J. Hansson, S. Brynolf, R. Hackloch, M. Taljegård, "The role of electrofuels: a cost-effective solution for future transportation?," Report No 2016:13, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden, 2016.

Hasanbeigi, A., Arensoch, M., Price, L., 2014. Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review. Renew. Sustain. Energy Rev. 33, 645–658.

Heinisch, V., Göransson, L., Odenbergeroch, M., Johnsson, F., 2019. Interconnection of the electricity and heating sectors to support the energy transition in cities,". Int. J. Sustain. Energy Plan. Manag. 24, 57–66.

Heinisch, V., Göransson, L., Erlandsson, R., Hodel, H., Johnsson, F., Odenberger, M., 2021. "Smart electric vehicle charging strategies for sectoral coupling in a city energy system,". Appl. Energy 288.

HYBRIT, "Fossil-free steel – a joint opportunity!," HYBRIT, [Online]. Available: ⟨https://www.hybritdevelopment.se/en/⟩. [Accessed 18 07 2024a].

HYBRIT, "Positive decision on support for LKAB and HYBRIT," HYBRIT, 14 12 2023. [Online]. Available: ⟨https://www.hybritdevelopment.se/en/positive-decision-on-support-for-lkab-and-hybrit/#:~:text=The%20electricity%20demand%20for%20the,for%20the%20direct%20reduction%20process⟩. [Accessed 18 07 2024b].

HYBRIT, "HYBRIT: SSAB, LKAB and Vattenfall to begin industrialization of future fossil-free steelmaking by establishing the world's first production plant for fossil-free sponge iron in Gällivare," HYBRIT Fossil Free Steel, 24 03 2021. [Online]. Available: ⟨https://www.hybritdevelopment.se/en/march-24-2021-hybrit-ssab-lkab-and-vattenfall-to-begin-industrialization-of-future-fossil-free-steelmaking-by-establishing-the-worlds-first-production-plant-for-fossil-free-sponge-iron-in/#:~:text=Total%20capacity%20wil⟩. [Använd 12 06 2024c].

IEA, 2023. Hydrogen production and Infrastructure Projects Database. International Energy Agency.

IEA, "Energy, Carbon Dioxide and Sulphur Taxation," 15 November 2017. [Online]. Available: ⟨https://www.iea.org/policies/267-energy-carbon-dioxide-and-sulphur-taxation⟩. [Accessed 09 August 2024].

Inayat, A., 2023. "Current progress of process integration for waste heat recovery in steel and iron industries,". Fuel 338, 127237.

Jafari, M., Khan, M.I., Al-Ghamdi, S.G., Jaworskioch, A.J., Asfand, F., 2023. Waste heat recovery in iron and steel industry using organic Rankine cycles. Chem. Eng. J. 477, 146925.

Karakaya, E., Nuuroch, C., Assbring, L., 2018. "Potential transitions in the iron and steel industry in Sweden: Towards a hydrogen-based future? J. Clean. Prod. 195, 651–663.

A. Krook-Riekkola, B. Unluturk, J. Forsbergoch, S. Simoes, "SureCity Deliverable 3.1 Outline of the City-level modelling framework," SURECITY Project, 2018.

Länsstyrelserna, "Energistatistik," Länsstyrelsernas energi- och klimatarbete, 2017. [Online]. Available: ⟨https://www.leks.se/energistatistik/⟩. [Använd 23 07 2024].

LKAB, "HYBRIT: LKAB will be responsible for the construction of the demonstration plant in Gällivare," LKAB, 1 11 2023. [Online]. Available: ⟨https://lkab.com/en/press/hybrit-lkab-will-be-responsible-for-the-construction-of-the-demonstration-plant-in-gallivare/⟩. [Accessed 12 08 2024].

R. Loulou, G. Goldstein, A. Kanudia, A. Lettilaoch, U. Remme, Documentation for the TIMES Model, 2016.

Magnusson, D., 2012. "Swedish district heating—A system in stagnation: Current and future trends in the district heating sector,". Energy Policy 48, 449–459.

K. Lygnerud, S. Werner, "Risk of industrial heat recovery in district heating systems," i The 15th International Symposium on District Heating and Cooling, 2017.

Mark-och miljödomstolen, Mål nr M 2840-16, 2017.

Meier, P., 1984. "Energy System Optimization Models. Energy Systems Analysis for Developing Countries," i Lecture Notes in Economics and Mathematical Systems. Springer, Berlin, pp. 293–306.

Miljöförvaltningen Göteborgs Stad, "2023:12 Rapport från Göteborgs Stads klimatråd 2023," Miljöförvaltningen, Göteborg, 2023.

Ministry of the Environment, "Sweden's long-term strategy for reducing greenhouse gas emissions," Ministry of the Environment, 2020.

Miró, L., Brückneroch, S., Cabeza, L.F., 2015. Mapping and discussing Industrial Waste Heat (IWH) potentials. Renew. Sustain. Energy Rev. 51, 847–855.

Pardo-García, N., Simoes, S.G., Dias, L., Sandgren, A., Sunaoch, D., Krook-Riekkola, A., 2019. Sustainable and Resource Efficient Cities platform – SureCity holistic simulation and optimization for smart cities. J. Clean. Prod. 2015, 701–711.

Pelda, J., Stelteroch, F., Holler, S., 2020. Potential of integrating industrial waste heat and solar thermal energy into district heating networks in Germany. Energy 203, 117812.

Preem, "Års- och hållbarhetsredovisning 2023: Vi håller kursen," Preem, Stockholm, 2023.

Renova, "Hållbarhetsredovisning," Renova, Göteborg, 2023.

Romanchenko, D., Odenberger, M., Göranssonoch, L., Johnsson, F., 2017. Impact of electricity price fluctuations on the operation of district. Appl. Energy 204, 16–30.

Rosén, S., Göransson, L., Taljegardoch, M., Lehtveer, M., 2024. Modeling of a 'Hydrogen Valley' to investigate the impact of a regional pipeline for hydrogen supply. Front. Energy Res. 12.

S. Samadi, S. Lechtenböhmer, C. Schneider, K. Arnold, M. Fischedick, D. Schüweroch, A. Pastowski, "Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam," Wuppertal Institut, Wuppertal, 2016.

Santin, M., Chinese, D., Angelisoch, A.D., Biberacher, M., 2020. Feasibility limits of using low-grade industrial waste heat in symbiotic district heating and cooling networks. Clean. Technol. Environ. Policy 22, 1339–1357.

SCB, "Land- och vattenarealer," Statistikmyndigheten, 20 02 2024. [Online]. Available: ⟨https://www.scb.se/hitta-statistik/statistik-efter-amne/miljo/markanvandning/land-och-vattenarealer/⟩. [Accessed 23 07 2024a].

SCB, "Befolkningsstatistik efter region och kön. Månad 2000M01 - 2024M04," Statistikmyndigheten SCB, [Online]. Available: ⟨https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START_BE_BE0101_BE0101G/ManadBefStatRegion/⟩. [Accessed 27 05 2024b].

P. Sobha, Future Energy Landscapes in Northern Sweden: Sustainable Transition Scenarios for Municipalities, Luleå: Luleå University of Technology, Department of Engineering Sciences and Mathematics, Energy Science, 2023.

SSAB, "HYBRIT®. A new revolutionary steelmaking technology," SSAB, [Online]. Available: ⟨https://www.ssab.com/en/fossil-free-steel/insights/hybrit-a-new-revolutionary-steelmaking-technology⟩. [Accessed 18 07 2024].

St1, "Game Changer: Integrated Report 2023," St1 Nordic Oy, Helsinki, 2023.

Stegra, "Why Stegra?," Stegra, [Online]. Available: ⟨https://stegra.com/why-stegra⟩. [Använd 05 05 2025].

V. Stenberg, K. Eriksson, S. Heyne, C. Eklöf-Österberg, L. Lindkvistoch, N.Ó. Egilsson, "Flexibel och robust vätgasproduktion och -lagring i Lysekil," CIT Renergy AB, Göteborg, 2024.

E. Svensson, P. Bokingeoch, S. Harvey, "Targeting excess heat recovery in an oil refinery plant implementing large-scale carbon capture and power-to-hydrogen," i Proceedings of ECOS 2022 - 35th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Copenhagen, 2022.

SvK, "Grid development plan," Svenska Kraftnät, 2023.

Swedish Energy Agency, "Förslag till Sveriges nationella strategi för vätgas, elektrobränslen och ammoniak," Swedish Energy Agency, 2022.

Swedish Energy Agency, "Statistics," 15 12 2022. [Online]. Available: ⟨https://www.energimyndigheten.se/en/facts-and-figures/statistics/⟩. [Accessed 23 05 2024].

Swedish Environmental Research Institute, "The Potential of Hydrogen in a Swedish Context," Energiforsk AB, 2024.

Trinca, A., Patrizi, D., Verdone, N., Bassanooch, C., Vilardi, G., 2023. "Toward green steel: Modeling and environmental economic analysis of iron direct reduction with different reducing gases. J. Clean. Prod. 427, 139081.

Yang, X., Kong, Y., Zhou, Y., Liuoch, D., Xia, J., 2024. Case study on combined heat and water system for district heating in Beijing through recovery of industrial waste heat in Tangshan. Energy 300, 131316.

Ziemeleoch, J., Dace, E., 2022. An analytical framework for assessing the integration of the waste heat into a district heating system: Case of the city of Riga. Energy 254 (nr Part B), 124285.