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Heat recovery from low emission steel production through electrolysis and hydrogen reduction

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Master Thesis in Civil Engineering
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Abstract

The steel industry is a large emitter of carbon dioxide and uses a lot of energy. Because of an increased awareness of the detrimental effects of climate change, research in alternative ways to operate steel plants have been made. It is now possible to build plants with far less emissions by using electrolysis and hydrogen reduction. Electrolysis is a technology with a long historical background that can be used to produce hydrogen gas by splitting water molecules with the input of electricity. The electricity can be renewably produced, and the gas can then be used instead of carbon to reduce iron ore. Even though the emissions of carbon dioxide can be lowered (up to 95 %!) heat losses from furnaces and other processes remain high.

The steel and hydrogen plant which is planned to be built in Boden in Sweden by H2 Green Steel (H2GS) is studied in this report. Heat sources are identified and quantified as well as different usage areas of heat. A cost analysis is carried out to determine the profitability of different usages. Four main sources of heat have been found: cooling water, electrical arc furnace (EAF) off-gases, a tail gas from the direct reduction of iron ore and off-gases from the EAF slag handling. Concerning the usage areas, it has been found to be technically possible and economically justifiable to deliver district heating from H2GS to Luleå municipality, and that a condensing turbine can be part of this solution. However, the demand of heat from Luleå municipality must be clarified. Moreover, it has been found useful to further study how waste heat can be used to heat the facilities at site. This seems viable from an economic and technical perspective and is more circular than purchasing heat. On the other hand, using heat to produce electricity through low temperature ORC is not motivated economically for H2GS.

Keywords

Electrolysis, H2 Green Steel (H2GS), waste heat recovery, district heating.

Acknowledgments

I would like to thank Bror Styren for being my mentor at H2GS and supporting me by providing great ideas for how to present data and carry out the cost analysis. The data, contacts and advice given have also been an immense help in this project. I would also like to thank Magnus Genrup for the support given throughout the project and the knowledge provided about steam cycles which has helped me understand the topic of heat recovery more fully. Moreover, I would like to thank Hedvig Paradis for giving me the opportunity to write this thesis at H2GS and being a moral support.

Stockholm, February 2023
Sofia Kongshöj

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List of acronyms and abbreviations

AWE – Alkaline Water Electrolysis
BAF – Batch Annealing Furnace
CAPEX – Capital Expenditure
CAPEXdep – Capital Expenditure Depreciated (per year over lifetime)
DRI – Direct Reduced Iron
EAF – Electrical Arc Furnace
EBIT – Earnings Before Interest and Tax (yearly profit)
HBI – Hot Briquetted Iron
HRSG – Heat Recovery Steam Generator
LHV – Lower Heating Value
OPEX – Operating Expense
ORC – Organic Rankine Cycle
PEM – Polymer Electrolyte Membrane
ROCE – Return on Capital Employed (yearly profit/total CAPEX)
SOEC – Solide Oxide Electrolyser Cell

List of definitions

Off-gas – Exhaust gas either from the EAF furnaces or EAF slag
Quality of heat – Temperature of heat

Introduction

Background

The steel industry accounts for about seven percent of the global carbon dioxide emissions but has a large potential to reduce emissions and contribute to meet national and global climate targets. This can be done by replacing coal used to reduce iron ore with hydrogen produced from renewable energy. H2 Green Steel (H2GS) are building a facility for large scale production of steel in Boden where this will be done. The emissions are expected to be reduced by 95 % compared to traditional steel making. Additional to replacing coal they will minimize energy and material demand by reducing and recovering waste streams in the production line. (H2 Green Steel 2022a) In this report, the best way to recover waste heat will be evaluated.

Problem

There is not an infinite amount of renewable energy available today, and scientists and politicians agree that fossil energy must be phased out to minimise global warming. It is therefore important for industries to be energy efficient and not use more resources than necessary. Besides the environmental perspective it can be of economic value for a company to recover heat. Less heat must then be purchased for internal use and an excess generation of heat can be sold to nearby municipalities in the form of district heating. In some cases, heat can also be used to produce electricity and thereby reduce the amount that must be purchased from the grid. There may also be other interesting ways to use heat.

The balance between the available heat and the heat needed for different usage areas will be studied in this report, as well as the most energy and cost-efficient ways to recover it. First, the amount of waste heat found at different stages in the production line and the quality (temperature) of this heat will be identified. Thereafter, the quantity and quality of heat required for different usage areas will be studied. A cost analysis including the components needed for recovery and the revenue from different uses will then be carried out. Accordingly, the aim of this report is to answer the following research questions:

1. What heat sources exists in the hydrogen and steel plant?
2. How can this energy be extracted and at what quality?
3. What usage areas exist for the heat from the entire plant?
4. What is the most economical way to recover and use heat?

Delimitations

In this report, ways to increase the efficiency of specific processes to minimize heat generated will not be studied. Nor will detailed information about how processes work and data regarding flows of steam/gas/water be included. This is for confidentiality reasons. Instead, the order of magnitude of flows and data will be presented.

The report is also delimited according to early interviews about usage areas of waste heat. The usage areas studied are delivering heat to fish/shrimp farms, removing snow from streets, internal heating, purification of water, district heating and low temperature Organic Rankine Cycle (ORC). Early findings resulted in brief evaluations of some usage areas and deeper dives into other usage areas concluded to be more interesting for H2GS. This includes district heating and internal heating of the facilities at site.

For internal heating, and other usage areas requiring low-quality heat, the exact placement of heat exchangers and pipes have not been evaluated. This is because of the many options available and lack of detailed process diagrams including cooling water flows. Some options for further evaluation are however presented. Moreover, there is no design of the heating systems of each building available yet.

When it comes to district heating, two cases are presented. These are delivering district heating to Boden and delivering district heating to Luleå. A combined system between the two municipalities and H2GS's facility has not been evaluated since discussions are at an early stage and it would require an excessive analysis with a lot of speculations about future conditions.

The report has also been delimited according to information available today. For example, the possible supply of heat from the PEM electrolysers and SOECs have not been determined since the design has not been confirmed by the suppliers. The timing of questions about this was inappropriate during the contract negotiations.

Research methodology

The methodology used to answer the questions above has been a combination of qualitative interviews, a literature review, use of internal company data and presentations, contact with suppliers and calculations. A broad range of methods were used since this report is specific to one company's conditions and some information had to be given by the company, whereas some could be found by contacting related stakeholders and other information could be found by studying previous research. Additionally, some calculations and estimates were needed.

Data was supplied by H2GS and was used to find and quantify sources of heat available. Some calculations were needed in this process. Internal presentations were then studied to get an understanding of how the steel making process works and what previously has been researched on this topic. Moreover, two people at H2GS, who have studied heat recovery previously, were interviewed to include their ideas. Interviews were also held with one person working within industry and one professor with research in industry to get their ideas of how waste heat can be used. The answers were similar and confirmed what was already anticipated, which led to the conclusion that no more interviews about this were needed.

An interview was held with a process technology engineer at H2GS to understand the cooling systems of the plant. This was important to understand and predict how cooling systems can be combined with for example district heating. Further, an interview was held with a project manager at a steel producing company that aim to deliver district heating by using two-step cooling at their electrolysers. Their specific design is not presented in this report because of confidentiality but information from the interview made it possible to predict the possibility and cost of designing a similar system at H2GS.

Luleå Energi and Bodens Energi were contacted and interviewed about their heat demand and heat supply today and in the future. Further, suppliers of waste heat use solutions and suppliers of heat exchangers and heat pumps, were contacted. This was to gain technical and cost specific information about their technologies. In some cases, talks were followed up by email. Calculations were carried out to complement the information given, both when it comes to energy use and costs.

A literature review was performed to get an understanding of how electrolysers and heat recovery technologies work as well as to find cost estimates and specific data, such as duration diagrams for Luleå municipality. The literature was gathered from scientific papers and Google Scholar was used as the primary search engine. Some price information was gathered by looking up industry specific data.

Less formal conversations with the company supervisor and experts in different areas of the plant were held along the process to learn more about steel making.

Structure of the thesis

In the background of the report, the importance of recovering heat and the steel making process at H2GS is briefly described. In the results section, the first part describes the process in depth by going through it step by step and identifying and quantifying sources of heat. The hydrogen plant is described first and thereafter the steel plant. In the second part of this section the usage areas of heat are described and in third part a cost analysis, including ways to recover and use heat, is presented. The results section is followed by a discussion which includes suggestions for H2GS. Thereafter the conclusion summarizes the main takeaways.

Summary

In this report, different ways to make use of waste heat from H2 Green Steel’s (H2GS’s) plant that will be built in Boden is evaluated. The methods used are interviews, studying company data and files, studying literature on the topic and performing calculations. The sources of heat at the plant are identified by studying the entire steel making process, first the hydrogen plant and then the steel plant. The temperature (quality) and quantity of this heat is also presented. The sources of heat are divided into low- and high-quality and the uses into low- and high-quality heat requirements for easy comparison. The study also includes a cost analysis and suggestions for best use. In the cost analysis, the costs related to recovering heat, devices such as boilers/heat exchangers, as well as the costs related to using heat, pipes for district heating, turbines for electricity production etc., are included.

The usage areas found for low-quality heat are fish/shrimp farms, snow removal from streets and internal heating of the facilities at site. According to the findings, the most promising usage area is to heat the facilities at site. An internal heating system can be installed early in the building process and has the potential to save costs since the alternative is to purchase heat. This could for example be from Boden’s district heating system. Supplying heat to fish/shrimp farms could be profitable but is recommended to be prioritized lower since there is no company with a clear plan on how to finance such a project today. Snow removal from streets by install heating ducts have been found not to be economically justifiable since traditional snow removal with plowing machines is comparatively cheap. This option can however have other benefits such as an increased safety for the workers at site and a decreased use of fuel.

For the high-quality heat, the usage areas found are district heating to Boden or Luleå, electricity production through a condensing turbine, low temperature ORC and water purification. Delivering district heating to Luleå appears to have the largest profit and can utilize a large amount of heat. A condensing turbine that produces electricity could be part of this solution if the steam used would not require further investments. If an investment in a heat recovery steam generator would be needed for this, it would not be economically justifiable. For low temperature ORC, another way to produce electricity from waste heat, an investment does not seem to be economically viable today since the current electricity price for H2GS is low. However, using waste heat to produce electricity has an environmental value since it increases resource efficiency.

When it comes to waste heat purification of water the technology has not been tried out at large scale and the price must be negotiated to compete with traditional purification of water. If H2GS proceeds with a collaboration with the technology supplier, it is suggested that the technology is tested at a small scale to begin with to not risk the supply of demineralized water to all the electrolysers, and thereby hydrogen production for the reduction of iron ore.

Even if all uses are implemented, the need for cooling will be large and the investment in cooling towers would most likely be the same.

Background

General

H2GS is in the forefront of technological development and has taken on the massive challenge to decarbonise one of the most polluting industries, the steel industry. Unlike other steel making companies, H2GS will use hydrogen in the reduction process of iron ore to iron. The hydrogen will be produced from renewable energy, mainly hydropower, produced in the north of Sweden close to where the facility will be built. The goal is to have the production up and running by 2025 and the construction work has already begun. (H2 Green Steel 2022b)

H2GS's low carbon dioxide emissions will, apart from using hydrogen, arise from a sustainable approach to the entire process, from iron ore to finished steel product. The steel will for example not be cooled in between different production steps which saves a lot of energy. (H2 Green Steel 2021a) Moreover, the company will install an energy recovery system for the off-gases from the electric arc furnaces, a relatively novel technology. The company are also evaluating ways to recover waste streams such as heat and oxygen which will exist at large quantities at the plant. This is of importance both to get permission to operate the plant and to gain social acceptance.

According to a key principle in the environmental code the responsible for a business must economize on raw materials and energy and reduce the amount of waste so that a cycle is promoted. (2 kap.5§ MB) More specifically, a cost-benefit analysis should be carried out to review the possibility of taking in and/or supplying waste heat. (Lagen om vissa kostnads-nyttoanalyser på energiområdet (2014:268)) Moreover, energy auditing should be performed, if there are no other environmental management systems or an energy management system covering this, where options for energy efficiency measures should be stated. (Lagen om energikartläggning i stora företag (2014:266)) The company can then choose which cost-efficient energy savings measures to pursue.[1] These are only a few legal examples of the environmental responsibility large businesses have.

H2GS's project in Boden

H2GS will produce hot briquetted iron (HBI) and direct reduced iron (DRI) refined to different steel types with different qualities and usage areas. The facility will be built with short transport distances, minimizing heat losses and transportation of material. In a first step, green steel coils and hot briquetted green iron, for external sales, will be produced. Thereafter an expansion of the production of green steel coils is planned. In the first step, an electricity consumption of 9,5 TWh per year is expected and a maximum power usage of 1 700 MW if all processes run at the same time. (H2 Green steel 2021a) More than 40 % of the electrical power input will become heat losses according to findings in this report, further proving the importance of heat recovery.

An overview of the entire process can be seen in figure 1 below. In the lower right corner of the figure the rail and main road will be placed where iron ore will be transported to the facility. The ore will then be stored in a storage hall outside of the DRI towers, to later be reduced by hydrogen in the DRI towers. In the top right of the figure, the electrical grid is situated where electricity will be supplied for use in the electrolysers, devises that produce hydrogen, and other processes.

[1] Energy coordinator at Alleima, interview 27 October 2022

The reduced iron will be mixed with steel scrap and melted in electric arc furnaces (EAFs). The melt will then be added to ladle furnaces in which the chemical composition is adjusted. Some steel types also go through a vacuum treatment to drive out unwanted components. Thereafter, the steel is casted and hot rolled to form strips of steel. This step corresponds to the CSP process in the figure below. Iron oxide is then removed from the steel surface and the strips are welded together to form one long strip, which is then cold rolled. This is the PLTCM process shown in the figure. Lastly, there are four different production lines for surface treatment of the steel seen to the left in the figure. (H2 Green steel 2021a)

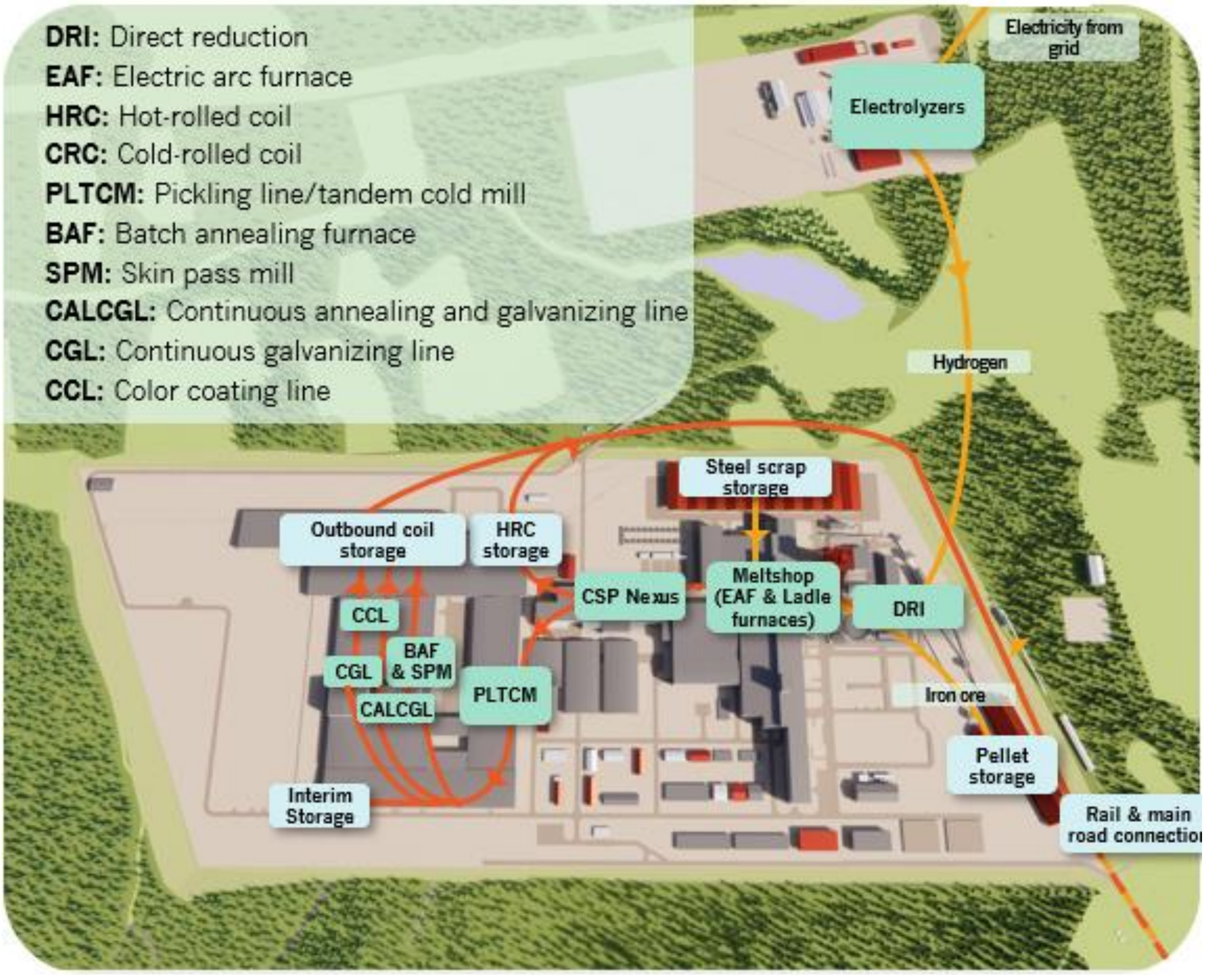

Figure 1: Overview of the hydrogen and steel plant.
(H2 Green Steel 2021b)

There will also be a water treatment plant at the facility, not shown in the figure, and a hydrogen storage of 30-ton hydrogen gas as a security back-up for the plant and to balance the grid. (H2 Green steel 2021a)

Results

Sources of heat

When evaluating the use of heat the temperature is of large importance. Therefore, both the energy amount and the temperature of the heat sources are described.

Electrolysers

In the electrolysers, electricity splits water molecules into hydrogen and oxygen in a process called electrolysis. Three types of electrolysers will be built at H2GS's facility: Alkaline Water Electrolysis (AWE), Proton exchange membrane (PEM) and Solid oxide (SOEC), and they each have specific advantages.[2] AWE is the most established technology on the market and has the lowest capital cost. It already exists on a commercial scale. PEM is not as technically developed but can be switched on and off in a short time which makes it well suited for balancing the power grid. It is also highly efficient. SOEC is compared to the other technologies far behind in its technological development but is efficient since it operates at high temperatures. An advantage is also that waste heat from the steel production can be used as a heat input, creating a circular energy flow. Thereby less electricity needs to be provided.

In electrolysis, electrical energy is transformed into chemical energy and the reaction can be summarized as follows:

$$Electricity/Heat + H_2O \rightarrow \mathrm{H}_2 + ½\, \mathrm{O}_2 \qquad (1)$$

It is a highly endothermic process which means that energy must be supplied for the reaction to occur. The enthalpy of electrolysis of water is composed of two parts which can be seen in equation 2. The change in Gibbs free energy, ΔG, represents the electrical energy input needed for the reaction to occur whereas the entropic part, T×ΔS, represents the thermal energy needed. (Rashidi Et. al. 2022)

$$\Delta H = \Delta G + T \times \Delta S \qquad (2)$$

More energy, ΔH, must be provided at 80 °C than at 750 °C, which are approximate operating temperatures for AWE/PEM and SOEC respectively. Thereby electrolysis is enhanced by operating at higher temperatures. The additional energy needed at 80 °C is supplied by electricity, ΔG, which can be seen in table 1.

[2]Styren, Bror; Project Analyst. Introduktion till företaget 4 September 2022.

Table 1: Energy requirements as heat and electricity in the electrolysers.

Temperature [°C]	ΔH [kJ/mol]	T×ΔS [kJ/mol]	ΔG [kJ/mol]
80	284	55,7	228
750	248	56,7	191

(Data from Sundén 2019, 218)

However, PEM and AWE electrolysers do not need heat to be externally supplied since the losses from the electrochemical reactions provide enough heat for the reaction to occur. For the SOEC on the other hand, external heat is required.[3] At H2GS this heat will come from the exhaust gases of the melt shop which will be supplied as steam after heat conversion in a boiler.

An electrolyser is made of two electrodes (sometimes plated with a metal catalyst) connected to an electrical circuit which is placed in an electrolyte. Water has a low degree of dissociation into O_2^- and H^+ ions and is not conductive. Therefore, the electrolyte often contains a salt or an acid, typically $NaSO_4$, NaOH or H_2SO_4. As power is supplied to the system the cathode is charged negatively and attracts positive ions whereas the anode is charged positively and attracts negative ions. In some electrolysers a solid membrane is used to supply the water with its conductive capability. This is the case for PEM electrolysers and SOECs. (Sundén 2019, 40)

AWE

Alkaline water electrolysis, AWE, electrolysers use an alkaline solution of sodium hydroxide (NaOH) or potassium hydroxide (KOH) as the electrolyte. At H2GS's facility KOH will be used. Water molecules are dissociated at the cathode and the hydroxide ions (OH^-) are transported from the cathode to the anode. (Sundén 2019, 42) Figure 2 illustrates the process, and the half cell and overall reactions are as follows:

Anode: $2OH^- \rightarrow H_2O + ½\, O_2 + 2e^-$
Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
Overall reaction: $H_2O \rightarrow H_2 + ½\, O_2$

[3] Genrup, Magnus; professor at the institution for energy science at Lunds Tekniska högskola. Supervisor meeting 6 September 2022.

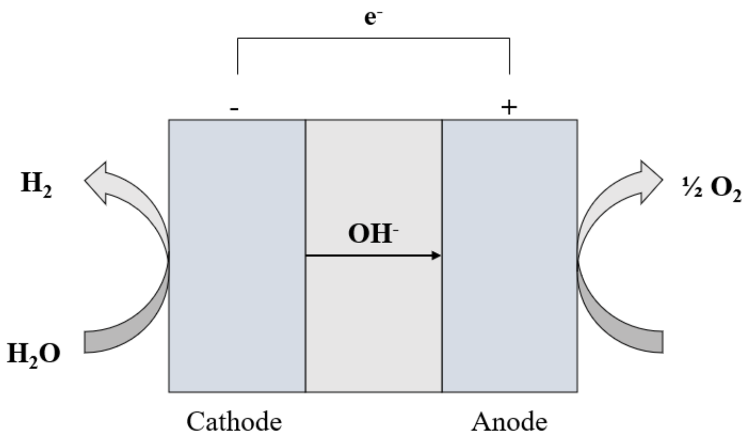

Figure 2: Illustration of Alkaline Water Electrolysis, AWE.
(Modified from Shiva Kumar & Himabindu 2019)

In AWE electrolysers, circulating lye (electrolyte) regulates the operating temperature. At H2GS's plant the lye will go into the electrolysers at a temperature of about 45 °C and out at about 85 °C.[4] The lye will then be cooled by a cooling water of 45 °C that gets heated to about 75 °C.[5] This is according to the current design of the cooling system.

To transfer heat from the cooling water, a heat exchanger can be used and this comes with some losses in the heat transfer. The performance of a heat exchanger can be described by its approach temperature which is the smallest temperature difference between the cold and hot streams. For liquid-to-liquid heat exchange, a 7 °C approach can be assumed.[6] Smaller approach temperatures are usually not economically justifiable since the heating area, thereby the size of the heat exchanger, must be very large. The correlation between the heating area and the heat transfer rate, Q, can be seen in the equation below (EnggCyclopedia 2022):

$$Q = U \times A \times \Delta T \qquad (3)$$

In this, Q is the heat transfer rate in kW, U is the heat transfer coefficient in kW/m^3*°C, A is the heat transfer surface area in m^3 and ΔT is the temperature difference between the cold and the hot streams in °C.

Because of the transfer loss, the highest temperature that can be gained from cooling water at 75 °C is 68 °C. This temperature is too low for some uses, such as district heating, but a temperature closer to the lye temperature could be more useful. It has been found that a cooling system like the one shown in figure 3 below possibly could be constructed. [7] This

[4] Dhar, Anu; Process Expert Engineer. 19 September 2022.
[5] Data provided by Styren, Bror; Project Analyst. 5 September 2022.
[6] Dhar, Anu; Process Expert Engineer. 8 September 2022.
[7] Interview with project manager at reference company. 3 October 2022.

would result in a higher output temperature. In this, there are two cooling water loops: one with hotter water connecting directly to a district heating network and one with cooler water cooling the lye to the preferred input temperature of the electrolysers. 146 MW of heat at 78 °C could be obtained this way. The energy has been calculated by considering the number of AWE electrolysers that will be installed at H2GS's site compared to a reference company. See appendix A5 and equation 4.

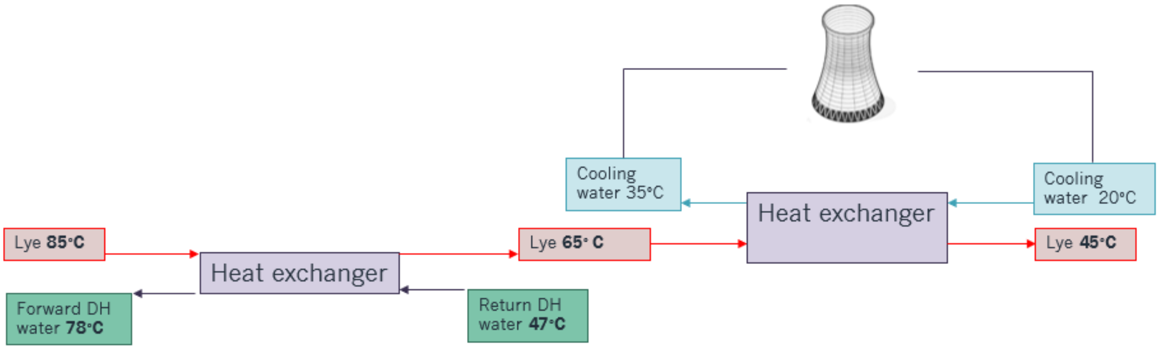

Figure 3: Sketch of a two-step cooling system at the AWE electrolysers.

In the figure, 47 °C is an estimate of the district heating return water temperature. The top right figure illustrates a cooling tower.

PEM

Polymer electrolyte membrane, PEM, electrolysers use a proton exchange membrane which conducts protons from the anode to the cathode. Water is pumped to the anode and is split into oxygen, protons and electrons. The protons pass through the membrane and are combined with electrons from the electrical circuit to form hydrogen gas. PEM electrolysers commonly operate at 70-90 °C. (Sundén 2019, 42) Figure 4 below shows an illustration of the process, and the half cell and overall reactions are as follows:

Anode: $H_2O \rightarrow 2H^+ + \frac{1}{2} O_2 + 2e^-$
Cathode: $2H^+ + 2e^- \rightarrow H_2$
Overall reaction: $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

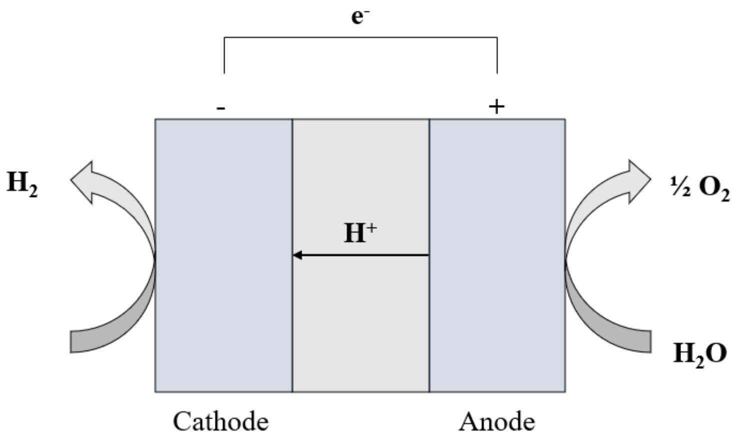

Figure 4: Illustration of a Polymer Electrolyte Membrane, PEM, electrolyser.
(Modified from Shiva Kumar & Himabindu 2019)

There are two possible cooling systems for PEM electrolysers, excess flow of cooling water and separate cooling circuits. The latter avoids risks of contamination and allows for a more flexible design whereas the first ensures a large surface contact area and an effective cooling. If separate cooling circuits are used in large-scale industrial PEM electrolysers, at least some of the cooling ducts must be internal to maintain a stable temperature of the system. This is because a small surface area compared to the volume of the electrolyser stack does not result in enough cooling. However, exact designs of large-scale electrolyser cooling systems are protected by the designers and cannot be found in open literature. (Rashidi Et. al. 2022)

In the current design of the cooling system of the PEM electrolysers at H2GS the temperature of the cooling water in is about 30 °C and out about 45 °C. [8] According to a recent study, the temperatures can be increased by decreasing the flow of the water. Thereby, cooling water of higher temperatures can be available for heat recovery. If the electrolysers operate at 80 °C, cooling water with an output temperature of 77 °C could be achieved according to the study. (Tiktak 2019) However, cooling water directly regulates the temperature of the electrolyser stack, and the electrolyser suppliers would have to accept the higher temperatures and potential risks that comes along with it.

This option has not been evaluated further in this report but is an option for further studies. How this energy relates to the entire heat available at the hydrogen and steel plant and how much heat that is needed for different uses has been studied instead. It was then concluded that more heat at this temperature would be of no use. 146 MW could likely be supplied from the AWE electrolysers relatively cheap at similar temperatures.[9] Moreover, the timing of discussing a redesign of the cooling system for the PEM electrolysers with the suppliers was inappropriate. At a later stage it could be possible to do this and to compare the costs and risks associated with redesigning the cooling system of the PEM electrolysers and installing a two-step cooling system at the AWE electrolysers.

SOEC

Like PEM electrolysers, the SOECs uses a solid electrolyte. In this case a ceramic material that conducts negatively charged oxygen ions (O^{2-}) to the anode at high temperatures. The O^{2-} are formed when water is split into hydrogen gas at the cathode side of the electrolysers. O^{2-} then releases its electrons to the electrical circuit and forms gaseous oxygen, O_2. The SOECs operate at 700–800 °C. (Sundén 2019, 42) Figure 5 illustrates the process, and the half cell and overall reactions are as follows:

Anode: $O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$
Cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$
Overall reaction: $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

[8] Data provided by Styren, Bror; Project Analyst. 5 September 2022.

[9] Interview with project manager at reference company. 3 October 2022.

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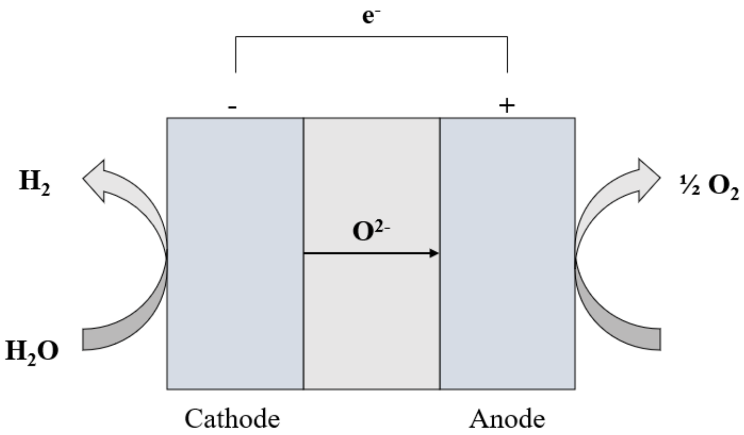

Figure 5: Illustration of a Solid Oxide Electrolyser Cell, SOEC.
(Modified from Shiva Kumar & Himabindu 2019)

SOECs operate at much higher temperatures than the other electrolysers studied and have a complex cooling system where heat is reused in different internal processes.[10] The outcoming hot stream for example heats incoming water vapour to the electrolyser. After internal reuse of heat, water of about 80 °C is cooled to about 40 °C with cooling water. In the current design, the cooling water has an incoming temperature of 30 °C and an outgoing temperature of 40 °C.[11] These temperatures might be possible to adjust for further use of the heat, like for PEM electrolysers, but this is not studied further since the flow of cooling water is comparatively small, and the timing of discussions with the supplier was inappropriate.

Direct reduction of iron

As previously stated, the hydrogen produced in electrolysis is used in the direct reduction of iron ore. The direct reduction stands for the largest part of the carbon emission reduction compared to traditional steel making. (H2 Green steel 2021a) The reduction reaction is endothermic and requires heat which is supplied by an electrical heater.

The reduction reactions are as follows:

$$H_2 + 3Fe_2O_3 \rightarrow 2Fe_3O_4 + H_2O \quad (1)$$
$$3H_2 + 3Fe_3O_4 \rightarrow 9FeO + 3H_2O \quad (2)$$
$$H_2 + FeO \rightarrow Fe + H_2O \quad (3)$$

The emissions from the production of Direct Reduced Iron, in the DRI tower, exits at a temperature of 300-350 °C and this heat could be recovered. (H2 Green steel 2021a) However, heat recovery is not part of the current design and would add significant technical complexity and costs. It could also be installed later. The recoverable amount of heat from this has previously been estimated to 20 MW in the first phase of production.[12]

[10] Process diagram provided by Dhar, Anu; Process Expert Engineer. 19 September 2022
[11] Data provided by Styren, Bror; Project Analyst. 5 September 2022.
[12] Internal H2GS document. 6 November 2022.

However, a tail gas from the DRI tower could more easily be recovered. High pressure nitrogen gas is used to seal the DRI furnace so that useful reduction gases do not escape.[13] This process is called blanketing. Consequently, the main gas stream is infiltrated with some nitrogen gas. To maintain a hydrogen rich gas stream, a pressure swing adsorbent unit is used where the hydrogen gas is separated and recycled back to the process. This saves approximately 15 % of the hydrogen gas. A tail gas is produced, i.e., a gas that has no further use in the process, which has a lower heating value (LHV) of 3200 kcal/Nm^3. The LHV is the amount of heat released when combusting the gas at 25 °C and returning the combustion products to 150 °C. (Hydrogen Tools 2022). The gas could be recovered by using a gas fired hot water boiler where the combustion of the gas releases heat and heats water. (Jouhara, Hussam et al. 2018) Since the lower heating value does not include the latent heat of condensation, but many gas boilers make use of this, the typical efficiency is high. It is about 95 % (Esa Kari Vakkilainen 2017) and over 100 % is possible. This means that all heat can be recovered. By multiplying the flow of the gas, 9000 Nm^3/h, with the lower heating value, 3200 kcal/Nm^3 and a conversion factor 1,16*10^{-6} kcal/h=1 MW, 33 MW of heat can be recovered. The alternative to recovering the tail gas as heat is to flare it to reduce CO emissions.

After combustion the only product left is carbon dioxide, which in theory could be taken up by Carbon Capture and Storage (CCS) to reduce emissions.[14]

Electrical arc and ladle furnaces

Electrical Arc Furnaces (EAFs)

Material such as DRI, HBI, scrap and alloys will be melted in three EAFs in which the composition of the melt will depend on the required outcome. The material is melted in batches by letting an arc arise between electrodes and the material. To clean the steel, a slag forming material is added to the melt. Moreover, anthracite and oxygen gas is added to form a frothy slag that increases the electrical transference between the electrodes and the material. This also isolates the melt keeping it hot for longer. (H2 Green steel 2021a)

Smoke fumes from the EAFs, also called off-gases, have a temperature above 1600 °C. The gases are used to dry scrap and to produce steam for heating in the galvanizing lines and cold rolling mills, and as an inlet to the SOECs. (H2 Green steel 2021a) The steam has a temperature of about 195 °C and excess steam produced could be used further. In the current design, the steam has a pressure of 1,2 MPa and a maximum flow of 81 t/h.[15] It is assumed that 25 t/h of this will be used for internal processes, resulting in an excess steam production of 56 t/h. This number is not finalized yet and may change but has been used as a basis for the analysis in this report. If the excess steam were to be condensed in a steam-to-liquid heat exchanger, 31 MW of heat could be recovered. See appendix A6 for a specification on the heat exchanger type analyzed. The production of steam from the EAFs is however intermittent which may impact the possibility of energy recovery. This will be discussed further in the report.

[13] Meeting with Durgesh Gupta; SVP of DRI. 30 November 2022.
[14] Engström, Fredrik; VP Electrical Solutions. 8 November 2022.
[15] Data provided by Styren, Bror; Project Analyst. 6 October 2022.

Ladle Furnaces

After the EAFs, the melt is treated in three ladle furnaces to adjust the chemical composition and the temperature of the melt before casting. The furnaces are equipped with electrodes with about a fifth of the installed power of the EAFs. Natural- or biogas is used to preheat ladles to prevent cracking when the melted steel is poured in the ladle. Solutions with carbon free fuel are not available yet. (H2 Green steel 2021a) The off-gases from the furnaces are low in volume and therefore have a less obvious role in heat recovery. It may be an option to explore in further studies.

Slag

The slag from the EAFs has a temperature above 1600 °C. Heat can be recovered from this through a dry air granulation process where slag granulates are formed and an off-gas at 400-600 °C is produced. The off-gas can then produce steam or hot water in a heat recovery steam generator (HRSG). The heat content in the gas has been estimated to 25-35 MW and if an 80 % efficiency is assumed, which is typical for HRSGs (Jouhara, Hussam et al. 2018), 20-28 MW could be recovered. In previous cases of heat recovery from dry air granulation systems, at similar sizes as the one that could be built at H2GS facility, 20-30 t/h, 400-500 °C steam was generated in one case and 30 t/h, 150-200 °C steam and 10-20 t/h, 100-150 °C water in another.[16]

A HRSG consists of several parts such as a superheater, an evaporator, an economiser, and a steam drum. The economizer is placed in the path of the coolest gas stream and the superheater in the path of the hottest stream. In the economizer the incoming fluid is preheated to increase the overall efficiency. The fluid is then further heated in the evaporator which vaporizes the fluid and is coupled to a steam drum in which the produced steam is stored. The steam is thereafter superheated to convert the saturated steam to superheated steam which has a larger range of usage. This steam can for example be used to produce electricity in a steam turbine. (Jouhara, Hussam et al. 2018) If only hot water, and not steam, would be of interest, a simpler system such as a hot water boiler could possibly be installed.

Slag is also produced from the ladle furnaces but only at about 10 % of the EAF slag volume and some of this is recovered as steel. It is therefore not at useful for heat recovery. [17]

Vacuum Treatment

As mentioned, some steel products undergo vacuum treatment to get rid of unwanted elements. This is a process where the pressure is reduced in a tank in which the melt circulates. Components such as hydrogen are removed. Coal can also be removed by blowing oxygen into the material. (H2 Green steel 2021a)

Treatment of emissions from the furnaces

Emissions from the furnaces are treated in five processes: direct suction/hood system, fast cooling, cyclone separator, injection of activated carbon and textile latch filters. One treatment plant will be installed at each EAF and will also be able to treat the emissions from

[16] Data provided by Styren, Bror; Project Analyst. 12 October 2022.
[17] Internal H2GS document. 10 November 2022.

the associated ladle furnaces and vacuum treatment plants. (H2 Green steel 2021a)

Downstream processes

Direct casting and hot rolling in Compact Strip Production plant (CSP)

Steel slabs are casted and hot rolled directly after the furnaces without intermediate cooling. Electrical induction heaters are used instead of gas burners in these steps to reduce carbon emissions. No treatment of the emissions will be needed as they consist of pure steam. (H2 Green steel 2021a) The steam will not be in a closed system and will thereby be difficult to recover as heat.[18]

Pickling, oiling and cold rolling (PLTCM)

Once the slabs are casted into strips, excess iron oxide is removed from the surfaces by adding hydrochloric acid. The strips are then welded together into one endless strip. The strips that will be delivered as hot rolled strips will have a layer of oil added to their surfaces to prevent oxidation. Thereafter, in the cold rolling process, the surface smoothness will be improved, and the strips lengthened. This is a process driven by hydraulic cylinders. (H2 Green steel 2021a)

Treatment of the PLTCM waste

The waste from the pickling process is treated in three steps: encapsulated beets, a drip separator, and an absorption tower. For treating the cold rolling waste, a fog separator and a textile latch filter will be used. (H2 Green steel 2021a)

Surface treatment of steel + annealing furnace

Most of the produced steel will be surface treated and four production lines are planned for this at the site. Three which include galvanization, of which one includes electrogalvanization. The fourth production lines are for painting (varnishing) the material. Common steps for the surface treatment lines are degreasing and cleaning, rinsing and drying, annealing, cooling, hot dip galvanizing and passivation. (H2 Green steel 2021a)

In the annealing step, heat is supplied to a batch annealing furnace (BAF) to change the properties of the steel such as its hardness and strength. Exhaust gases are produced in this process with a maximum temperature of 600 °C.[19] There is also a tunnel furnace used for annealing and welding. Since annealing is a batch processes, and it is difficult to collect the gases, it is not well suited for heat recovery. It has previously been estimated that the energy in the exhaust gases corresponds to about 0,5 MW, which is not much compared to other sources of heat at the plant.[20]

[18] Styren, Bror; Project Analyst. 10 November 2022.
[19] Internal H2GS document. 11 November 2022.
[20] Internal H2GS document. 11 November 2022.

Cooling water

At the electrolysers, furnaces, downstream processes etc. cooling water will pass by the processes and collect heat. This heat will then be cooled off in cooling towers and the water will be circulated back to the processes to collect more heat. The heat that is taken up can be calculated by the difference between the incoming and outgoing cooling water. See equation 4.

$$Q = \dot{m} \times Cp \times \Delta T \quad (4)$$

In this, Q is the heat collected in kW, Cp is the isobaric specific heat capacity in kJ/kg×°C, $\dot{m}$ is the mass flow in kg/s and ΔT is the temperature difference in °C. The specific heat capacity is slightly temperature dependent but for water at moderate temperatures an average Cp can be used.

The magnitude of heat taken up by the cooling water at different parts of the plant is shown in the figure below, figure 6.[21]

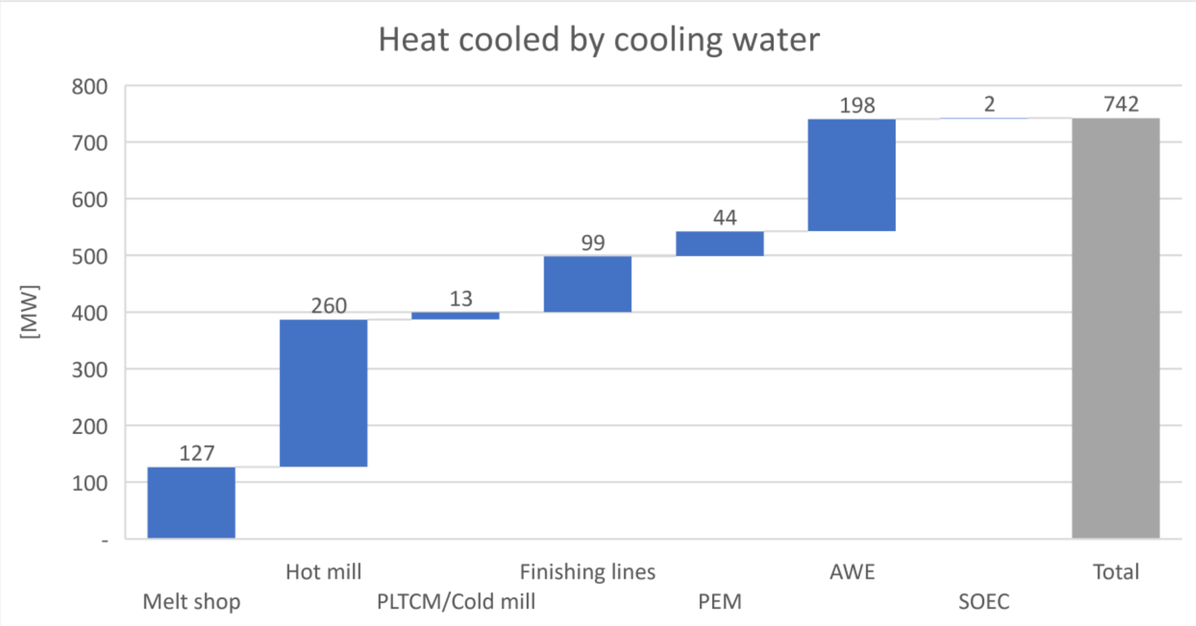

Figure 6. Heat cooled off at different processes at the hydrogen and steel plant.

The total amount of energy taken up is about 742 MW and a large part of this is from in the melt shop, hot mill, finishing lines and by the AWE electrolysers. Instead of cooling the heat it could possibly be used further and the output temperature would determine the possible usage areas. In figure 7 below, the energy is divided into 5 °C intervals of the output cooling water temperatures.

[21] Data provided by Styren, Bror; Project Analyst. 5 September 2022.

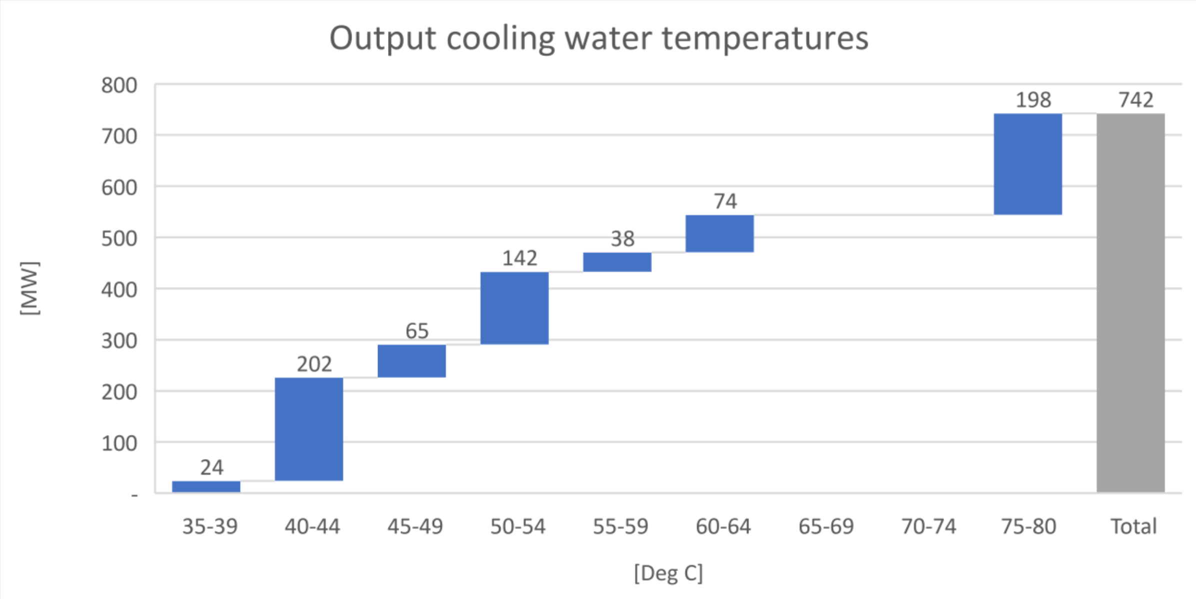

Figure 7: Energy in cooling water in output temperature intervals of 5 °C.

It should be noted that these are temperatures in the cooling systems in the current design. It would look different if a two-step cooling system by the AWE electrolysers would be installed or higher temperatures would be gained from the PEM electrolysers and SOECs.

Heat pump

If the sources of heat stated above would not be enough to provide heat for the usage areas, a heat pump could be installed. Cooling water could then be used as an inlet. Heat pumps usually operate with low temperature inlet water, at about 30 °C, but can in theory work with higher temperatures. Advantages of this is that the heat output and the Coefficient of Performance (COP) slightly increases[22], which can be seen in table 2 below. However, the flow through the evaporator, the heat source flow, becomes very low and may cause technical issues.

Table 2: Characteristics of a heat pump operating at different temperatures. [23]

Heat source temperature in	42	56	60
Heat source temperature out	35	35	35
Heat source flow	1 017	354	300
Cooling capacity [MW]	26	27	28
Heat sink temperature in	50	50	50
Heat sink temperature out	90	90	90
Heat sink flow [kg/s]	201	209	210
Thermal heat load [MW]	34	35	35
COP	4,1	4,2	4,2
Electricity in [MW]	8	8	8

[22] Supplier information; 25 October 2022.
[23] Supplier information; 25 October 2022.

The table illustrates the result when upgrading cooling water from three different temperature intervals 40-44 °C, 55-59 °C, and 60-64 °C (see above) to 90 °C. For the specific heat pump studied the energy output is roughly 35 MW and output temperature can be adjusted up to 100 °C. For other types, the energy output can be higher, and the temperature can be raised even further. (Supplier information 2023a) The energy output (thermal heat load) is about 1,3 times the energy input (cooling capacity) and the electricity input is about 8 MW in the three studied cases. This is calculated from the COP.

Summary of heat sources

In this section, the sources and ways to recover heat that are considered most promising are presented. This is based on the amount of heat that is generated at the processes and the technical possibility to recover it. The sources are cooling water at the hydrogen plant, cooling water at the steel plant, DRI tail gas, excess steam produced from the EAF off-gases and heat from the EAF slag off-gases. In table 3, the heat that can be used further is divided into low- and high-quality and is colour coded as blue and red respectively.

Table 3: Summary of heat sources.

Heat source	Heat recovery technology	Energy output [MW]	Output temperature [°C]
Cooling water at steel mill	Liquid-to-liquid heat exchanger	498	38-60
Cooling water at hydrogen plant	Liquid-to-liquid heat exchanger	244	40-75
Two-step cooling at AWE (hot step)	Liquid-to-liquid heat exchanger	146	78
Cooling water steel or hydrogen plant	Heat pump	34-35	90
DRI tail gas	Gas fired hot water boiler	33	~100
Steam from EAF off-gases	Condensing heat exchanger	31	~100
EAF slag recovery (dry air granulation) off-gas	Heat recovery steam generator (HRSG)	20-28	~100

Usage areas of heat

By evaluating the requirements of heat for different usage areas, the uses can be matched with the sources. Eight main usage areas have been found through this project: fish/shrimp farming, growing food in a green house, snow removal from streets, internal heating, water purification, district heating, electricity production by low temperature ORC and electricity production with a condensing turbine.

Fish/shrimp farming + Greenhouse

There is a company that can use waste heat and oxygen to farm fish and shrimp and grow plants in a green house. (Supplier information 2023b) Oxygen can be used to oxygenate the water for the fish and shrimp and the carbon dioxide emitted can be used to grow plants in a greenhouse. The company have estimated that 14-40 % of the oxygen emitted from H2GS's facility can be taken care of this way.[24] They have also estimated that this would correspond to building a 225 000 m^3 pool and a 16 hectares greenhouse. The required pool temperature would be 30 °C all year around and the required temperature in the green house would be 28 °C.

According to the data provided, the mean energy consumption for heating the pool and green house has been calculated to about 5 MW. See appendix A1. The heating requirement would depend on the season of the year and to make sure to supply enough heat in winter, the dimensioned heat load would have to be about 10-15 MW. This is according to signature load behaviour in locals (Fjärrvärme och Fjärrkyla 2015, 73). The idea is that the company would pay for the heat and oxygen. There are also other actors on the market with similar ideas.[25]

As seen in table 3, the cooling water found at the steel- or hydrogen plant could be used for this, and the recovery device needed would be a liquid-to-liquid heat exchanger. Some of the cooling water could heat the incoming water from the shrimp/fish farm and greenhouse, instead of being cooling through cooling towers. See figure 8 for an example sketch. Water pipes to and from the facility, and to connect the heat exchanger to the cooling system, would be needed. It has however been assumed that only pipes within H2GS's site is part of their scope.

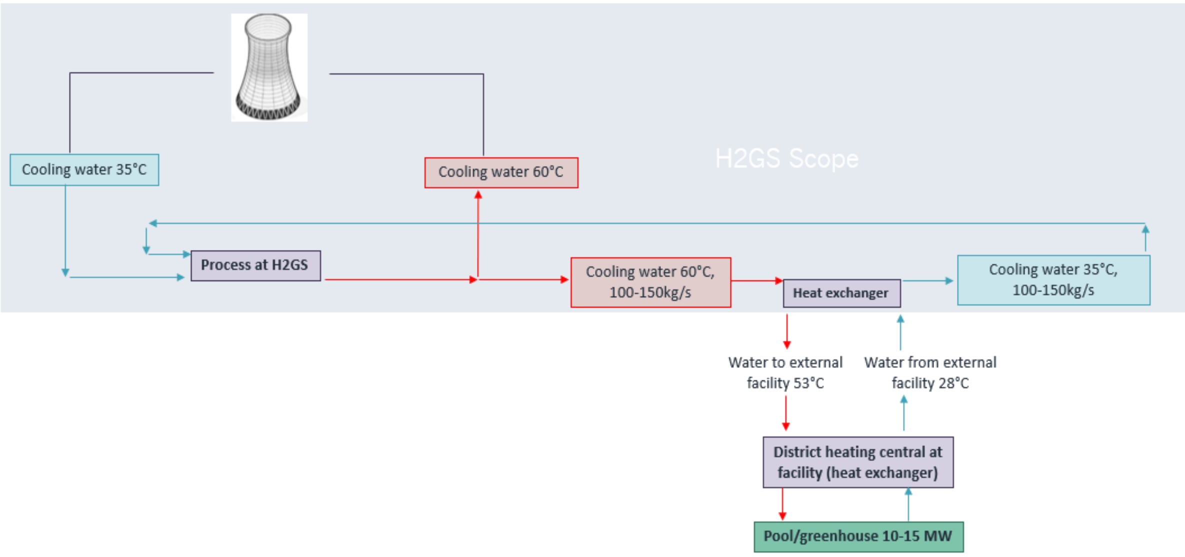

Figure 8: Example of a cooling system for a pool/green house.

In this sketch it is assumed that the 60 °C cooling water at the steel plant is used. The amount needed for 10-15 MW has been calculated to about 100-150 kg/s, see equation 4, and these quantities of cooling water exist.[26]

[24] Supplier information. 1 November 2022.
[24] Internal H2GS presentation. 8 November 2022.
[24] Data provided by Styren, Bror; Project Analyst. 5 September 2022.

Snow removal from streets

Low quality heat can also be used to remove snow and ice from roads or from scrap transported to the facility in wintertime. There are many examples where roads are kept free from ice in Sweden by using heat loops under the asphalt. (Lundberg 2000) The temperature needed for this is 35 °C and upwards. (Supplier information 2022a) The heat can come from district heating return water, which has a temperature of about 50 °C, or waste heat. An example is in Västerås where an area of 150 000 m^2 has been kept free from ice and snow this way. (Lundberg 2000) This area is in the same order of magnitude as all roads that will be built at H2GS's site. The heat loops can be dimensioned to up to 350 W/m^2 and the heat needed depends on the outdoor climate. (Supplier information 2022a)

The roads at site can be divided into general access roads, heavy traffic roads and extra heavy traffic roads.[27] If the roads would be heated this way, and the heat load would be the dimensioned to 350 W/m^2, the energy consumption would be 26 MW, 28 MW and 12 MW for the road categories respectively, a total of 66 MW. See appendix A2 for calculations. Note that this is at maximum capacity which will not be needed all year around. The heating ducts could be installed in a similar way as for fish/shrimp farming where the cooling water from the steel- or hydrogen plant could be used, and liquid-to-liquid heat exchangers could be installed. There are cooling water flows at both the hydrogen and steel plant large enough to supply enough heat.[28] It is required that the outgoing cooling water stream from the process is larger than the 100-660 kg/s required to supply 12-66 MW of heat. See figure 9 for an example sketch.

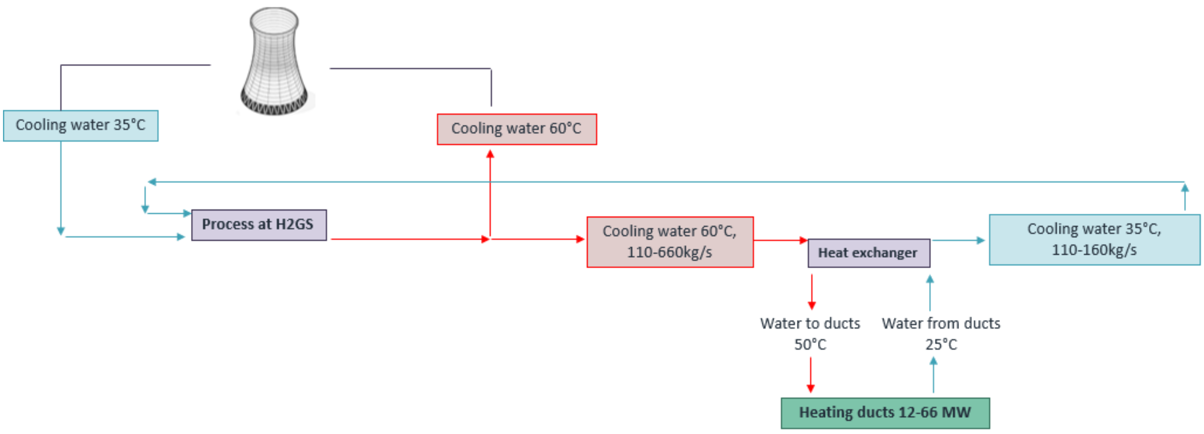

Figure 9: Sketch of a system for snow removal.

Note that less cooling in the cooling towers would be needed in winter if this system would be installed since heat would be cooled by the roads. In summer, the roads would not be heated, and the cooling requirements would remain the same as without a road heating system. The cooling towers can therefore not be downsized but the total yearly operation, and thereby the operational cost, could be decreased.

Snow and ice could also be removed from scrap by using waste heat. However, the amount of heat required has not been calculated. Steam could likely also be used for this.

[27] Internal H2GS document. 18 November 2022.

[28] Data provided by Styren, Bror; Project Analyst. 5 September 2022.

Internal heating system

The temperature needed for internal heating is about 50-55 °C if the system is optimized. However, higher temperatures, up to 60-70 °C, decreases the complexity of the system. (Dansk Fjernvarme, 2014) In Brunnshög in Sweden a low temperate district heating system has been installed where the consumer receives a forward temperature of 65 °C. (Tidningen Energi 2020)

The heat load needed depends on the area to be heated and the outdoor temperature. At H2GS's site, all buildings where people will work will have to be heated. The area of the buildings at the steel plant has been estimated to about 250 000 m^2 and at the hydrogen plant to 20 000 m^2. This has been done by measurements in a 3D map of the site, see appendix A3. The mean specific heat use in locals in Sweden 2010 was approximately 140 kWh/m^2 (Fjärrvärme och Fjärrkyla 2015, 58) and the energy consumption of the hydrogen and steel plant together, if this use is assumed, would be 39 GWh/year. This equals an average heat load of 4 MW. To dimension a system where the load is sufficient even on the coldest winter days, 10-15 MW would have to be installed according to signature load behaviour (Fjärrvärme och Fjärrkyla 2015, 73)

The cooling water at the steel plant at 60 °C, the hotter cooling water of the AWE electrolysers at 75 °C or heat from a two-step cooling system at the AWE electrolysers could be used. In figure 10 a sketch of a system where the 75 °C cooling water is used is provided. It has been calculated that 100-150kg/s would be needed for this, see equation 1, and that these quantities of cooling water exist at the hydrogen plant.[29]

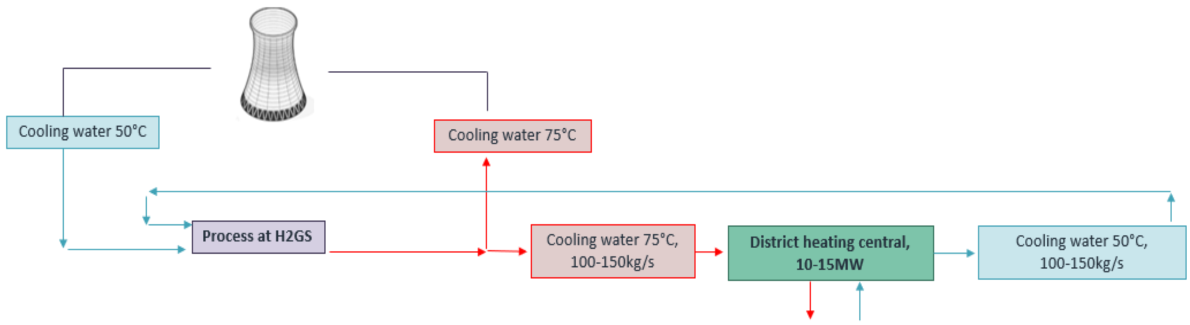

Figure 10: Sketch of cooling water design for internal heating.

When installing district heating in a building a district heating central (heat exchanger), radiators and pipes for the radiators and tap water are needed. This is needed regardless of if the heat is supplied to the system from a district heating network or from waste heat at the plant. See figure 11. In this, the lines represent cold and hot water, blue and red respectively, the squares to the right represent radiators and the square to the left represents a district heating central.

[29] Data provided by Styren, Bror; Project Analyst. 5 September 2022.

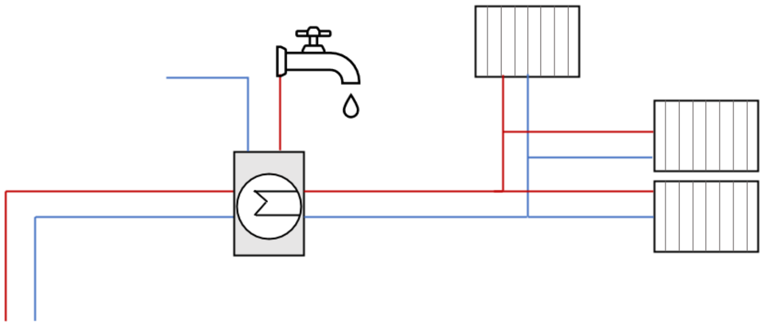

Figure 11: Sketch of a district heating installation in a facility.
(Modified from Wilson 2007)

The extra components required if waste heat is used as in figure 11 are pipes that connect the cooling system to the district heating central. Different cooling water streams could be used for heating different buildings. The exact design of the cooling water loops and a study of what buildings are to be heated is needed to calculate the length and the cost of these pipes. This is outside the scope of the report.

If the design would be based on a two-step cooling system by the AWE, the cost analysis would have to include extra heat exchangers needed as well as the costs of pipes leading heat to the district heating centrals. The main advantages of using internal heating are that less cooling is needed and that the heat is free of charge, although heat would be lost during maintenance periods of the equipment providing the heat. Therefore, a backup heat source might be needed.

Purification of water

Heat at about 80 °C can be used to purify water. The technology works by heating water until its vaporization temperature and then letting the evaporated water droplets pass through a membrane. The water condenses and is pure on the other side of the membrane. (Supplier information 2022b) The pure water can then be used in the electrolysers.[30] A company who does this has estimated the heat demand needed to supply enough demineralized water to operate all alkaline electrolysers. This amount of heat could be found if the cooling system by the alkaline electrolysers would be replaced by a two-step system. The technology is an alternative to purifying water in a traditional water treatment plant and the advantage is that heat replaces some of the electricity needed, thereby increasing circularity, and possibly decreasing costs.

District heating

District heating could be delivered to Boden municipality or to Luleå municipality from H2GS’s site. When it comes to Boden, the demand is low since they have waste incineration and an excess of total supply.[31] In summer, Bodens Energi could even benefit from cooling since their cogeneration plant would be able to generate more electricity (they are willing to pay for this service). In winter however, Q1 and Q4, Bodens Energi could benefit from some additional heat at temperatures above 100 °C since a few older, more maintenance heavy,

[30] Supplier information. 19 October 2022.

[31] Interview with Bodens Energi. 2 November 2022.

boilers could be replaced. If so, a total of 40 GWh during December, January and February could be delivered from H2GS with a maximum heat output of 80 MW. H2GS could also contribute with redundancy if Bodens Energi would have operational difficulties with their boilers.

For Luleå Energi the demand is larger than for Boden in the long-term perspective. Today most of the heat comes from SSAB's steel production but in 10 years' time, when SSAB plans to rearrange their production to fossil free steel, the company might not be able to supply as much high-quality heat.[32] The current agreement between Luleå Energi and SSAB stretches until 2030 and thereafter H2GS might be able to contribute with district heating. Luleå Energi estimates that a supply of 35-100 MW from H2GS would create profitable business case for both parties.[33] This corresponds to 36-100 % of their total energy use today. The maximum temperature in the district heating network in Luleå today is 115 °C but they strive to lower it to about 100 °C within 10 years to make better use of waste heat and reduce the wear on the pipes. 74 °C is already today enough for heating during the warmer half of the year.

In a forward temperature diagram (Värmemarknad Sverige 2021, 3) and a duration diagram (Sveby 2016, 16) it can be seen that 74 °C is sufficient when the outdoor temperature is above 5 °C and that this is the case 3760 h/year, which corresponds to about 43 % of the year. A forward temperature diagram illustrates the forward temperature at different outdoor temperatures and a duration diagram illustrates the number of hours per year the outdoor temperature is above or below a certain value. The forward temperature depends on the season of the year because the outdoor temperature, and thereby the heat demand for space heating, does. In summer, heat is mostly used for tap water whereas a large part of the heat load is used for indoor heating of buildings in winter.

It is roughly 30 km between Boden and Luleå and the temperature drop because of losses depends on the outdoor temperature, the dimension of the pipe, the thickness of the isolation and the speed of the water flow. The temperature drop in the direction of the flow can be calculated by the equation below:

$$\Delta T = (-4 \times K \times L \times d_0 \times (t_s - t_a)) \div (v \times d_i^2 \times \rho \times \mathrm{c})$$

ΔT - temperature drop in the direction of the flow [°C]
K - heat transfer coefficient [W/m^2K]
L - length of the pipe [m]
t_s - forward temperature [°C]
t_a - outdoor temperature [°C]
v - speed of water flow [m/s]
d_0 - outer diameter of the pipe [m]
d_i - inner diameter of the pipe [m]
ρ - density of water [kg/m^3]
c - specific heat capacity of water [J/kgK]

(Fjärrvärme och Fjärrkyla 2015, 84)

[32] Interview with Luleå Energi, 2 November 2022.
[33] Interview with Luleå Energi. 2 November 2022.

The heat transfer coefficient, K, depends on the outer diameter, d_0, and the isolation thickness. Typical values for Sweden are 0,8-1,0 W/m^{2}K (Fjärrvärme och Fjärrkyla 2015, 85) but for well isolated pipes with large circumferences, it can be as low as 0,2 W/m^{2}K (Fjärrvärme och Fjärrkyla 2015, 79). The mean diameter of pipes in Sweden is 0,14 m and a pipe of this size is about 3,6 mm thick, resulting in an outer diameter of about 0,142 m and an inner diameter of 0,138 m (Fjärrvärme och Fjärrkyla 2015, 85; Uponor 2023). The speed of the water flow is typically 2 m/s but can be up to 3 m/s. (Fjärrvärme och Fjärrkyla 2015, 448) It is lower in summer because of lower heat demand.

If the equation above is used for a 30 km pipe when the outdoor temperature is 5°C and the water from the facility is 78°C, the temperature drop along the pipe becomes 7°C. This is if typical values for the heat transfer coefficient, diameters and water speed are used. The density of water is estimated to be 1000 kg/m^3 and the specific heat capacity to 4,19 kJ/kgK. If the pipe is thick and well isolated and a heat transfer coefficient of 0,2 W/m^{2}K is used, the temperature drop becomes 1,6°C. This means that district heating can be provided from 78°C water from a two-step cooling system at the AWE electrolysers and reach customers in Luleå with a temperature above 70°C, when the outdoor temperature is above 5°C. As mentioned, this corresponds to 43 % of the year.

When the outdoor temperature is lower, the required forward temperature is higher and the heat from the AWE electrolysers will not be enough. However, the heat from other sources can be used. The temperature drop because of losses is lower in winter because of a higher water speed caused by a higher demand. The loss because of distance is therefore not a big obstacle for district heating to be installed.

One thing that must be taken into consideration if installing district heating from electrolysers is that these will not always operate. During some parts of the year, they will be stalled for inspection and maintenance. During these times, an accumulator tank for heat might be needed to supply a steady flow of heat. The same goes for boilers or other heat recovery devices.

Utilizing heat in the cooling water for district heating

One option is to let steam from the heat recovery system of the EAF furnaces, or other heat sources, heat output cooling water and then let the cooling water heat the return of a district heating system. See figure 15. This is instead of letting steam heat the district heating return water directly. See figure 16.

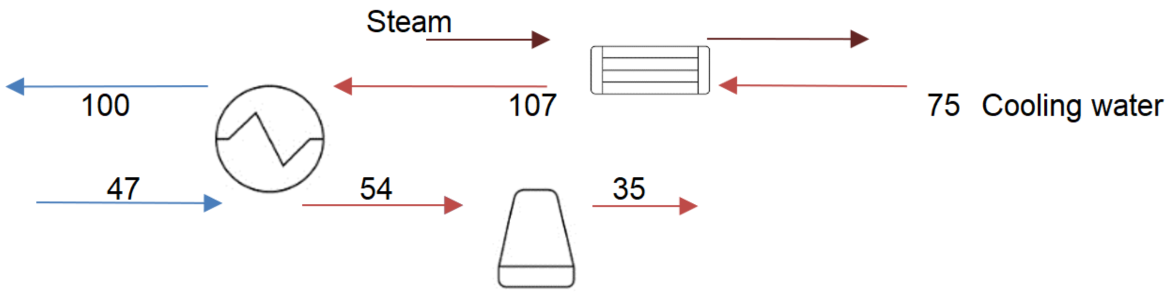

Figure 12: Sketch of a district heating design where heat in the cooling water is utilized.

The numbers in the figure illustrate temperatures where 100 °C is assumed to be the forward temperature to the district heating system and 47 °C is assumed to be the return temperature.

75 °C cooling water could be found by the AWE electrolysers. Utilizing the heat in the cooling water is of value if the cooling water temperature, 75 °C in this case, is significantly higher than the return of the district heating system, 47 °C. The top right symbol in figure 15 represents a condenser, the symbol to the left represents a heat exchanger exchanging heat between the cooling water and the district heating water and the lower right symbol represents a cooling tower. This design would require extra heat exchangers compared to the design below, figure 16.

If the excess EAF steam of 56 m^3/h would be used to heat the district heating water directly, as in figure 16, 37 MW of district heating could be delivered. If the same amount of steam would instead be used to heat the cooling water that then could heat the district heating network, 62 MW could be delivered and 6 MW less cooling would be required. A 7 °C approach temperature and equation 4 is used for this calculation, see the AWE and the cooling water section of the report. Less cooling would result in a saved cost due to a reduced operation of the cooling towers, but as mentioned extra heat exchangers would be needed. The added value would be the amount of district heating that could be delivered and the revenue from this. See appendix A4 for calculations. An obstacle could however be that the hottest cooling water is found at the hydrogen plant and the steam at the steel plant. Therefore, this solution would require a significant amount of piping on site.

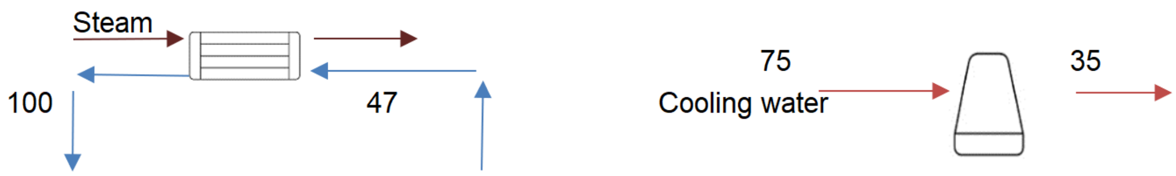

Figure 13: Sketch of a district heating design where heat in the cooling water is not utilized.

Condensing turbine

Excess steam generated from the heat recovery system of the EAF furnaces could be used in a condensing turbine to produce electricity. This would then be a part of the solution for district heating since the heat released in the condenser after the turbine could be used further to deliver district heating. The furnaces operate batch wise which means that the steam production is irregular. However, steam accumulator tanks are installed to smoothen out the peaks. As mentioned in the Electrical Arc Furnaces section it is estimated that a maximum of 81 t/h steam at 12 bar and 195 °C is released from the accumulator tanks and that 25 t/h of this will be used internally by different processes. Thereby an excess of 56 t/h will be produced. This might change as the balance of plant of steam is finalized and since the steam production is irregular the flow can also be lower, depending on for example the batch content.

The power that can be generated from 56 t/h steam has however been calculated using the formulas below:

$$h1(p,t)$$

$$\eta_T = (h1 - h2) \div (h1 - h2s) = 0{,}85$$

$$h2 = h1 - 0{,}85 \times (h1 - h2s)$$

$$P = \dot{m}_1 \times (h1 - h2)$$

The first is an expression that shows that the enthalpy before the turbine is a function of the temperature and pressure at that state, which can be found in tables. The second row defines the isentropic efficiency of the turbine which is estimated to 0,85. The isentropic case, $h2s,$ is the ideal state after the turbine where losses are neglected. This state is found by knowing the pressure after the turbine and the entropy before the turbine. The entropy before the turbine is a function of the pressure and enthalpy at that state. Rearranging the equation on row two results in the equation on the third row which describes the enthalpy after the turbine, $h2$. In the equation on the last row the power output is calculated. This depends on the mass flow of steam through the turbine in kg/s, $\dot{m}_1$, and the enthalpy change across the turbine, $h1 - h2$, in kJ/kg. (Cengel and Boles 2015, 559)

A power output of 5,4 MW can be calculated for the steam of 12 bar, 195 °C and 56 t/h. The power output also depends on the pressure of the condenser which is placed after the turbine. In this case a condenser pressure of 1,1 bar is assumed, corresponding to a temperature of condensation of about 102 °C. This heat can be further used in a district heating system and corresponds to about 31,6 MW. The forward temperature would then be 2 °C lower than the condensing temperature, i.e. 100 °C. This is because of losses in the condenser and 2 °C is an empirical measure applicable for condensers.[34] If a higher temperature of district heating would be needed this can be gained by sacrificing some of the electricity output, and vice versa.

If the steam production is too irregular, despite the accumulator tanks, a base flow of steam could be produced and could be used as an input to the turbine to reduce tear on it caused by switching it on and off. (Gustafsson and Ternström 2016) Another option is to install a valve that ensures a continuous flow to the turbine.[35]

Steam could also be the product of the heat recovery of EAF slag. However, hot water could also be produced in this recovery system and might have a higher value than steam.

Low temperature ORC

Heat at the temperature of 80 °C-120 °C can be used in low temperature ORC, a technique that produces electricity from hot water. Two companies supplying this has been studied. The first is a well-established company that are working on developing a that has an output electricity production of up to about 350 kW. (Supplier information 2022c) For this, an input of 30-120 kg/s hot water and an additional 30-120 kg/h of cooling water is needed. The temperature of the outgoing hot water depends on the mass flow and is generally 5-15 °C cooler than the incoming hot water. The modules can be coupled up to a production of about 50 MW, where larger installations have not been proven to be economically viable.[36] Nor has installations with a lower input temperature than 80 °C. The general idea is that a working medium is heated by the incoming hot water and then evaporates. It has a lower boiling point than the water and does therefore not need as high temperature to evaporate. The steam drives a turbine which is coupled to a generator to produce electricity. The working medium is then condensed by the incoming cooling water and gets circulated back to the evaporator. (Supplier information 2022d)

The other company's modules require slightly higher temperatures, > 100 °C, to be efficient. (Supplier information 2022e) The company offers modules from 50 kW to 500 kW which can be coupled in parallel to give a non-limited production of electricity. The company has calculated that a 31 MWth input, which corresponds to the output of energy that can be

[34] Genrup, Magnus. Supervisor meeting 17 October 2022.
[35] Genrup, Magnus. Supervisor meeting 8 November 2022.
[36] Supplier information. 30 October 2022.

delivered from the EAF steam, results in an electrical output of about 1200 kW.[37] This means that the efficiency is about 4 %. 31 MW of heat could also be supplied from the DRI tail gas.

Summary of usage areas

The table below shows the energy and temperatures needed for different usage areas. The temperatures are categorised in the same way as the sources of heat for easy comparison, where the blue fields represent usage areas that can use low-quality heat and the red field usage areas that require high-quality heat.

Table 4: Energy and temperature needed for different usage areas.

Usage areas	Energy needed [MW]	Temperature needed [°C]
Fish/shrimp-production / Green house	10–15 (Dimensioned load)	35–50
Snow removal from streets/processes	12–66 (Dimensioned load)	35–50
Low temperature internal heating	10–15 (Dimensioned load)	50–70
Water purification	117	~80
District heating (+ alt. condensing turbine)	35–100	80–120
Low temperature ORC	1–50	80–120

Note that the dimensioned load has been presented for the low-quality heat and not the average use. The heat load would be smaller during most of the year.

Cost analysis

The revenues of the different usages are analyzed in this section of the report and the analysis is divided into low- and high-quality heat. The result has however been scaled for confidentiality reasons and shows only how the costs are related. An exception is the cost analysis for snow removal since the included numbers are estimated and non-confidential.

Recovery of low-quality heat

For the cooling water from the steel and hydrogen plant the cost of heat recovery is low. The only components needed are heat exchangers and some additional piping. If the low-quality heat could be recovered it would result in less cooling needed in cooling towers. There are three main uses of this heat: fish/shrimp farming combined with growing food in a green house, snow removal and internal heating.

Fish/shrimp farm + greenhouse

The heat needed to farm shrimp/fish and grow plants in a greenhouse for the size suggested by the reference company is about 5 MW in average, 10-15 MW peak load. If this heat were

[37] Supplier information. 12 November 2022.

to be sold form H2GS at the same price as district heating, despite the low temperature, the revenue would be about **624 EUR/year**. The mean district heating price for Boden 2021-2022 has been used (Energiföretagen 2022).

The cost for H2GS would include a pipe connecting the cooling water system to a heat exchanger, the heat exchanger itself and a connection on site. As seen in the "Fish/shrimp farming + Greenhouse"-section it is assumed that the district heating pipe outside of H2GS's site is in the scope of the consumer. The connection cost within site can be assumed to be 0,31 EUR/m^2 and the cost of a heat exchanger to be like that of the heat exchangers for a two-step cooling system. See appendix A5. Assuming a 500 m connection on site with a 50-year lifetime, a heat exchanger dimensioned to 15 MW and an installation cost of 30 % of the Capital Expenditure (CAPEX)[38], the depreciated Capital Expenditure (CAPEXdep) becomes 6 EUR/year. See table 5.

Table 5: Cost analysis of a fish/shrimp farm and greenhouse.

Capex dep		**EUR/yr**	**6**
	Capex offtake	*EUR*	*258*
	Connection	EUR	201
	Heat exchangers	EUR	57
	Lifetime connection	*Years*	*50*
	Lifetime heat exchangers	*years*	*25*
Revenue		**EUR/yr**	**624**
Temperature		C	30-50
Profit/EBIT		**EUR/yr**	**618**

The length and cost of the pipe connecting the cooling water system to a heat exchanger is not estimated since it depends on the design of the cooling system where the heat is taken from. It can however be assumed to be a small since the heat can be taken from one place in the cooling system and have one connection point at the receiver, which means that the complexity is low.

It can be concluded that the CAPEX is relatively low compared to the revenue that can be generated. This is true even if the low-quality heat is sold cheap compared to district heating. H2GS could as mentioned also sell oxygen which would result in further revenue.

Snow removal from streets

The cost analysis for snow removal is based on a comparison between the cost of installing heating ducts and the cost of ploughing all roads one time. How many times traditional ploughing must be done for an investment in heating ducts to pay off is calculated. Unlike the other analyses, this is not scaled. See figure 17 below.

The material cost of heating ducts for snow removal depends on the area to be heated and has been estimated to about 20 EUR/m^2 of ground area. The roads have been divided into the three categories of roads mentioned previously. The installation cost of heating ducts has been assumed to be 30 % of the material cost.

[38] Estimate provided by Styren, Bror; Project Analyst. 20 September 2022.

Assumptions		
Plough width	4,5	m
Speed	30	km/h
Driver salery	3 000	EUR/month
Employer's contribution	31,4	%
Fuel cost	2,25	EUR/L
Fuel consumption	20,5	L/hr
Material cost heating ducts	20	EUR/m2
Construction cost heating ducts	30	%
Plough rounds per year	100	nbr

Cost heating ducts

		General access roads plant area	Heavy traffic plant roads	Extra heavy traffic plant roads	Total
Length	km	7,4	8,0	1,2	16,6
Width	m	10,0	10,0	27,0	
Area	m2	73 620	80 390	33 264	187 274
Rough material costs	EUR	1 472 400	1 607 800	665 280	3 745 480
Total cost	EUR	1 914 120	2 090 140	864 864	**4 869 124**

Cost for ploughing all roads one time

		General access roads plant area	Heavy traffic plant roads	Extra heavy traffic plant roads	Total	
Lenth plough distance	km	22,1	24,1	7,4	53,6	
Time to plough	h	0,7	0,8	0,2	2,2	
Salery for driver	EUR	24,6	24,6	6,1	55,4	
Total cost for H2GS	EUR	70,8	70,8	17,4	**159,0**	(Salery + fuel)

Comparison

Plough rounds for PB	nbr	30 629
Years for PB	yr	306

Figure 14: Cost analysis for snow removal.

According to the estimate, more than 30 000 rounds of ploughing are needed for the investment to pay off. Even if assumptions such as plough width, speed of ploughing, fuel cost etc. would change, it would not become a reasonable investment.

Internal heating

When it comes to internal heating, the amount of money that can be saved is the alternative cost of buying heat. The energy amount equals about 39 GWh/year, see use of heat section, and the mean price of district heating for Boden 2021-2022 has been used.

The saved cost from not buying heat, ca **549 EUR/year** for 50 years (the approximate lifetime of district heating pipes) can be weighed against the cost of a design where the waste heat is used, and pipes are installed between the cooling system and the district heating centrals of the buildings, see figure 11. It is assumed that this cost is low compared to the possible savings from not purchasing heat. It is possible that a district heating pipe from Boden is built to the site even if internal heating is installed (for back up), and this saving is therefore not included.

Another way of calculating is by including the cost of heat exchangers needed in a two-step cooling system, as well as pipes. This cost is known and makes up the largest part of the investment in district heating according to the source.[39] The only difference is that the heat is

[39] Interview with project manager at reference company. 3 October 2022.

used at site instead of sold. The cost of heat exchangers corresponding to 15 MW would be about 48 EUR, and the lifetime 25 years. Compared to purchasing heat for 549 EUR/year, installing in a few heat exchangers and pipes makes perfect sense.

Summary of cost analysis for low-quality heat uses

To summarize, installing heating ducts for snow removal does not seem economically viable whereas selling heat to a fish farm/greenhouse can result in a business case that benefits both parties and having an internal heating system can save costs for H2GS. This is because the costs of heat exchangers and pipes are low compared to the cost of heat. On the other hand, using plough trucks is cheap compared to that of installing a new road heating system. The trucks will likely be on site either way as a backup.

Recovery of high-quality heat

High quality heat can come from EAF steam production, a two-step cooling system at the AWE electrolysers, DRI tail gas heat recovery, slag heat recovery or from upgrading cooling water with a heat pump. For this heat, four main usage areas have been found: purification of water, district heating, low temperature ORC and electricity production in a condensing turbine. The recovery of high-quality heat comes with a significant cost and must be weighed in when estimating the revenue from the uses. The cost analysis is therefore based on using the cheapest way to recover heat at the temperature and amount needed for the usages. The cost of each heat recovery solution is presented first and thereafter the cost analysis of the usage areas. Note again that the analysis is scaled for confidentiality reasons.

Heat recovery solutions

The excess steam from the EAF heat recovery system could be recovered in a steam-to-liquid heat exchanger with an output temperature of 100 °C. It has been calculated that about 31 MW can be recovered from 56 t/h steam and that the cost of a heat exchanger of this size is about 17 EUR.[40] The large energy recovery is possible due to the phase change of water which releases a lot of heat. The lifetime has been estimated to 25 years and the maintenance cost to 2 % of the CAPEX[41]. This includes periodical inspections. The electricity cost has been neglected since pumping water on the cold side of the heat exchanger, for example a district heating network, is not part of H2GS scope. On the hot side, the pressure of the steam might be enough for a steady flow. As a result, the yearly cost of the condenser, including both CAPEXdep and OPEX, is estimated to **1 EUR/year**. See table 6.

A two-step cooling system could be installed to recover heat from the AWE electrolysers at 78 °C and this would require heat exchangers that can tolerate high temperatures. The cost of these is calculated by scaling up the cost of the heat exchangers for a company that recovers heat this way.[42] See appendix A5. As mentioned, in sources of heat section, 146 MW can be recovered this way. Like the condensing heat exchangers, the lifetime is estimated to 25 years and the maintenance cost to 2 % of the CAPEX. Electricity needed to pump water on the cold side is neglected. This results in a total yearly cost of **26 EUR/year**. See table 6.

[40] Supplier information. 25 November 2022.
[41] Supplier information. 25 November 2022.
[42] Meeting with Project Manager at reference company. 2022, 30 September.

The DRI tail gas can be combusted in a gas fired hot water boiler where the heat of combustion is transferred to hot water. 33 MW at 100 °C can be recovered this way, see section 1.1.1.2. It has been found that the CAPEX of such a boiler 3143 EUR, that the operational cost is 20 EUR/year and that the lifetime is 30 years. (Energiföretagen 2020, 40) Since the fuel is a tail gas with no further use it has been considered free. The operational cost instead includes inspections and maintenance. This results in a cost of **124 EUR/year**. See table 6.

From the slag heat recovery system about 24 MW of 100 °C water can be extracted. The costs given from the supplier is based on the entire dry granulation system but only the heat recovery steam generator is of interest. A fraction of the cost from the supplier has thereby been used. The CAPEX has been estimated to **3095 EUR** this way[43]. The electricity use has also been scaled accordingly. The OPEX thereby consists of both electricity and maintenance and the lifetime is estimated to 25 years. The electricity price used corresponds to what H2GS has negotiated through fixed contracts.[44] The grid tariff is neglected since it is a small part of the electricity cost for H2GS and is part of contracts related to investment in switchgear etc. The total yearly cost, including CAPEX and OPEX, results in **154 EUR/year.** See table 6.

Another way of recovering heat from the tail gas is by exchanging if from the gas without combusting it. This is cheaper but far less heat can be recovered. A gas-to-liquid heat exchanger in stainless steel costs about 15 EUR but can only about 0,5 MW can be delivered this way. This is because only the sensible heat in the gas is transferred and not the heat of combustion.[45] It has thereby not been further studied.

A heat pump could be installed and upgrade heat to higher temperatures. A heat pump that transfers 35 MW heat at 90 °C has been studied. The CAPEX of such a pump is about 1905 EUR and the lifetime 25 years.[46] A heat pump has a large operational cost since electricity, in this case 8 MW, is needed for operation. The same electricity price as mentioned above is used. The heat pump also has a maintenance cost of 2-3 % of the installation cost including refilling cooling media, inspections and larger maintenance work every 6 years.[47] The total cost becomes **562 EUR/year**. See table 6.

Table 6: Heat recovery solutions for high-quality heat.

			EAF steam condenser	AWE heat exchangers	DRI tail gas fired boiler	Slag heat recovery system	Heat pump
Capex dep		**EUR/yr**	**0,7**	**17**	**105**	**124**	**76**
	Capex	EUR	17	429	3 143	3 095	1 905
	Lifetime	Years	*25*	*25*	*30*	*25*	*25*
Opex		**EUR/yr**	**0,3**	**8,6**	**20**	**30**	**486**
	o/w fuel/electricity	EUR/yr	-	-	-	25	448
	o/w maintainance	EUR/yr	0,3	8,6	20	5	38
Heat transferred		MW	31	146	33	24	35
Temperature		C	100	78	100	100	90
Yearly cost		**EUR/yr**	**1**	**26**	**124**	**154**	**562**

[43] Data provided by Styren, Bror; Project Analyst. 2022, 12 October.

[44] Styren, Bror; Project Analyst. 17 January 2023.

[45] Supplier information. 25 November 2022.

[46] Supplier information. 9 November 2022.

[47] Supplier information. 9 November 2022.

Accordingly, the cheapest way to recover heat is by condensing EAF steam. Using a heat pump is the by far most expensive way.

Heat recovery usage areas

Two companies that provide low temp ORC has been studied and the cheapest recovery solution, condensing steam, has been used for the cost analysis since the temperature and energy amount is enough.

For the first company, the mean price per module has been multiplied with the number of modules that can absorb 31 MW thermal energy. This constitutes the CAPEX. The price also includes installation, and the lifetime has been estimated to 25 years by the company itself.[48] The modules also require extra piping, and this cost can be estimated to about 9 % of the CAPEX. (Mohamed Gomaa et al. 2020) The OPEX of the modules has been estimated to 2 % of the yearly cost of the equipment. (Mohamed Gomaa et al. 2020) The revenue consists of the alternative cost of purchasing electricity corresponding to the amount that can be produced from 31 MW thermal energy. The same electricity price as mentioned in the heat recovery solutions section has been used. This results in earnings before interest and taxes (EBIT) of about **9 EUR/year** and a return of capital employed (ROCE) of **0 %**, see table 7.

Similarly, an analysis for the second company's modules has been made with the same assumptions for electricity price, pipes and operation. The CAPEX of equipment is lower than for the first company and so is the electrical efficiency of the system (electrical output/thermal input).[49] In this case the EBIT is about **18 EUR/year** and the ROCE **1 %**, see table 7.

For district heating to Luleå at least 35 MW has been suggested for a profitable case. It is therefore not enough to supply heat only from the EAF furnaces and the cost analysis has been based on a supply from both the EAF furnaces and a DRI tail gas fired boiler. It is possible that a two-step cooling system from the AWE electrolysers could supply heat as well, but the temperature is lower, ~80 °C, and Luleå Energi has argued that a 100 °C forward temperature is aimed for (the lower temperature can only supply enough heat in the warmer parts of the year). The cost analysis is thereby built on a delivery of 64 MW heat.

The equipment cost consists of pipes and pumps and has been provided by Luleå Energi.[50] Additional piping on site of 500m, the connection cost, has also been added. (Vattenfall 2022) Moreover, a cost of installation, 30 % of the CAPEX, has been assumed as well as an operational cost of to 2 % of the CAPEXdep of equipment, like for the low temperature ORC. The OPEX includes the operating costs of the pumps which require electricity. The revenue is related to the price of district heating where the same price as in the heat recovery solutions section has been used. However, only the part of the price that relates to the energy delivered, about 60 % (Göteborg Energi 2023), has been used. The rest constitutes of a cost relating to peak power use. Since this analysis is based on that H2GS would replace the base load, this part has a low correlation to the revenue. This results in an EBIT of about **4243 EUR/year** and a ROCE of **17 %**, see table 7.

[48] Supplier information. 30 September 2022.
[49] Supplier information. 9 December 2022.
[50] Meeting with Luleå Energi. 9 December 2022.

For Bodens Energi the yearly energy demand is maximum 40 GWh and this has been used in the cost analysis. Like for Luleå, an installed heat output of 64 MW has been assumed, which will be required during the cold days that Boden may have a demand. The CAPEX of equipment has been scaled to a pipe length of 4,5 km, an estimated distance from the district heating network and the site.[51] Installation and operating costs have also been added, see paragraph above. This results in an EBIT of about **221 EUR/year** and a ROCE of **3 %**, see table 7.

A turbine has been added to the cost analysis to evaluate the profitability in using the steam from the EAF furnace heat recovery system, or slag heat recovery system, to produce electricity as well as heat. The price and installation cost of a turbine has previously been estimated from supplier data.[52] The OPEX has been estimated to 2 % of the CAPEX of the equipment. The revenue is the alternative cost of buying electricity and as seen in the condensing turbine section, about 5,4 MW can be supplied from the EAF furnaces at peak production. This results in an EBIT of about **177 EUR/year** and a ROCE of **6 %,** using the same electricity price as before. The heat released in the condenser, 31,6 MW, can be used further. If the slag heat recovery system is used, the investment is barely profitable since the CAPEX rises. The ROCE becomes 1 %. Note that the revenue increases linearly with the alternative cost of electricity, i.e., the electricity price.

Finally, the cost of the water purification technology has been analysed. Since ~80 °C is enough for this and a large amount of energy is needed (117 MW) a two-step cooling system has been used for the analysis. The cost has been scaled to 117 MW and not the total of 146 MW that can be supplied. The cost of the modules has been estimated by the company[53] and an additional installation cost of 30 % has been assumed. Further, an OPEX of 2 % has been assumed. The revenue has been set to the alternative cost of traditional purification of water.[54] This results in an EBIT of about **-75 EUR/year** and a ROCE of **-3 %**, which means that the technology is more expensive than the purification of water in the current design.

Summary of cost analysis for high-quality heat

The table below shows a summary of the cost analysis, and the arrows represent the recovery solution used for the different usage areas.

[51] Estimate provided by Bodens Energi. 2 February 2023.
[52] Data provided by Styren, Bror; Project Analyst. 20 September 2022.
[53] Supplier information. 15 November 2022.
[54] Engström, Fredrik; VP Electricity Solutions at H2GS. 7 December 2022.

Table 7: Summary of the high temperature cost analysis.

			EAF steam condenser	AWE heat exchangers	DRI tail gas fired boiler	Slag heat recovery system	Heat pump
Capex dep		**EUR/yr**	**0,7**	**17**	**105**	**124**	**76**
	Capex	EUR	17	429	3 143	3 095	1 905
	Lifetime	Years	*25*	*25*	*30*	*25*	*25*
Opex		**EUR/yr**	**0,3**	**8,6**	**20**	**30**	**486**
	o/w fuel/electricity	EUR/yr	-	-	-	25	448
	o/w maintainance	EUR/yr	0,3	8,6	20	5	38
Heat transferred		MW	31	146	33	24	35
Temperature		C	100	78	100	100	90
Yearly cost		**EUR/yr**	**1**	**26**	**124**	**154**	**562**

Offtakes			Low temperature ORC		District heating		Turbine using EAF steam	Water purification
Company			*1*	*2*	*Luleå Energi*	*Bodens Energi*	3	*4*
Capex dep		**EUR/yr**	**130**	**49**	**437**	**69**	**124**	**149**
	Capex offtake	*EUR*	3 242	1 327	21 873	3 456	3 095	3 714
	Capex equiptmen	EUR	2 974	1 217	16 825	2 659	2 381	2 857
	Capex extra	EUR	268	110	5 048	798	714	857
	Lifetime offtake	*Years*	*25*	*25*	*50*	*50*	*25*	*25*
OPEX		EUR/yr	2,4	1,0	7	1	1,9	2,3
Revenue		EUR/yr	142	69	4 812	570	303	94
Temperature		C	80-120	100	100	100	-	80
Profit/EBIT		**EUR/yr**	**9**	**18**	**4 243**	**221**	**177**	**- 75**
ROCE		**%**	**0%**	**1%**	**17%**	**3%**	**6%**	**-3%**
Total CAPEX		**EUR**	**3 259**	**1 234**	**25 033**	**6 616**	**3 095**	**3 201**

District heating to Luleå is by far the most profitable way to recover heat but requires a large investment. District heating to Boden is also possible if there is a demand. However, note that the cost analysis for district heating is based on a project where the suppliers (Bodens Energi and Luleås Energi) will invest in the pipes outside of H2GS's site and will want to take part of the profit. This means that the total CAPEX and the profit is lower for H2GS than indicated in table 7. Installing a turbine can also be of interest whereas low temperature ORC barley pays off and purifying water with waste heat is not competitive today.

Discussion

Use of low-quality heat

For the low-quality heat, it should be prioritized to analyse in detail how an internal heating system could be installed. The money saved by not having to buy district heating from Boden is large and the installation costs of pipes connecting the cooling water systems to the district heating centrals, or need of extra heat exchangers, are comparatively low. There is also a large amount of heat at the required temperature span, 50-70 °C, available both at the hydrogen and steel plant, see the cooling water section. It is recommended to use the heat that is closest to the buildings that are to be heated to reduce the amount of piping. Additionally, there is an environmental value in using heat available at site compared to buying heat and this may positively impact the social acceptance of the project. Another possible way is to use the same sources as for district heating and use at the facility. If district heating would be delivered to Luleå or Boden, no new heat recovery systems would be required and some of the heat could be used at site instead of selling.

Selling low-quality heat for use in green houses, fish farms etc. can be profitable for H2GS but is not urgent in the building process as a heat exchanger can be installed later. Moreover, there is no clear plan for how the reference company could finance their project today. When they or another company/the municipality have a plan, it could be beneficial for H2GS to cooperate. This would show an interest in the local economic growth and efficient use of energy and could increase the social acceptance of H2GS. Moreover, the investment cost is relatively low since only a heat exchanger and some pipes are needed. The brief cost analysis shows that it is profitable. A business case that benefits both parties would be needed.

Installing heating ducts for snow removal is not recommended since it comes with a large investment cost that will not be paid back during the lifetime of the pipes. However, it has an environmental value as up to 66 MW waste heat could be utilized this way and would be cooled off by the roads instead of in cooling towers. Additionally, the fuel consumption of the ploughing machines would decrease, or be discarded completely, and it would be safer since no one would have to drive the trucks and no one could be hit by them.

Use of high-quality heat

For the high-quality heat, investing in district heating is the most profitable usage area according to the cost analysis. Luleå municipality appears to be the most promising costumer since their demand will likely increase within 10 years and the demand for Boden municipality is low. The investment cost in district heating to Luleå is however large, mostly because of the large infrastructure of pipes needed to connect Boden to Luleå. Since the connection cost is much larger than the cost of recovering heat, the profit and ROCE would be in the same order of magnitude even if more expensive recovery solutions were used. All heat sources are thereby candidates for district heating. It is however likely that H2GS will stand for a large part of the investment cost at site and that Luleå Energi will stand for a large part of the investment cost in pipes. If this is the case, the ranking of heat sources become more important for H2GS, and a heat pump would be the last resort. In addition to the high price, a reason for not recommending a heat pump is that it requires electricity as an input and that it is more sustainable to use energy already existing as heat.

If only the DRI tail gas fired boiler producing 33 MW were to be installed, the revenue and ROCE would be about half as big as in the current cost analysis. The case would still be profitable, but a lower ROCE and profit would make the investment harder to motivate. The cost analysis supports Luleå Energi's conclusion that district heating is profitable if H2GS can supply more than 35 MW heat, and that the profit is larger the more heat that could be supplied. If the steam use of the plant increases, causing less excess steam to be available, it could therefore be profitable to recover heat from the slag instead.

Even though Luleå Energi has argued that a 100 °C forward temperature is to strive for, at least in early calculations, this report suggests that a two-step cooling system by the AWE electrolysers can supply enough heat 43 % of the year. This can be an option if there is not enough EAF steam available and if a DRI gas fired boiler is decided not to be installed. If a gas fired boiler is installed, it could be used in summer as well since the operating cost is comparatively low and it likely provides enough heat.

If there is a large supply of steam it is recommended to further investigate the option of using heat in the cooling water as a step between the steam condenser and the district heating network. See the district heating subsection. The possible supply of energy would largely increase, and the cooling needed would decrease. The investment cost would only consist of extra heat exchangers and pipes. It could also be profitable to install a condensing steam turbine in this case, provided that the steam flow is relatively constant. The ROCE is only 6 % but could become higher if electricity prices rise. The condenser could then be coupled to a district heating network.

However, note that the cost analysis assumes that there will be a constant high demand of heat from Luleå. It is too early to determine this, and the analysis is taken forward as a basis for further discussion. If there will be a demand it will, as mentioned, not arise until 2030. The analysis is also based on a case where H2GS takes over the base load and stands for about 65% of the energy use. This may or may not be possible.

When it comes to Boden the ROCE is smaller even though the maximum demand is assumed. This is because the demand is still low and there is no district heating network nearby the site. If the CAPEX can be scaled according to the distance to the network in Boden compared to that in Luleå, as in this analysis, the profitability may not be enough to motivate the investment. If the heat demand is lower, the ROCE further decreases.

Further, it is suggested to install an accumulator tank if heat is delivered from the plant since heat will not be produced at times. Sometimes the processes generating heat will be stalled due to inspections and maintenance. The dimensions of one or more accumulator tanks must be further evaluated and depends on the requirements for heat delivery from the district heating suppliers.

According to the cost analysis, low temperature ORC has no clear economic profit today. The profit is closely related to the electricity price, and would have to increase a lot for an installation to be considered. Neither does it have the flexibility in use of heat sources as district heating has. Cheap recovery solutions such as heat exchangers are needed. If a gas fired boiler at the DRI would be installed for this the ROCE would be negative. From an energy efficiency perspective, it would be of value if heat from a two-step cooling system at the alkaline electrolysers could be used. A lot of heat is available, and it may not be used in any other way since the temperature is only enough for district heating in summer and water purification modules do not seem profitable. Even if the purification modules are installed there would be excess heat available. It is technically possible for the first company delivering low temperature ORC modules to operate at 78 °C, but the efficiency would be very low. It could be of value to let them perform a business case with the amount of energy and temperature available but as mentioned, their product has not been proven economically viable below 80 °C. The other company require even higher temperatures. Compared to district heating it is noteworthy that the installation cost of low temperature ORC is low, which could benefit the technique as it uses the same heat sources. However, the profit from district heating can be higher. Although it has not been found during this project, there might exist technologies with higher efficiencies at 78 °C that can generate a larger added value.

When it comes to the water purification technique it does not seem competitive today. It may be a more sustainable way to purify water since waste heat energy is used, which adds to the social acceptance and efficiency of the plant. It might also become competitive in the future if electricity prices rise, and the technique matures. The company has not previously proven to deliver at large scale which adds a risk factor. If H2GS proceeds with a collaboration with this company it is suggested that the price of the modules is negotiated, and that the technique is used at a smaller scale to begin with. By trying the technique at a smaller scale H2GS does not risk the supply of demineralized water to all the electrolysers, and thereby hydrogen gas to the entire steel production. If it is installed at large scale however, the cooling capacity and need of cooling towers may decrease.

General discussion

It can be concluded that a lot of cooling is needed even if all uses are implemented. This can be seen in the figure below showing the order of magnitude of heat available and a possible way to use the heat. In this, district heating has been prioritized before low temperature ORC since it is more profitable and uses the same sources. The maximum dimensioned energy use of the usage areas is assumed, which means that it is not representative for all times of the year. In summer for example, internal heating of the buildings will not be needed. Thereby, the current dimensioned cooling capacity, i.e the cooling towers, will be needed unless waste heat water purification is installed at large scale.

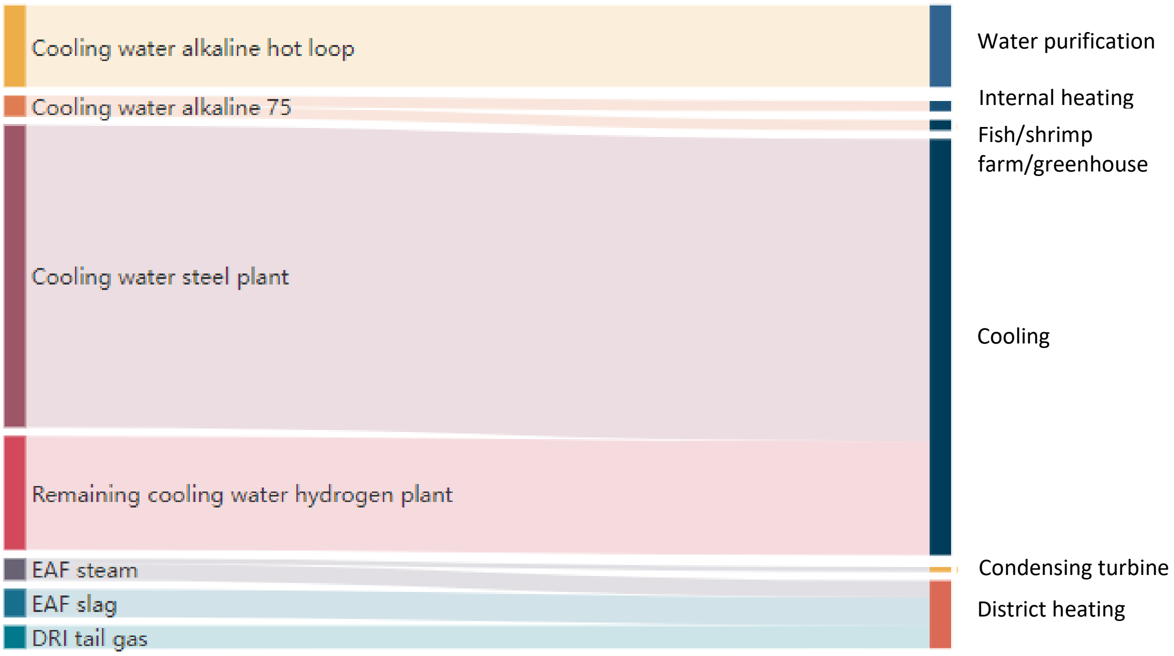

Figure 15: A possible outcome of heat distribution on usage areas.
(Visual Paradigm Online 2023 used for illustrating results)

Choice of method

The choice of method may have impacted the results in this report. The results are for instance limited to the knowledge of the people interviewed. If more people were contacted more usage areas of heat may have been found. Instead, only well-known technologies were studied whereas other potential energy and cost-efficient usage areas were excluded. The use of this report as a guide for industries wanting to make use of their waste heat is thereby limited. To strengthen the assumption that all interesting usage areas have been included, a scoping review using keywords to search for literature could have been carried out. This was overlooked because of time constraints and an aim to follow up on already known usage areas.

The results may also have been impacted by the literature studied. The sources may have over- or underestimated certain values, such as the efficiencies of different technologies or their associated costs. In this case, the comparison between the technologies becomes skewed and does not fully represent reality. For example, if the efficiency of a HRSG would be 70 % instead of the 80 %, that was argued for in the literature chosen, the amount of recovered heat would be lower. However, the overarching conclusion that more energy can be delivered from the alkaline electrolysers than from the slag remains the same. In the same way, if the installation cost related to low temperature ORC would be different, this would skew the cost analysis. But again, the overarching conclusion that the revenue from an ORC is lower than for district heating in this case is the same. Thus, the literature may have an impacted the heat recovered in different cases and the competitiveness of specific heat usage areas and the results should be read with some reservation. However, it is unlikely that the literature itself changes the overarching conclusions.

Another possible flaw is the accuracy of the formulas used, for example when calculating heat available at different parts of the plant or temperature losses in district heating pipes. Because of the high-level approach of this study, it is considered acceptable and even correct not to use detailed formulas including more parameters. Moreover, the data about temperatures and flows used in the calculations are based on early estimations of how the processes will operate and this also affects the correctness of the calculations. Very few value figures have been included to make up for these errors, but it is possible that the report would also benefit from a sensitivity analysis.

To summarize, the choice of method has impacted the level of certainty when it comes to what usage areas exists, energy available to extract, energy required for different usage areas and the costs and revenues associated with these. This should be borne in mind when reading the report. However, a more limited interview and literature scope as well as using simple equations and early estimations about processes has made it possible to, in a short period of time, provide an overall picture of the options available for heat recovery and their technical and economic potential.

Conclusion

There are many sources of waste heat from low emission steel production and many ways to utilize this heat. However, some uses do not make sense economically and others are not technically mature, introducing risks and complexity. The usage areas that have been found to be economically viable and technically mature, and thereby interesting to evaluate further at this stage for H2GS, is district heating and internal heating of the buildings.

For delivery of district heating discussions must be followed up with Luleå Energi and Bodens Energi to find the best way to combine the district heating networks with H2GS's plant. The energy to be delivered must also be clarified and depending on this different heat sources can be used. The highest amount of waste heat that can be delivered from H2GS's plant and has a potential to be used for district heating comes from the alkaline electrolysers. However, this is at a temperature slightly below 80 °C. Higher temperatures can be gained from the electrical arc furnaces, the tail gas by the direct reduction of iron or from a dry air slag granulation system. It is also possible to use a heat pump to gain higher temperatures, but this is more expensive and requires electricity as an input. If steam is available at the steel plant without extra investments installing a condensing steam turbine could be profitable. Further, the need of heat storage in accumulator tanks to account for stability in the delivery of heat must be evaluated.

When it comes to internal heating using waste heat, the temperatures needed are low and heat from cooling of processes would be enough. This could either be through a two-step cooling by the alkaline electrolysers or by simply installing heat exchangers by the output cooling water of other processes. The alternative to this solution is to purchase heat from Bodens Energi which, according to the brief cost analysis, introduces larger costs than installing components needed for an internal heating system. The design of such a system must be further evaluated.

Delivering heat to nearby industries such as a fish/shrimp farm could also be interesting for H2GS but is not urgent in the building process. Heat exchangers and pipes for this could be installed later if such projects would be realized. This solution can thereby be prioritized lower.

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Appendix

A1

Basis for pool calculations*:

Vav =Speed of vaporization = εA(Pv-Pl) [g/h]	
A = Pool area [m2]	
Pv = Saturated steam pressure at water temperature [hPa]	
Pl = Pressure of steam at ambient temperature [hPa]	
ε = Vaporization factor	
ε without pool cover	0,5
ε with pool cover	5

*Poolar. 2022. *Hur mycket vatten kan avdusta från polen?* https://www.poolar.se/hur-mycket-vatten-kan-avdunsta-fran-poolen/. (2022-12-15)

Pool calculations:

Estimated depth of pool	6	m	*1
Area of pool	37 500	m2	
Vaporization factor	5		With cover
Saturated steam pressure 30degC	42	hPa	*2
Steam pressure at ambient air temperature	20	hPa	Estimated
Speed of vaporization	4 213	kg/h	*3
Heat of vaporization 30degC	2 430	kJ/kg	
Energy loss of vaporization no cover	2,84	MW	
Other losses	1,22	MW	*4
Energy loss of vaporization with cover	0,28	MW	
Total losses/heating requirements	1,50	MW	

*1 Email from supplier. 18 December 2022.
*2 The Engineering Toolbox. 2022. Water - Saturation Pressure vs. Temperature. https://www.engineeringtoolbox.com/water-vapor-saturation-pressure-d_599.html. (2022-12-15)
*3 The Engineering Toolbox. 2022. Water - Heat of Vaporization vs. Temperature. https://www.engineeringtoolbox.com/water-properties-d_1573.html. (2022-12-15)
*4 Heat cover. 2022. Om HeatCover. https://www.heatcover.se/om-heatcover. (2022-12-15)

Basis for green house calculations:

Statistics for Sweden 2020*:		
Area of greenhouses	320	hektar
Energy consumption of greenhouses	610	GWh/yr
Energy consumption per hektar	2	GWh/yr/hektar

*Jordbruksverket. Energianvändning i växthus 2020. Tomat, gurka och prydnadsväxter. 2022. https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2022-04-25-energianvandning-i-vaxthus-2020.-tomat-gurka-och-prydnadsvaxter. (2022-12-15)

Green house calculations:

Greenhouse area	16	Hektar	*
Greenhouse energy consumption	31	GWh/yr	
Mean energy consumption in MW	3,48	MW	

* Email from supplier. 11 November 2022.

Total energy demand pool and green house: **5 MW**

A2

Roads

Property	Unit	General access roads plant area	Heavy traffic plant roads	Extra heavy traffic plant roads	Total
Length	m	7 362	8 039	1 232	16 633
Width	m	10	10	27	47
Area	m2	73 620	80 390	33 264	187 274
Heat required	W/m2	350	350	350	1 050
Total heat	MW	**26**	**28**	**12**	**66**

A3

Hydrogen plant building area

Side 1 [m]	Side 2 [m]	Area [m2]
100	40	4 000
100	40	4 000
100	40	4 000
100	40	4 000
130	35	4 550
Total		20 550

Steel plant building area

Side 1 [m]	Side 2 [m]	Area [m2]
80	412	32 960
96	255	24 480
40	200	8 000
420	50	21 000
36	250	9 000
120	500	60 000
40	190	7 600
375	80	30 000
375	80	30 000
370	50	18 500
40	330	13 200

Total	254 740

Total area [m2]	Energy consumption [kWh/m2/yr]	Heating power [MW]
275 290	140	4

A4

Alternative 1

Cooling water

Forward temperature	**C**	**100**
Return temperature	C	47
Cooling water temp in	**C**	**75**
Cooling temp out	C	35
Cooling water flow	kg/s	170
Specific heat capacity	kJ/kg*K	4,19

Steam requirements

Steam temperature	C	195
Steam pressure	bar	12
Enthalpy of steam	kJ/kg,K	2 803
Condense temperature	C	100
Condense pressure	bar	1
Enthalpy of condensed s	kJ/kg,K	417
Steam needed	**kg/s**	**16**

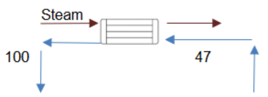
Cost analysis

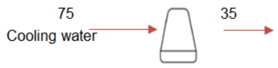
Electricity price	36,55	EUR/MWh
Electricity consumption per MWth (high)	0,04	MWel
Electricity consumption per MWth (low)	0,01	MWel
Cost per year high	12 807	EUR/(MW*år)
Cost per year low	1 724	EUR/(MW*år)
Cost of cooling (opex)	**207**	kEUR/yr

Source:https://files.slack.com/files-pri/T01JUFZEQ57-F04ASCJ3222/image.png

47-100	37	MW
75-35	28	MW

37 MW





Alternative 2

Cooling water

Forward temperature	**C**	**100**
Return temperature	C	47
Cooling water temp in	**C**	**75**
Cooling water temp out	C	107
Cooling temp in	C	54
Cooling temp out	C	35
Cooling water flow	kg/s	280
Specific heat capacity	kJ/kg*K	4,19

Steam requirements

Steam temperature	C	195
Steam pressure	bar	12
Enthalpy of steam	kJ/kg,K	2 803
Condense temperature	C	107
Condense pressure	bar	1,30
Enthalpy of condensed s	kJ/kg,K	449
Steam needed	**kg/s**	**16**

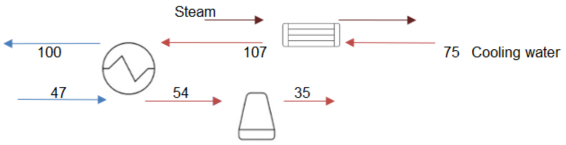
Cost analysis

Electricity price	36,55	EUR/MWh
Electricity consumption per MWth (high)	0,04	MWel
Electricity consumption per MWth (low)	0,01	MWel
Cost per year high	12 807	EUR/(MW*år)
Cost per year low	1 724	EUR/(MW*år)
Cost of cooling (opex)	**162**	kEUR/yr
Extra cost of cooling alt. 1	**45**	

Source:https://files.slack.com/files-pri/T01JUFZEQ57-F04ASCJ3222/image.png

75-107	37	MW
47-100	62	MW
54-35	22	MW

62 MW



A5

Per electrolyser (EoL) - Reference company

Flow [l/h]	Flow [kg/s]	T1	T2	dT	Energy [MW]	Modules	Total energy [MW]	Cost [EUR]
14 039	3,90	75	47	28	0,46	8	3,7	50 000

For H2GS:

Flow [l/h]	Flow [kg/s]	T1	T2	dT	Energy [MW]	Modules	Total energy [MW]	Cost [EUR]
14 039	3,90	78	47	31	0,51	288	146	1 800 000

A6

Specification

Customer :
Model : **CPX50** **Product range: Compabloc**
Project : **P&A Project file/**
Item : **H2GS Steam Heater** **Date : 25.11.2022**

		Hot Side	Cold side
Fluid		Water-Steam	Water-Steam
Mass flow rate	kg/s	15.00	124.3
Fluid Condensed/Vapourized	kg/s	15.00	0.000
Inlet temperature	°C	191.6	50.0
Outlet temperature (Vapour/Liquid)	°C	191.2/166.9	110.0
Operating pressure (in/out)	bara	13.0/12.9	
Pressure drop(Perm/Calculate)	kPa	260/11.4	100/17.5
Velocity connection(in/out)	m/s	18.7/0.546	1.00/1.04
Heat exchanged	kW	31230	
Mean temperature difference	K	110.6	
Relative directions of fluids		Crossflow	
Unit orientation		Horizontal	
Plate material / thickness		Alloy 316 L / 1.00 mm	
Sealing material		GRAPHITE	GRAPHITE
Lining material		ALLOY 316 L	ALLOY 316 L
Connection diameter (A1/A2 or B1/B2)	mm	400/200	400/400
Nozzle orientation		A1 -> A2	B1 -> B2
Pressure vessel code		PED ASME	
Fluid danger group*		No Danger	No Danger
Has risky vapour pressure		Yes	Yes
Connection standard		EN-1092 (PN#)	
Design pressure	bar	20.0	20.0
Test pressure **	bar	28.6	28.6
Design temperature	°C	220	220
Weight, empty / full	kg	3392 / 3785	
Shipping Dimensions (width x length x height)	cm	150.0 x 150.0 x 115.0	

Note :
**According to the new regulation PED 2014/68/EU related to Classification and Labelling of Chemicals, Seller should ensure that end user evaluate and provide the information regarding hazardousness of the fluids to the manufacturer.*
***Hydrostatic tests will be performed with liners installed, no pressure retaining welds will be leak tested before liners are installed.*

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