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# PREFEASIBILITY STUDY ON UTILIZATION OF WASTE HEAT FROM PEM ELECTROLYSIS IN 40MW PEM PLANT IN KRISTINESTAD, FINLAND.

Technology

## ACKNOWLEDGEMENTS

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## ABSTRACT

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|---|---|
| Author | Rajitha Somathilake & Pabash Priyankara |
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This research investigates the potential of utilizing low temperature waste heat from a 40 MW PEM electrolyser for integration into Finland’s district heating networks. As hydrogen production scales up in the transition toward green energy, its associated thermal byproduct presents an underexplored opportunity for improving overall energy system efficiency.

The objective of the study explore the quantity and quality of waste heat produced, suitable recovery and utilization technologies, and the economic feasibility of integrating this heat into district heating systems.

A technical and economic assessment was conducted using modeling approaches, supported by literature data and a prefeasibility case study based on a planned PEM electrolyser installation in Kristinestad, Finland.

Results indicate that approximately 20–30% of input energy is released as usable low-grade heat, well-matched to 4th Generation District Heating systems. With optimized heat exchanger setups and minimal conversion losses, system efficiency can exceed 90% when heat is recovered effectively. The Levelized cost of hydrogen (LCOH) was found to be as low as 3.35 €/kg, and the Levelized cost of heat (LCOh) ranged from 3.72 €/MWh (existing networks) to 49.69 €/MWh (new piping). These results demonstrate strong economic and technical viability, particularly when leveraging existing infrastructure.

The study concludes that waste heat recovery from electrolysis offers a cost-effective path to enhance district heating sustainability and recommends further dynamic modeling and pilot implementations.

Keywords PEM, hydrogen, waste heat, financial, financial, economic, prefeasibility

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## List of Abbreviations and Terminology

| **Term** | **Meaning** |
|---|---|
| % | Percentage |
| 1GDH | First Generation District Heating |
| 2GDH | Second Generation District Heating |
| 3GDH | Third Generation District Heating |
| 4GDH | Fourth Generation District Heating |
| 5GDH | Fifth Generation District Heating |
| ABB | ABB Ltd |
| AEL | Alkaline Electrolysis |
| AI | Artificial Intelligence |
| ATDH | Ambient Temperature District Heating |
| ATES | Aquifer Thermal Energy Storage |
| BF-BOF | Blast Furnace – Basic Oxygen Furnace |
| c | Cents |
| CAPEX | Capital Expenditure |
| CCF | Capital charge factor |
| CF | Plant capacity utilization factor |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide equivalent |
| COP | Coefficient of Performance |
| DH | District Heating |
| DHN | District Heat Networks |
| DHS | District Heating System |
| DRI | Direct Reduction of Iron |
| DRI-$H_2$-EAF | Direct Reduction of Iron making using EAF and $H_2$ |
| EAF | Electric Arc Furnace |
| EU | European Union |
| € | Euros |

| | |
|---|---|
| GHG | Green House Gases |
| GW | Gigawatt |
| GWh | Gigawatt Hours |
| GWP | Global Warming Potential |
| H2 | Hydrogen |
| $H_2$-DRI | Steel making from Direct reduced Iron from H2 |
| HBI | Hot Briquetted Iron |
| HHV | Higher Heat Value |
| hrs. | Hours |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IE3 | International Efficiency Class 3 |
| IEC | International Electrotechnical Commission |
| IRENA | International Renewable Energy Agency |
| IRR | Internal Rate of Return |
| kg | Kilo Grams |
| kW | Kilo Watt |
| kWh | Kilo Watt Hour |
| KJ/mol | Kilo Joule per mole |
| km | Kilo Meters |
| LCOE | Levelized Cost of Energy |
| LCOH | Levelized Cost of Hydrogen Production |
| LCOh | Levelized Cost of Heat Production |
| LHV | Lower Heat Value |
| LKAB | Luossavaara-Kiirunavaara Aktiebolag - Company |
| LMTD | Log Mean Temperature Difference |
| LPSC | Levelized steel production cost |
| LTDH | Low-Temperature District Heating |
| m | Meters |
| $m^3$ | Cubic Meter |
| M€ | Millions of Euros |

| | |
|---|---|
| ML | Machine Learning |
| MPTY | Annual metric tons of expected steel production |
| MW | Megawatt |
| MWh | Mega Watt hours |
| NPV | Net Present Value |
| $Oc_{fix}/OC_{Var}$ | fixed and variable operating costs |
| ODP | Ozone Depletion Potential |
| OPEX | Operating Expenditure |
| ORC | Organic Rankine Cycle |
| PBP | Payback Period |
| PCM | Phase Change Material |
| PEM | Proton Electrolysis Membrane |
| PHE | Plate Heat Exchangers |
| RES | Renewable Energy Sources |
| ROI | Return on Investment |
| SAF | Submerged Arc Furnace |
| SCADA | Supervisory Control and Data Acquisition |
| SMR | Steam Methane Reforming |
| SOEC | Solid Oxide Electrolysis Cell |
| SSAB | SSAB AB – Company |
| TES | Thermal Energy Storage |
| $T_O$ | Environment Temperature (Thermodynamics) |
| TOC | Total cost of building the facility |
| US | United States of America |
| USD | United State Dollar |
| Vattenfall | Vattenfall- Company |
| VFD | Variable Frequency Drive |

# 1. INTRODUCTION

Proton Exchange Membrane (PEM) electrolysis is one of the most advanced and efficient methods for green hydrogen production. In addition to producing hydrogen, PEM electrolysis generates significant amounts of waste heat, which, if captured and utilized effectively, can significantly improve the overall efficiency of the system and reduce the cost of hydrogen production.

According to reports by the International Renewable Energy Agency (IRENA), green hydrogen production is expected to increase substantially in the coming decades to meet decarbonisation targets. Finland, with its extensive district heating networks and favourable regulatory environment for renewable energy projects, is an ideal location for investigating waste heat recovery applications in PEM electrolysis systems. Previous research by Pärssinen et al. (2022) highlights the potential for integrating waste heat from electrolyser operations into district heating systems, which could offer substantial economic and environmental benefits. By combining a literature-based approach with a financial model, this study aims to provide a comprehensive framework for assessing the viability of waste heat recovery systems in large-scale PEM electrolysis plants.

The transition towards the sustainable energy future are a global priority and hydrogen plays an enormous role in carbon neutrality. The European Union (EU) already set a target to reach zero emissions by 2050 and Finland is taking far more actions by targeting carbon neutrality in 2035 (Saranapaa, 2024). One of the most efficient technologies is Proton Exchange Membrane (PEM) electrolysis to produce green hydrogen by using renewable energy sources such as wind and solar power. Compared to alkaline electrolysis (AEL) and solid oxide electrolysis (SOEC), PEM electrolysis offers higher efficiency (typically 70–80%) due to its lower operating temperature and rapid response time, making it well-suited for fluctuating renewable energy sources (Kari et al., 2022; Smith & Brown, 2021). However, the whole process generates significant waste heat, which is not usually recovered or utilized. This decreases the roundtrip efficiency of the system, leading to higher energy losses. If it becomes possible to effectively recover and use this waste heat, there is significant potential to improve the overall efficiency of the system and reduce the cost of hydrogen production.

Hydrogen production through PEM electrolysis will start in Finland with a plan to install 200 MW electrolysis capacity by 2025 and hope to scale up to 1 GW by 2030. To gain the effective progress of the process, it is needed to find an innovative solution for improve the efficiency of whole process by utilizing waste heat on district heating systems or other heat demanding industrial applications.

By combining a literature-based approach with a financial model, this study further aims to provide a comprehensive framework for assessing the viability of waste heat utilization systems for large-scale PEM electrolysis plants by identifying key parameters for a financial model. Final results will help to identify innovative solutions to improve the productivity and efficiency of PEM electrolysis process by utilizing the waste heat.

Plug Power is starting a significant project in Kristinestad where it is located in the western part of the Finland on the shore of the Bothnian Sea, with aim to produce green hydrogen for green steel iron (HBI). DRI or HBI will be exported from the port of Kristinestad to support production. The project plan involves 1 Gigawatt (GW) hydrogen Proton Exchange Membrane (PEM) electrolysis plant. This plant is designed to generate green hydrogen that will be utilized for producing of 2 million tons per year of Direct Reduced Iron (DRI) or Hot Briquetted Iron (HBI), where there is a huge excess heat that can be used for different options, if it is possible to recover.

In the Kristinestad PEM electrolysis plant, a significant amount of excess heat is generated, which, if recovered, could be utilized for various applications in the region. Potential uses of waste heat include district heating, industrial processes, greenhouse farming, swimming pool heating or even electricity generation through Organic Rankine Cycle (ORC) technology. Additionally, integrating waste heat utilization with local industries could improve overall energy efficiency and contribute to sustainability goals. Exploring these options can enhance the economic and environmental benefits of the hydrogen production process. This study seeks to explore the technical and economic feasibility of waste heat recovery from PEM electrolysis, using a large-scale 40MW PEM electrolyser plant in Finland as a case study.

## 1.1 Problem Statement

Our motivation for the study is based on the urgent global need to transition to cleaner and more sustainable energy systems. Hydrogen, particularly green hydrogen produced via renewable energy-powered Proton Exchange Membrane (PEM) electrolysis, has emerged as a cornerstone in this transition. However, despite its potential, hydrogen production via PEM electrolysis faces challenges related to efficiency and cost competitiveness. One of the critical opportunities to improve these areas lies in utilizing the significant amounts of waste heat generated during the process, which is often underutilized or discarded. Our aims are to improve energy efficiency and reduce hydrogen production costs so that we can fill the knowledge gap in waste heat recovery on large scale hydrogen production using PEM, to ensure that Finnish companies derive the economic benefit and generate motive for large scale investments in green hydrogen production. The research helps Finnish authorities in pursuing their decarbonisation goals and helps the world reduce dependency on fossil fuels and maximizing the bene-fit of renewable energy systems which mitigates climate change. Although PEM electrolysis is an area that is well- researched, the utilization of waste heat remains underexplored, especially in the context of largescale plants such as 40 MW electrolyser. This study aims to address this gap and provide actionable insights into how waste heat can be effectively harnessed.

Though PEM electrolysis is an effective method for green hydrogen production, the process operates with around 60%–70% efficiency, meaning a significant amount of energy is lost as waste heat (Xiao et al., 2019). If this waste heat is recovered and utilized, it would reduce energy costs, improve system sustainability, and enhance the overall techno-economic viability of hydrogen production (Ahmed et al., 2023). However, the process of waste heat recovery and utilizing from PEM electrolysis is associated with several challenges. The existing research address hydrogen production rather than waste heat utilization. So, there are three main research gaps can be seen and we have address for those through this research. The lack of research on waste heat recovery and utilization is the main challenge while technical barriers are considerable challenges since, the waste heat recovery from PEM electrolysis and utilizing in to district heating or industrial applications technologies are very complex. The third one, capital investment and operational costs are very high for heat recovery and utilization systems. So, there is a requirement to analyze the financial viability when implementing for larger projects. So above three gaps will be considered through-out this research.

This research will contribute to the growing body of knowledge on improving the efficiency and economic viability of PEM electrolysis systems. By focusing on waste heat recovery, the study addresses a critical aspect of energy utilization that is often overlooked in hydrogen production projects. The findings will provide valuable insights for policymakers, energy planners, and industry stakeholders in Finland and beyond, supporting the transition to a more sustainable energy system.

## 1.2 Research Gap Analysis

Research on industrial electrolysis waste heat, practical examples, and publications are limited. Additionally, detailed system designs or analyses for waste heat utilization from PEM electrolysis are scarce (Van der Roest et al., 2023). Therefore, this research aims to address this gap with a study on the topic of “Prefeasibility study on utilization of waste heat from PEM electrolysis in 40MW PEM Plant in Kristinestad”.

A good theoretical framework provides the foundation for analyzing the technical and economic aspects of waste heat recovery from a 40 MW Proton Exchange Membrane (PEM) electrolyser plant in Kristinestad, Finland. It establishes the key concepts, principles, and methodologies for examining technical feasibility, economic viability, and the case study framework for this research. This section focuses on integrating waste heat recovery into district heating systems and its financial assessment, providing a blueprint for the subsequent analysis.

## 1.3 Research Aim and Objectives

The main aim of this research is to evaluate the technical and economic feasibility for waste heat utilization from PEM electrolysis and develop a financial model to analyze the waste heat utilization. Under the techno economic viability, we consider a detailed case study on a 40 GW PEM electrolysis plant at Kristinastad in Finland, Our Aim is to assess the technical feasibility of waste heat recovery systems, including heat exchanger design, operational integration with district heating, and potential heat losses. Furthermore, analysis of economic implications, such as reduced dependency on conventional heating fuels, savings from $CO_2$ reductions, and capital cost recovery are seen as critical elements of the study. Further, in relation to the financial model development objective, we will identify key parameters influencing financial feasibility, including electricity prices, heat pumps efficiency, carbon abatement benefits, and capital expenditure. Sensitivity analysis is used to assess the impact of variable factors on profitability and provide a robust financial evaluation.

Finally through this research, we will be able to derive three main outcomes for potential clients. The first one is technical feasibility insights in to the amount of waste heat generated by the PEM electrolysis process to clearly understand the technical requirements for implementation of waste heat recovery system within the PEM electrolysis plant. The second one is to assess the technical and economic feasibility by means of a comprehensive analysis of cost savings, revenue potential, and financial risks associated with waste heat utilization. Then the third one is assess the sensitivity of the system variables to cost of hydrogen production using PEM and the levelised cost of heat production in the waste heat recovery process.

### 1.4 Reserch Questions

There are four main research questions that lead to the research.

1. How much waste heat is generated by a 40 MW PEM electrolysis plant, and what are the most viable technologies for capturing and utilizing this heat in Finland's district heating systems or other industrial applications?

2. What are the technical and economic requirements for implementing waste heat recovery systems in a 40 MW PEM electrolysis plant, including the capital and operational costs, potential revenue streams, and payback period?

3. What are the key parameters for developing a financial model to assess the feasibility of waste heat utilization, and how do factors such as CAPEX cost, electricity prices, heat pump performance, discounting rate and length of district heating network ect. affect the economic viability?

### 1.5 Research Framework

Conceptual, theoretical and methodical frameworks will provide a foundation for this research. It provides a structured approach to the research questions and objectives.

This research is mainly centered on three key concepts and they are PEM electrolysis, waste heat recovery and utilization, and the techno economic feasibility of such utilization. The relationships between three concepts will address how waste heat utilization leads the energy efficiency and economic sustainability in Finland’s energy sector. Mainly research is grounded on thermodynamic principals related to energy conservation and heat transfer. Further financial feasibility model will describe the Levelized cost of Hydrogen Production (LCOH), Levelized cost of heat production (LCOh) and Payback period (PBP) to evaluate the economic viability of waste heat utilization.

Then the methodological framework will provide a thorough theoretical framework and a case study approach to analyze the technical and economic aspects of waste heat utilization. Then the financial model will be used to perform a cost benefit analysis.

### 1.6 The Significance of Research

The research findings will be significant due to several reasons. By analyzing waste heat recovery and utilizing technologies, the study will help system operators to optimize energy efficiency in hydrogen production that leads the technical advancements and the financial model development will present economical insights to policymakers, investors and industry stakeholders to facilitate sound decision making in the initial project feasibility phases. The findings will shed insight for policy making or requirements on waste heat utilization in Finland's green hydrogen strategy. Utilizing waste heat from PEM electrolysis can contribute to Finland's climate neutrality goals by reducing dependence on fossil fuels in district heating applications and other industrial or municipal processes.

### 1.7 Structure of the Thesis

This thesis is structured as follows. Chapter 1 is Introduction. It provides an overview of the research background, problem statement, research aim and objectives, research questions and significance of the research.

Then chapter 2 mainly discusses the theoretical framework under the following sub topics. Hydrogen industry and Finland hydrogen production, waste heat recovery and utilization, system components and district heating generations, economic and financial feasibility, and finally the case study framework.

Chapter 3 discusses the Kristinastad specific business case. Suggested overview of the plant, selections of electrolysers, hydrogen production for DRI process, cooling water requirement, heat production, and applications for the recovered heat in Kristinestad are further discussed including swimming pool heating and district heating.

4th Chapter is methodology. Under this chapter we have discussed, how others previously did their research, especially what their methods were and how they collected data. Further on, we have discussed the method adopted by us for this research and how the data was collected.

In the 5th Chapter we had focused on financial modeling and results. Key parameters and assumptions, formulations for equations and financial modeling are main topics that are elaborated under this chapter. Financial modelling discusses both Levelized costs of hydrogen and heat and simple payback period considering heat sales to the district heating network under two scenarios of new piping and injection in to the existing infrastructure.

Final chapter summarizes the answers to our three research questions, the practical contribution of our study, identifies limitations and highlights scenarios for any future research.

# 2. THEORETICAL FRAMEWORK

## 2.1 Hydrogen Production

All EU countries must align with climate neutrality by 2050, and Finland has set an ambitious target to reach climate neutrality by 2035 (Saranpää, 2024). As a result, there is a significant demand for Renewable Electricity Sources (RES). This has led to an increasing need for hydrogen production, transportation, and storage (Janota, Surovezhko & Igissenov, 2022). If we can obtain a favorable outcome from this research, it will provide extraordinary value to the energy industry.

To meet Europe's future hydrogen demand, four primary platforms for hydrogen production are identified: coal power (18%), natural gas (48%), fossil fuels (30%), and electrolysis (4%) (Kannah et al., 2021). Currently, hydrogen production is predominantly reliant on fossil fuels, contributing significantly to carbon emissions. However, Europe is transitioning towards a clean hydrogen economy, emphasizing renewable-based hydrogen production to align with its climate neutrality goals. This shift highlights the importance of electrolysis, particularly Proton Exchange Membrane (PEM) electrolysis, as a promising technology for sustainable hydrogen generation.

By leveraging renewable energy sources, PEM electrolysis offers a low-emission alternative to conventional hydrogen production methods, making it a crucial component of Europe's future energy strategy. In the context of electrolysis, hydrogen can be supplied from mass-scale production sites, such as those located in oceans or deserts, as well as from local hydrogen production plants. Compared to mass-scale facilities, local cluster hydrogen or heat production is more adaptable to serving nearby services (Van der Roest et al., 2023).

## 2.2 Waste Heat Recovery

However, the electrolysis process is not fully efficient, generating heat as a by-product. Current-generation electrolysis technologies achieve an overall system efficiency of approximately 74–79% (Kannah et al., 2021). The efficiency of heat transfer from the system and waste heat recovery efficiency is approximately 77–80% (Cummins, 2021). The potential for technical is contingent upon the balance of stack efficiency. Additionally, when electrolysis systems are installed at shorter distances, the efficiency of heat recovery improves.

Butler and Spileoff (2018) highlight three key projects in the field of waste heat recovery. The BioCat project, which deployed a 1MW electrolysis installation for hydrogen production, was overseen by the Danish Energy Agency (2014). However, it achieved less than 1% success. Another notable project is Stromluckenfuller, where waste heat from a 200kW electrolysis system was integrated into a heating network, as reported by IKZ (2017). Furthermore, a project involving a 1MW electrolysis plant employed heat recovery within a district heating system, as discussed by GmbH GHE (2023).

In Hamburg, a 100MW electrolysis plant is proposed, integrating a district heating system for heat recovery, with operations set to begin by 2025 (Shell, Mitsubishi Heavy Industries, Vattenfall & Wearme Hamburg, 2021). Another study on waste heat utilization in PEM electrolysis presents three designs: using heat as an end-use customer, incorporating a heat pump for high-temperature heat, and delivering heat to a district heating system. Their techno-economic analysis concluded that utilizing PEM electrolysis can enhance overall system efficiency through heat recovery (Van der Roest et al., 2023).

PEM electrolysis usually operates between 50 – 80 C. Waste heat recovery plays a crucial role in improving the efficiency and economic feasibility of PEM electrolysis. According to Bananno et al. (2024), Operating PEM electrolysis in elevated temperature can enhance the performance by reducing the energy consumption and optimizing catalyst utilization. When operating with higher temperature, it will lead to better waste heat integration. Specially electrolyze operate in exothermal mode (where the voltage exceeds the thermoneutral voltage) resulting in additional heat generation. This waste heat can be directly used for industrial application or district heating purposes. This study indicated that lower temperature operations, heat recovery applications have already been implored and increasing the operating temperature could increase the economic feasibility of waste heat recovery and utilization. However further studies are needed about technical aspects of waste heat recovery and utilization especially for district heating integration (Bananno et al., 2024).

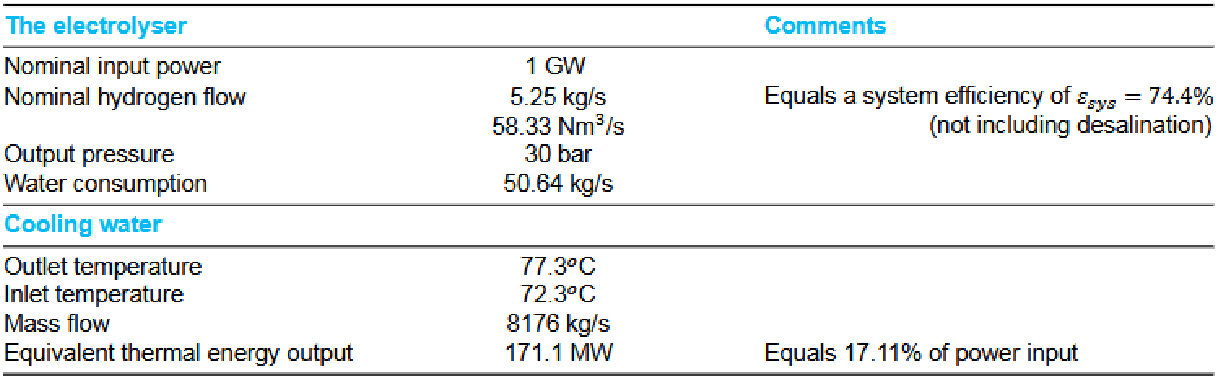
Proton Exchange Membrane (PEM) electrolysis produces a significant amount of waste heat due to inefficiencies in the electrolysis process. The amount and quality of recoverable heat depend on key factors such as the stack operating temperature, cooling water temperature, and system design. PEM electrolysis normally operates at lower temperatures, which affects the efficiency of heat recovery. However, optimizing the cooling system can enhance the potential for heat recovery (Saranpää, 2024).

It has been demonstrated that a redundant system design can effectively utilize heat from electrolysis without affecting the hydrogen production process. Efficient use and valorization of this heat from electrolysis could result in higher system efficiency, carbon dioxide ($CO_2$) savings, and improved economic feasibility. Regarding economic feasibility, the levelised cost of energy (LCOE) significantly increases with heat pump usage, making it a critical factor in designing a heat recovery and utilization system. In terms of heat utilization and sensitivity analysis, the heat transportation distance plays a crucial role, directly impacting the cost of heat utilization. Finally, this research highlights that heat recovery and utilization offer both environmental and economic benefits, adding value to local integrated energy systems (Van der Roest et al., 2023).

After recovered, the waste heat from PEM electrolysis can be integrated into district heating (DH) networks. It will contribute to a more sustainable energy system. The feasibility of heat utilization depends on several factors, including the distance between the electrolysis and the DH network, temperature requirements, and economic considerations such as the Levelized Cost of Heat (LCOh). Using heat pumps can improve heat integration, but electricity price fluctuations impact both hydrogen production and heat utilization. Further research with real-world data is necessary to optimize the integration of PEM electrolysis waste heat into DH systems (Saranpää, 2024).

Normally in the beginning, 20% electricity energy transform in to heat energy but, after 10 years, it will be around 30% and it is nearly 50% heat energy increment related to the started hydrogen slack. Based on the case a (recovery heat connected with end consumer), case b (recovery heat connected with heat pump and external consumer) and case c (recovery heat connected with district heating system), the highest total system efficiency can be taken from the case c. It means the best way is to connect with DHS according to Van de Roest et al. (2023).

The waste heat utilization possibilities are dependent on the location of the electrolysis and size of the project. Tiktak (2019) talks about two scenarios under excess heat utilization from PEM electrolysis. The first one is North Sea energy case study and second one is Nieuwegein case study. In the North Sea energy case, he gives the model data for excess heat generation and figure 1 below gives the data. The electrolysis is operated at high temperature, around 80 Celsius, implying that there is a high potential for taking substantial amount of excess heat. The electrolysis capacity is 1GW.



| The electrolyser | | Comments |
|---|---|---|
| Nominal input power | 1 GW | |
| Nominal hydrogen flow | 5.25 kg/s<br>58.33 Nm³/s | Equals a system efficiency of $\varepsilon_{sys} = 74.4\%$<br>(not including desalination) |
| Output pressure | 30 bar | |
| Water consumption | 50.64 kg/s | |
| **Cooling water** | | |
| Outlet temperature | 77.3°C | |
| Inlet temperature | 72.3°C | |
| Mass flow | 8176 kg/s | |
| Equivalent thermal energy output | 171.1 MW | Equals 17.11% of power input |

Figure 1. Heat data related to 1GW plant (Tiktak, 2019)

Based on above data, the hydrogen production efficiency is 74.4% and by using heat the total system efficiency can be improved up to 91.56%. The excess heat can be used for preheating process of the water before using in the electrolysis process. It is one of the methods that can be used to utilize waste heat from PEM electrolysis. The Nieuwegein case study mainly focuses on waste heat utilization with district heating systems. In district heating systems, heat is utilized for space heating or water heating in buildings. Some district heating systems operate by using around 80 C temperature and outlet water temperature around 40 C. These low temperature district heating system are considered in many studies to find out the feasibility of such utilization (Tiktak, 2019).

In Finland, there is a huge demand for heat from district heating systems and waste heat from PEM electrolysis process can be utilized leading to cost reduction of hydrogen production process. Studies shows that, utilizing low temperature waste heat can improve the overall energy efficiency of PEM electrolysis while reducing the cost. On the other hand, there is a possibility of waste heat usage in industrial applications but it is needs heat at moderate temperatures. As an example, drying, preheating and chemical production can be shown as possible applications. Sometimes this leads to lower operational costs, as it reduces the need of separate heating systems (Iummen et al., 2023).

Excess waste heat generated from a PEM electrolysis system can be effectively utilized for hot water generation. A study by Siecker et el. (2024) shows a scenario, where a circulating fluid transfers heat from the electrolysis stack to a hot water storage tank. This method has already been applied to the fuel cell systems practically and shows success even at the domestic level. Therefore, implementing similar heat recovery and utilization techniques in PEM electrolysis systems will enhance the overall efficiency of the system and contribute to sustainable energy solutions (Siecker et al. 2024).

## 2.3 System Components and District Heating Generations

### 2.3.1 Heat Exchangers

Heat exchangers are critical components in capturing and utilizing waste heat from industrial processes including PEM electrolysis. They facilitate the transfer of thermal energy from one medium to another without mixing the two. There are mainly two key types of heat exchangers relevant to this study.

Plate Heat Exchangers (PHE) that are compact and efficient. These are suitable for district heating applications due to their high heat transfer coefficients and small footprint (Kakaç et al., 2012). Hyfindr (n.d.) report that heat generated from the PEM electrolysis process can be effectively removed using plate heat exchangers to ensure that hydrogen production is optimal and the maximum temperature for the electrolyte is not exceeded. They stress on the importance of corrosion prevention to increase the longevity of PEM electrolyser and use of stainless steel (316) to prevent embrittlement of the plate material. They suggest use of gasketed plate heat exchangers for plants exceeding capacity of 1 MW and fully welded construction for the smaller plants. (Healey, 2022) indicate that plate heat exchangers are compact, keeps the heat transfer fluids separated and highly efficient in their operation, while SWEP Heat Exchangers (n.d.) report that efficiencies greater than 90% are achievable. Hence, we have used an efficiency of 85% for the calculations, as a conservative figure.

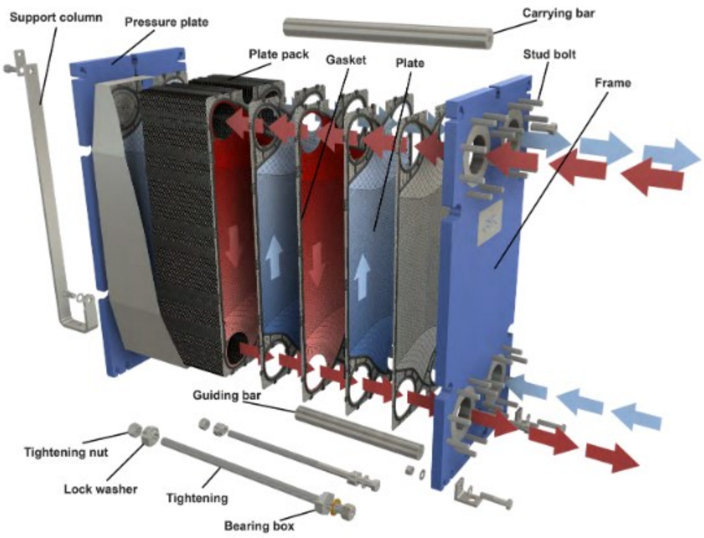


Figure 2. Gasketed plate heat exchanger construction (Alfa Laval., n.d.)

Shell and Tube Heat Exchangers are commonly used in industrial settings for their durability and ability to handle high-pressure fluids.(Incropera et al., 2007)

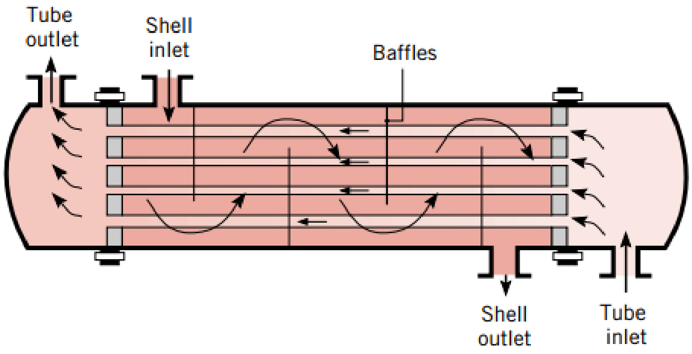


Figure 3. Shell-and-tube heat exchanger (Incropera et al., 2007)

The effectiveness of a heat exchanger is governed by:

- Log Mean Temperature Difference (LMTD): Measures the driving force for heat transfer. This formula is useful in calculations of heat transfer when entering and leaving fluid temperatures to the heat exchanger is known.

$$\Delta T_{\mathrm{lm}} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \quad \text{.............. ( 1 )}$$

$\Delta T_{lm}$ = Log mean temperature difference

$\Delta T_1$ = Temperature difference in side 1

$\Delta T_2$ = Temperature difference in side 2

- Heat Transfer Coefficient (U): Depends on the materials used, flow rates, and the heat exchanger design. (Incropera et al., 2007) suggest an overall heat transfer coefficient of 850–1700 $W/m^2$ K for water to water and 850–1700 $W/m^2$ K for water to air applications.
- Effectiveness (ε): Represents the ratio of actual heat transfer to the maximum possible heat transfer.

$$\mathcal{E} = \frac{Q}{Qmax} \quad \text{.............. ( 2 )}$$

Where, Q & Qmax are actual and maximum heat transfers

### 2.3.2 Heat Pumps

Heat pump is a device that supplies heat from a low temperature medium to a high temperature one by utilizing work energy supplied to it by means of a compressor. Heat pumps operate on the principle of reversed Carnot cycle and practically employ the vapor compression refrigeration cycle to upgrade low heat provided to high heat. Main component is the compressor, where the refrigerant is compressed increasing both pressure and temperature, followed by a condenser or a heat exchanger where the heat is rejected at a high temperature. The refrigerant then expand through an expansion valve to generate refrigerant vapor before being supplied to the evaporator, where it absorbs heat from the low temperature liquid.

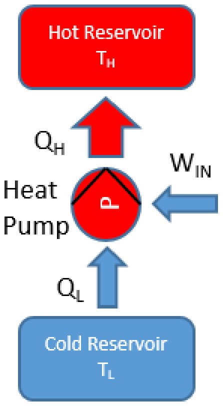


Figure 4. Heat Pump

Coefficient of performance of such a system is given by,

$$COP = \frac{Desired\ Output}{Input} = = \frac{Q_H}{Q_H - Q_L} = \frac{T_H}{T_H - T_L} \qquad \text{..............} (3)$$

There are many common refrigerants used for heat pumps. R-410A, R-32, R-134a, R-290, R-744 ($CO_2$) and R-290 (Propane) are most commonly used. Refrigerants play a main role in global warming and ozone depletion. Montreal protocol aims to ban the production of substances that deplete the ozone layer while Kyoto Protocol aims to regulate greenhouse gas emissions. European Environment Agency (2017) defines Ozone Depletion Potential (ODP) as integrated change of Ozone per unit mass emission of a substance as compared to that of CFC-11, while Global Warming Potential(GWP) for gases are measured compared to that of the reference gas $CO_2$, which is assigned GWP of 1. The below table 1 illustrates the ODP and GWP for various refrigerants used in manufacture of heat pumps.

Table 1. GWP/ODP – Refrigerants (Engineering ToolBox, n.d.)

| ***Refrigerant*** | ***ODP*** | ***GWP*** |
|---|---|---|
| R-134a | 0 | 1300 |
| R-32 | 0 | 677 |
| R-401A | 0.037 | 1100 |
| R-290 | 0 | <1 |
| R-744 - $CO_2$ | 0 | 1 |

Selection of a suitable heat pump is important from the life cycle perspective of any green energy project. Life cycle assessment must be performed to determine their carbon neutrality in terms of manufacturing, in use and disposal carbon inventories. Such studies are beyond the scope of this article and requires further research. Globally heat pump industry is large, as there are many applications, including smaller pumps for household/ building heating, for swimming pool heating, larger pumps for district heating and as a source for power generation. MAN Energy Solutions (n.d.) indicate that $CO_2$ as a good refrigerant based on the evidence that is naturally occurring, has zero ODP, very low GWP and no impending environmental legislations. Furthermore, they highlight that transcritical $CO_2$ heat pumps can deliver higher temperatures without cascading, can manage large temperature differentials between the source and sink and can be designed with smaller piping systems due to its high density. They report that their Model HPU43 as having a higher delivery temperature of $150^0$C, COP of 3.04 and a heating capacity of nearly 50MW, which is suitable for district heating applications. Figure 6 illustrates the performance of their units based on system temperatures.

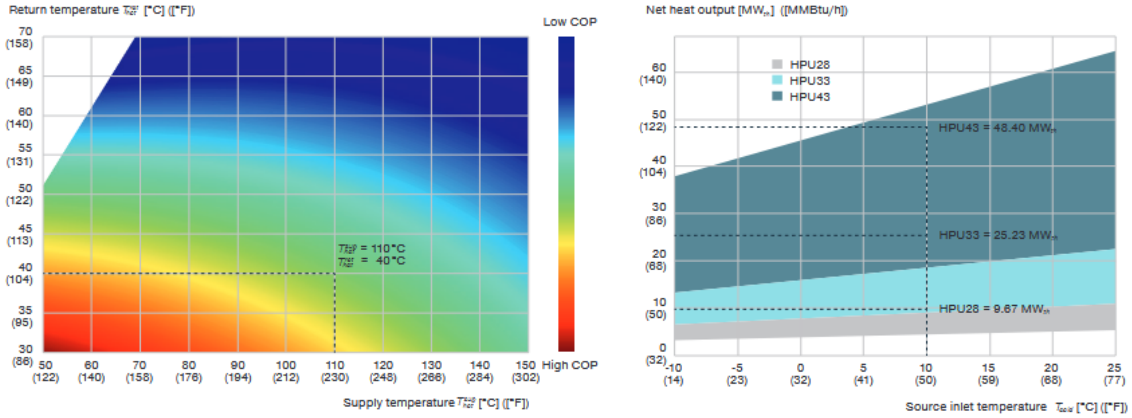


Figure 5. Performance of MAN heat pumps with different temperatures(MAN Energy Solutions, n.d.)

### 2.3.3 Thermal Storage Tanks

Thermal storage plays an important role for waste heat recovery in electrolysers. Thermal Energy Storage (TES) allows smaller system components in the face of heat demand variability. It allows a buffer storage where system peaks can be effectively managed without oversizing the heat generation components. For PEM electrolyser using waste heat from the electrolyser itself as the heat generator, design of the electrolyser plant depends on the requirement of hydrogen for steel production, and heat generation is not the primary application of PEM. Hence, TES is required when supplying the heat to external uses with variability in demand, while matching PEM components to the hydrogen demand.

Thermal energy storage systems at present mainly use sensible heat storage, latent heat storage or the storage of heat by phase change of material. Sensible heat storage uses volumetric heat capacity, that is density times the specific heat capacity of material to store the heat energy. As water has a higher density and heat capacity, it is commonly used in standard applications such as diurnal heat storage systems. Storage in the form of rocks can also be used to reduce the volume, however, this method is not ideal for pumping applications as the separate systems must be installed to transfer the heat to water for use in DHNs. Additional systems increases cost of installation and maintenance, thus increasing levelised cost of heat. Rocks may be used for seasonal storage applications, where storing large quantities of water may not be practical and cost effective. Water has a limitation in sensible thermal storage system applications as highest temperature of storage is limited to its boiling point at $100^0$C in in unpressurised storage systems.

Latent heat storages utilize the latent heat of vaporization and latent heat of fusion to store heat energy without any temperature change. Water/Ice storage systems used extensively in cooling systems use latent heat of fusion to supply the cooling peak demand as it reduces the system water volume storage requirements. Chemical phase change materials are available at present as PCM's, that can be used for both high and low temperature applications. Dincer & Rosen (2011) suggest that magnesium nitrate hexahydrate ($Mg(NO_3)_2 \cdot 6H_2O$) and magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$) can be used for applications in where the storage temperature range is between 40-$60^0$C, however, these are not ideal due to cycling stability and issues in maintaining a constant phase separation temperature of an eutectic mixture which may not change phase when required due to having many component parts and may also deteriorate in performance due to cyclic hysteresis.

Water is the most common and widely available material that can be readily used for sensible heat storage applications in the range of 0-$100^0$C, and is therefore the most reliable and cost effective storage method for diurnal storage. Dincer & Rosen (2011) suggests that a water tank for heat storage applications must have its mixing, dead water volume and heat loss from the tank minimized. Figure 7 shows the comparison of good and a poor water tank design based on dead water volume. Furthermore, the same source identifies the best design concepts for tanks of larger capacity build above ground as illustrated in figure 8. Dincer & Rosen (2011) also highlights the effectiveness of single medium storages where the storage and transfer mediums are the same with increased efficiency due to low intermediary losses and less system complexity resulting in lower costs.

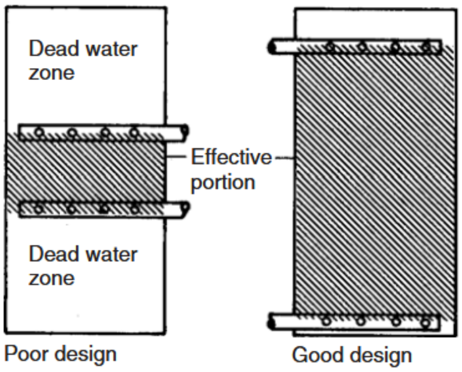


Figure 6. Minimizing dead water volume- (Shimizu and Fujita, 1985), as cited in (Dincer & Rosen, 2011)

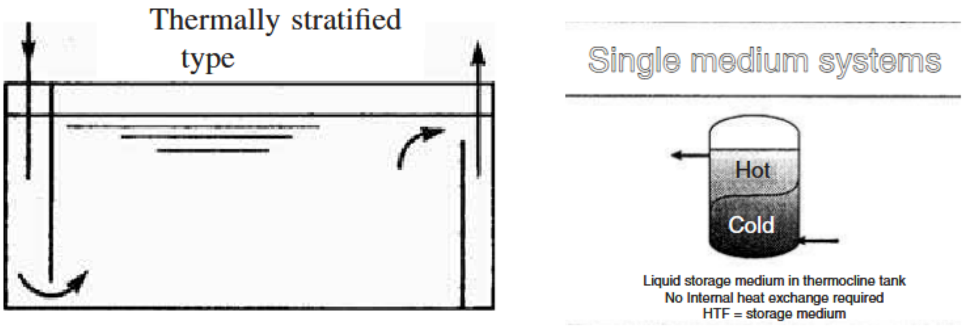


Figure 7. Best Design scenario for larger water tanks above ground - (Shimizu and Fujita, 1985), as cited in (Dincer & Rosen, 2011)

Aquifer Thermal Energy Storages (ATES) may also be used for thermal energy storage in waste heat application. This is especially useful in district heat load-levelling applications where the storage can be charged during periods of low demand, such as summer months and unloaded during high heat demand periods such as in winter (Dincer & Rosen, 2011). The authors also emphasize that ATES and deep ATES are suitable for high capacity systems, where existing capacities range from 50kW to 10 MW. ATES need load balancing to ensure that thermal energy input and output are balance so that ground water temperature remains unaltered by the operation of the ATES. These systems can be used for both summer cooling and winter heating using a single design as shown in figure 9. The systems have been shown to operate successfully in the temperature range of 10-40$^0$C successfully. There is an opportunity to decarbonize heating systems and avoid CFC greenhouse gases using ATES in heating/cooling applications. The authors also suggest the use of Deep ATES systems since they are irrelevant of ground water flows, unaffected by seasonal temperature variations and can operate at higher temperatures due to the natural geo thermal gradients. The authors report that unconfined aquifers have been used in countries such as Sweden, France and the US. Heat pumps can also be integrated to such systems easily for higher temperature applications.

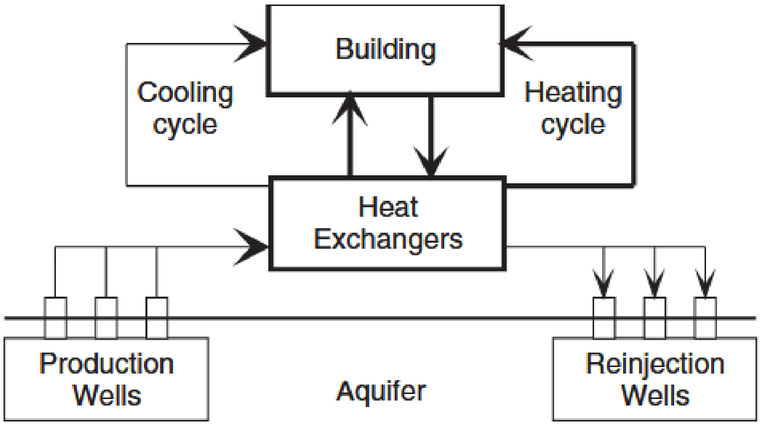


Figure 8. Operation of ATES - Heating and Cooling - (Dincer & Rosen, 2011)

Helen (2020) reports of a project in Mustikkamaa, Helsinki, where 2 abandoned oil caverns at a depth of 80m will be filled by 260,000 m$^3$ of water to act as a ATES, to balance the peak load fluctuations in Helsinki’s district heating network. The project is supposed to deliver 120MW at peak with an annual thermal energy capacity of 11,500 MWh and a saving of 21,000 tons of $CO_2$ emissions per annum. Though ATES systems are modern technology and appealing, they have drawbacks such as requiring expensive pilot studies to verify feasibility/ site specific, environmental barriers in getting approvals, influenced by the local climate and geological conditions and require more time in implementation. Hence, overall a known and established technology such as an aboveground water tank may be feasible for medium amount of diurnal thermal energy storage.

### 2.3.4 Water Pumps

Water pumps are one of the essential components in any heat transfer system. They assist in transferring the fluid between the TES and the heat exchangers. Further, they are used to transport the heated water from the TES to the district heating network and to transport the water in the district heating network pipes. Common types of pumps used for such applications include Centrifugal and axial flow pumps. Both these pumps have single stage and multistage impellers to increase the delivery pressure of the system.

For district heating applications, centrifugal pumps are preferred due to the requirement to transport the fluid over long distances. Pressure generated by axial flow pumps is usually lower than that generated by centrifugal pump of the same size. (Yunus A. Cengel & Cimbala, 2013) indicate that pump selection must be based on the intersection of the system curve and the pump performance curve as shown in figure 10. For larger volume flow rates cascading of several pumps in parallel must be considered and additional system pressure can be generated by installing inline axial flow pumps or installing several centrifugal pumps in series. The effects of such Installation on a head-flow curve are depicted in figure 11.

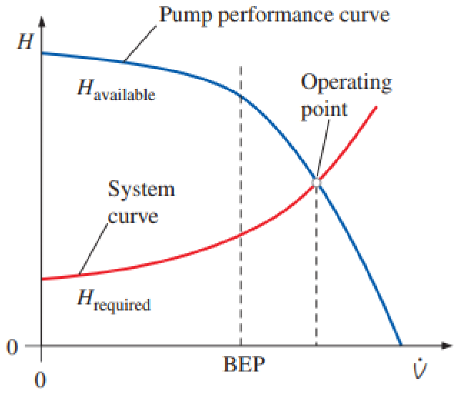


Figure 9. Pump selection criteria - (Yunus A. Cengel & Cimbala, 2013)

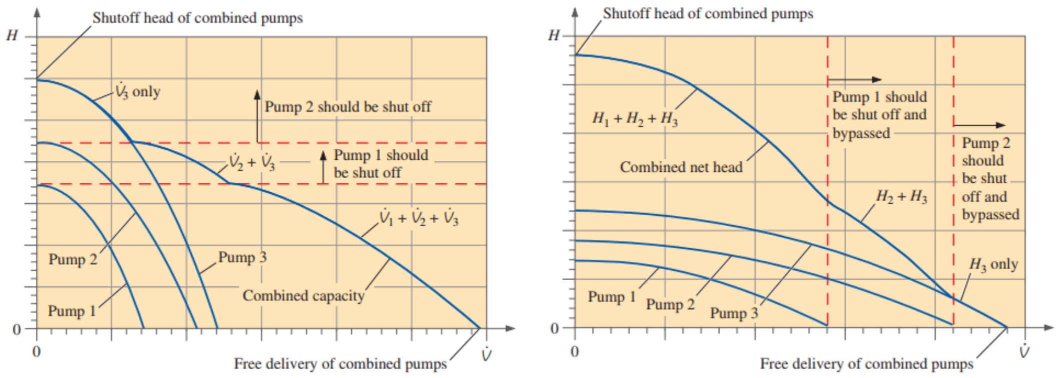


Figure 10. Parallel and Series cascading of pumps - (Yunus A. Cengel & Cimbala, 2013)

### *Pump motor*

Selection of the pump motor is important for energy efficiency. Motors must have at least IE3 (premium efficiency) classification or above according to International Electrotechnical Commission (IEC) standards. Continuous duty pumps such as those used in district heating applications require large amounts of electricity and gives the opportunity to save large amount of carbon emissions in the long run by selection of the correct motor for the pump. The high initial investment can be recovered by savings in electricity and offset of the carbon costs.

### *Pump Control*

Controlling of pumps to match the real-time thermal demand of the network is essential to optimize the performance of the pumps. Variable frequency drives (VFD’s) can be used to control the speed and the flow delivery in order to meet this end. This lowers the power consumption of the pump motors and reduces mechanical stress on the pump components thus further reducing the operation and maintenance requirements. ABB emphasizes that VFD-controlled motors in district energy systems enhance overall system efficiency and resilience by precisely managing energy production, transmission, and distribution processes. They further claim that savings from 20-60% are possible for DHN with the use of VFD’s (ABB, n.d.-b). Incorporating VFDs also allows for real-time monitoring and control, enabling operators to swiftly respond to fluctuating heating demands and optimize system performance. Consequently, the adoption of VFD technology in district heating not only promotes sustainability through reduced energy consumption but also enhances operational reliability and cost-effectiveness.

### 2.3.5 Smart Control Systems

Incorporating advanced control systems into district heating networks is essential for enhancing efficiency, reliability, and sustainability. Supervisory Control and Data Acquisition (SCADA) systems play a pivotal role by providing real-time monitoring and control over various network parameters, such as temperature, pressure, and flow rates. An example of such available system is ABB's Symphony® Plus SCADA system where the manufacturer claims that their system allows monitoring and control of the water networks remotely. Their system allows operators identify system anomalies at user and the plant level, while the inbuilt algorithms accurately predict the plant maintenance issues. They further emphasize that collection of user demands allows accurate future demand predictions and operation point adjustments and the system can be easily scaled according to growing system demand using a multi-client and multi-server architecture  (ABB, n.d.-a). Integration of smart metering systems allows accurate and timely measurements of heat demands from every user.  ABB have implemented such district heating control systems in Shangri-La city in china where the system serves nearly 50,000 residents at 3,300m above sea level.

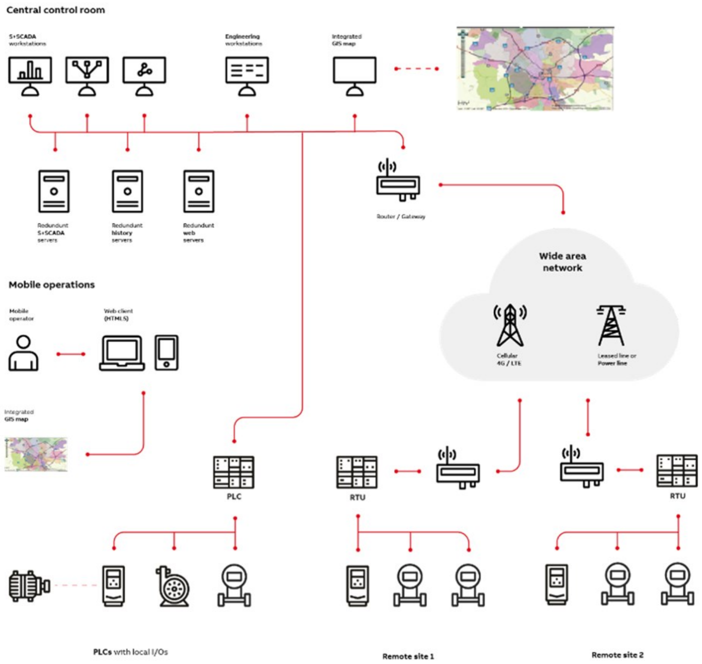


Figure 11 . System Architecture - Symphony® Plus SCADA - (ABB, n.d.-a)

Artificial Intelligence (AI) and Machine Learning (ML) is currently used for making preventive maintenance faster, institutive and more efficient. Siemens (n.d.) claim that AI is able to give the ordinary maintenance worker expertise knowledge of the system and component performance by continuous condition monitoring of critical parameters such as temperature, speed, vibration and flow, and further give predictive alarms and suggestions to prevent failure. Siemens' AI-based predictive maintenance solutions, utilize AI to detect patterns and provide reliable maintenance recommendations, thereby improving system uptime and performance (Siemens, n.d.). Collectively, these technologies contribute to the development of smart district heating networks that are characterized by adaptability, efficiency, and reduced environmental impact. The integration of SCADA systems, smart metering, and AI-driven analytics ensures optimal resource utilization and aligns with global sustainability goals.

### 2.3.6 District Heating Systems

District heating networks distribute thermal energy, typically in the form of hot water or steam, to multiple buildings from a centralized source. These systems can integrate waste heat from PEM electrolysis to improve overall energy efficiency and sustainability.

#### *Generations of District Heating Systems*

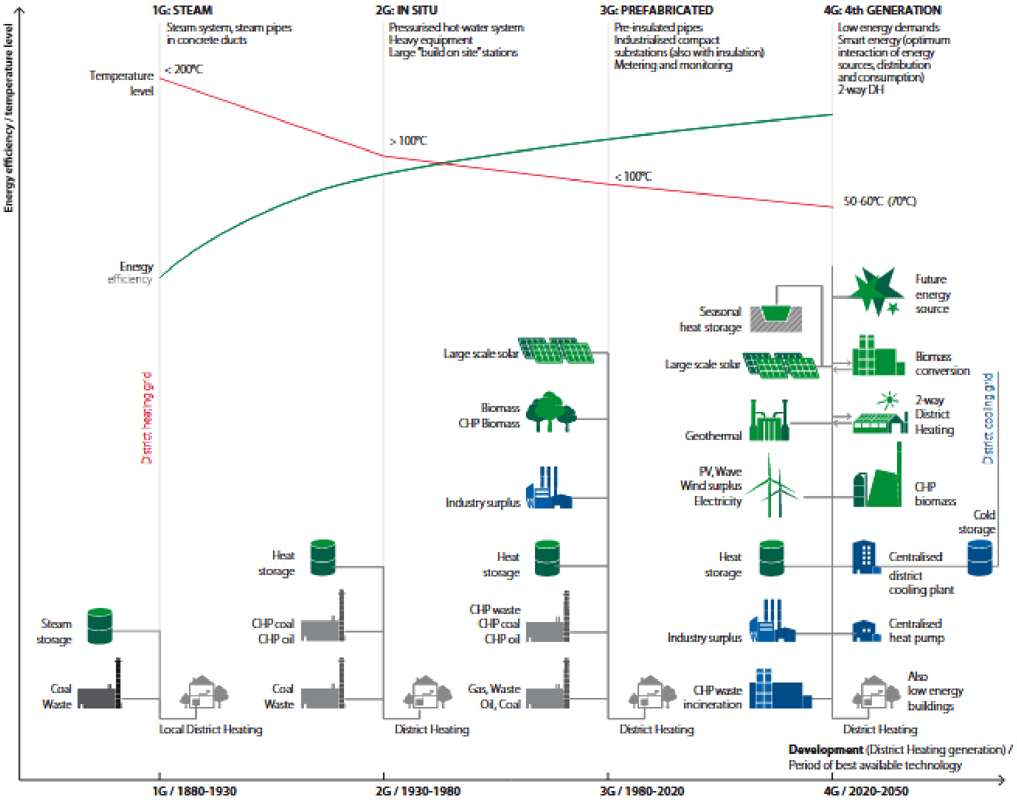


Figure 12. 4th Generation DH in comparison to the previous three generations - (Danfoss, n.d.)

District heating systems have evolved significantly over the years, advancing in efficiency, sustainability, and adaptability to modern energy demands. This evolution is categorized into distinct generations, each characterized by its technology, energy source, and integration capabilities. The development of these systems reflects a continuous effort to reduce greenhouse gas emissions and incorporate renewable energy sources into urban heating infrastructures (Danfoss, 2021-a).

The first generation of district heating systems emerged in the late 19th and early 20th centuries. These systems primarily relied on steam as the heat transfer medium, using coal-fired boilers as the primary energy source. Steam-based systems transported high-temperature steam (above 100°C) through heavily insulated pipelines to supply heat to buildings. However, these systems suffered from significant heat losses over long distances, high operational costs, and environmental concerns due to their reliance on fossil fuels (Danfoss, 2021-b).

The second generation of DH systems, which became prevalent during the mid-20th century, replaced steam with pressurized hot water as the heat carrier. This transition marked a substantial improvement in energy efficiency and operational reliability. Hot water was circulated at temperatures ranging from 100°C to 200°C, and energy sources expanded to include oil and natural gas alongside coal. Improved pipe insulation reduced energy losses, but the systems still depended heavily on fossil fuels and had limited integration of renewable energy sources (Danfoss, 2021-c).

The third generation, introduced in the 1970s and 1980s, focused on reducing the temperature of the hot water circulated in DH systems. These systems operated at temperatures below 100°C, enabling better compatibility with renewable energy sources and waste heat recovery. Pre-insulated pipes with minimal heat losses became standard, and the integration of waste heat from industries, geothermal sources, and biomass was increasingly adopted. This generation represented a major step forward in reducing carbon emissions and improving overall energy efficiency, although partial reliance on fossil fuels for peak load coverage remained a challenge (Danfoss, 2021-d).

The fourth generation of DH systems, currently being implemented in many regions, is characterized by ultra-low temperature heat distribution. These systems operate at temperatures as low as 30–60°C and are designed to integrate seamlessly with renewable energy sources. They incorporate advanced technologies such as thermal energy storage systems and digital controls for optimized energy use. The lower operating temperatures allow for the efficient utilization of low-grade waste heat from industrial processes, such as PEM electrolysis, and contribute to fully decarbonize heating solutions. However, the high initial costs of infrastructure development and the need for policy and regulatory support present ongoing challenges (Danfoss, 2021-e).

4th Generation District Heating (4GDH) is also known as Low-Temperature District Heating (LTDH), while 5th Generation District Heating (5GDH) is referred to as Ambient Temperature District Heating (ATDH). LTDH systems operate at supply temperatures between 50–65°C, which is adequate to meet all heating demands. Heat is distributed through insulated pipes from centralized sources, including surplus heat from data centers or industrial processes. If the heat source temperature is below the system's supply temperature, central heat pumps are employed to raise it. This configuration allows the utilization of various heat sources and maintains system simplicity and reliability. In contrast, ATDH systems function at significantly lower temperatures, ranging from 10–25°C, and distribute heat through uninsulated pipes. Due to these low temperatures, individual heat pumps are required in each building to boost the temperature to meet space heating and domestic hot water requirements. Typical heat sources for ATDH include natural bodies of water, low-temperature geothermal energy, or waste heat from processes. While this approach minimizes heat loss, it introduces higher complexity and potential points of failure due to the reliance on multiple decentralized heat pumps. (Danfoss, 2021-f).

Table 2. Comparative Table of District Heating Generations - (Danfoss, 2021-a, 2021-b, 2021-c, 2021-d, 2021-e and 2021-f)

| ***Feature*** | ***1st Generation*** | ***2nd Generation*** | ***3rd Generation*** | ***4th Generation*** | ***5th Generation*** |
|---|---|---|---|---|---|
| ***Operating Temperature Range*** | >100°C (Steam-based) | 100–200°C (Hot water) | 70–90°C | 30–60°C | <40°C |
| ***Prevalent Years*** | Late 19th to mid-20th c. | Mid-20th century | 1970s to 1980s | Current implementation | Emerging |
| ***Heat Pump Location*** | None | Centralized | Centralized | Decentralized or hybrid | Fully decentralized |
| ***Renewable Energy Integration*** | None | Limited | Moderate | High | Very high |
| ***Advantages*** | Reliable for early use | Improved efficiency, lower heat loss | Greater compatibility with renewable sources | Highly efficient, supports low-grade heat | Near ambient temperatures, ideal for energy sharing |
| ***Disadvantages*** | High heat losses, fossil fuel reliance | Limited renewables integration | Partial reliance on fossil fuels | High initial costs, requires regulatory support | High initial costs, complexity |
| ***Comparative LCOH*** | High | Moderate to high | Moderate | Low | Lowest |

The evolution of district heating systems from steam-based setups to modern decentralized and ultra-low temperature networks illustrates the sector's commitment to sustainability and efficiency. Each generation has built upon the lessons and technologies of its predecessors, enabling greater integration of renewable energy and waste heat sources. The fourth and fifth generations, in particular, align closely with the goals of utilizing waste heat from PEM electrolysis, making them ideal for case studies like the Kristinestad plant.

Generation 4 district heating (4GDH) systems are currently more advantageous than Generation 5 (5GDH) systems based on the findings from the study by Gudmundsson et al. (2022). The comparison highlights several practical and economic aspects that make 4GDH more favorable under present conditions. Figure 14 illustrates the thermal insulation used in the distribution network for both systems. 4GDH systems operate at temperatures between 30–60°C, minimizing heat losses while maintaining sufficient temperature gradients to efficiently transfer heat over medium distances. In contrast, 5GDH systems, which operate at near-ambient temperatures (<40°C), experience higher relative losses unless the distribution network is extremely compact.  This limits 5GDH's effectiveness in current urban settings, where buildings need to be located in close proximity to the heat source (Gudmundsson et al., 2022)

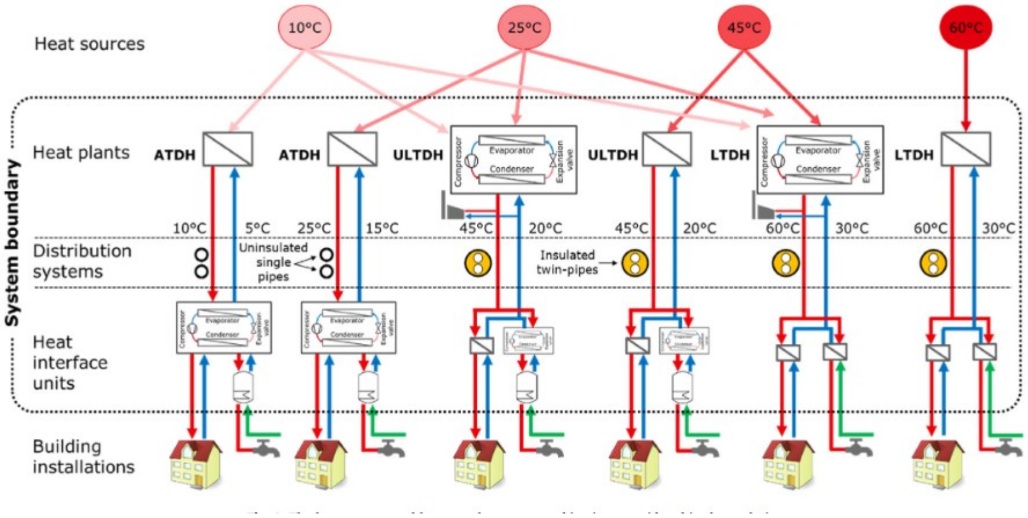


Figure 13. LTDH vs. ATDH system architecture - (Gudmundsson et al., 2022)

Comparison of the levelised cost of heat (LCOH) for 4GDH and 5GDH in the same study indicate that 4GDH systems have a lower LCOH in most scenarios due to their reliance on mature technologies and infrastructure. 5GDH systems, while promising innovative energy-sharing capabilities, demand higher initial capital investments for advanced technologies like decentralized heat pumps. These pumps are necessary to elevate low-grade heat to usable levels, increasing both operational complexity and energy consumption. As a result, the higher LCOH of 5GDH systems makes them less economically competitive at present (Gudmundsson et al., 2022).

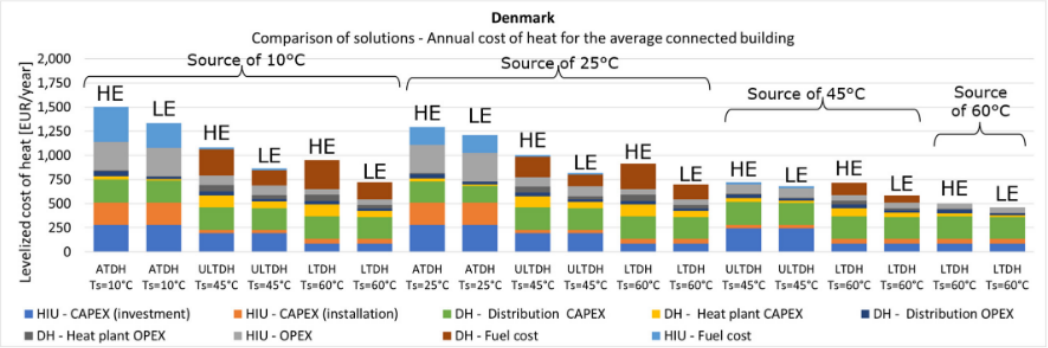


Figure 14. LCOH for the average high energy (HE) and low energy (LE) buildings in DK. - (Gudmundsson et al., 2022)

Furthermore, 4GDH systems align well with waste heat recovery from industrial processes, such as PEM electrolysis, which typically produces heat at around 60°C. This matches the optimal operating temperatures of 4GDH without requiring additional energy-intensive modifications. In contrast, 5GDH requires significant adjustments to integrate this waste heat, reducing overall system efficiency and increasing costs. Their study concludes that while 5GDH systems have the potential to revolutionize district heating in the future, their current technological and economic barriers make 4GDH the more practical choice for most applications today. 4GDH offers a balanced approach, combining efficiency, cost-effectiveness, and compatibility with existing energy infrastructure, making it the preferred option for near-term district heating implementation.

Integrating waste heat from industrial processes into district heating systems requires careful assessment of several key parameters to ensure technical and economic viability. The temperature of the waste heat is a critical factor, as it determines compatibility with the district heating system's operating range. Low-temperature waste heat, often below 100°C, aligns well with systems as fourth-generation district heating (4GDH). The distance between the waste heat source and the district heating network significantly impacts heat losses and infrastructure costs; shorter distances reduce transmission losses and increase the feasibility of integration. Furthermore, the variability of supply plays an important role in determining, if storage of thermal energy is required. Danfoss (2021-e) report that hot water tanks which played a significant role in 2nd and 3rd generation district a heating systems will play an even more significant role in 4th generation systems with integration of variable renewable energy sources. The tanks will become bigger to take in to account of fluctuations of renewable energy, thus enabling instantaneous thermal inertia as well as the economic benefit of being able to produce and store heat when electricity prices are low and avoid use of peak load boilers.

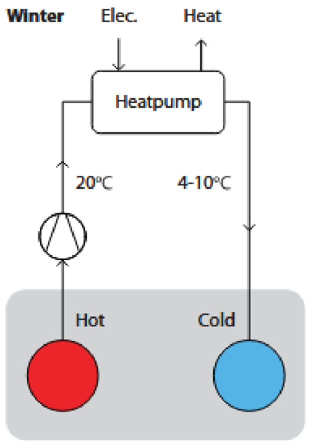


Figure 15. Aquifer TES with heat pump - (Danfoss, 2021-e)

Danfoss (2021-e) reports that for low temperature application such as 4GDH operating below 70°C, use of ground aquifer storage with pump will reduce the reliance on fossil fuel sources to supply peak heating demand in the network. HeatWater (2024) indicate that use of PCM’s in hot water storage reduces the carbon footprint by reducing the storage space as much as 1/3rd as compared to that of water. PCM’s can also be used in integral building components such as walls and ceiling, which allow them to release the heat based on the user heating demand (Demirbas, 2006). There are many radiator types used in buildings at present with district heating networks including panel, column, heated tower rail and cast iron radiators. (Steele, 2020) argue that column type radiators are more efficient due to their integral heating compared to energy wasted in panel radiators in heating the attached fins. Hence, the author argues that column heaters heat rooms faster thus saving energy for the tenant.

Figure 16. Common Home Radiators used in DHN - (Wairarapa Heating, n.d.)

## 2.4 Economic and Financial Feasibility

The profitability of heat sales increases with the size of the electrolysis system (Saranpää, 2024). Saranpää’s (2024) Master's thesis compares alkaline and PEM electrolysis for district heating systems, analyzing variables such as the Levelized Cost of Heat (LCOH) and heat price. Her study concludes that while alkaline electrolysis offers lower capital costs, PEM electrolysis provides greater flexibility and efficiency when integrated with fluctuating renewable energy sources. This finding is particularly relevant to our research, as it supports the techno-economic viability of utilizing waste heat from PEM electrolysis, especially in scenarios where intermittent renewable energy plays a significant role in hydrogen production.

Saranpää (2024) studies about electrolysis waste heat utilization for district heating systems and he also emphasis that waste heat utilization will increase the total hydrogen production system efficiency and improve the economics of hydrogen production. While district heating networks are common focus for waste heat utilization, local users also can be considered. For example, Van de Rostel et el. (2023) compared two cases: DH networks and local industrial laundry washing company (mentioned earlier in this chapter). Similarly, Saranapää (2024) explored techno economic optimization for district heating applications, reinforcing the feasibility of such integration.

Saranpää (2024) found that integrating a heat pump significantly increases the levelized cost of heat (LCOh), from 8.4–8.9 €/MWh without a heat pump to 36.9 €/MWh with one (pp. 38–39). The difference is in magnitude and there is a need to consider whether the heat pump usage is economical or not. Increasing waste heat recovery efficiency enhances the overall electrolysis system efficiency and reduces carbon dioxide emissions, thereby lowering the hydrogen production cost. Butler and Spliethoff (2018) state that utilizing waste heat recovery systems in PEM electrolysis can boost system efficiency from 75–80% to 86–95%. However, Saranpää (2024) found that integrating heat pumps for district heating may increase the Levelized Cost of Heat (LCOh), as additional energy input is required for heat extraction and distribution. This suggests that while waste heat recovery can improve system efficiency, the overall economic feasibility depends on specific system configurations, energy prices, and operational conditions.

### 2.4.1 Economic Terms in the Context of the Study

Recovering waste heat from PEM electrolysis is essential for achieving multiple objectives that contribute to the economic and environmental feasibility of hydrogen production systems. By effectively utilizing the waste heat generated during the electrolysis process, operators can enhance the overall performance of hydrogen plants while reducing operational costs and contributing to sustainability goals.

As PEM electrolysis generates significant amounts of waste heat due to system inefficiencies, it is crucial to optimize all aspects of energy utilization. By capturing and reusing the heat generated during the electrolysis process, operators can reduce the overall energy input required for hydrogen production. This increased efficiency translates to lower electricity consumption, which is particularly valuable when operating in markets with high energy costs.  Reducing hydrogen production is important for the economic standpoint of hydrogen energy when compared with well-established fossil energy sources.

Waste heat recovery opens additional revenue streams by allowing operators to sell recovered heat to district heating networks. In regions such as Finland, where district heating systems are well-established, this recovered heat can serve residential and commercial heating needs, creating economic value from what would otherwise be wasted energy. The integration of waste heat into district heating systems also reduces the reliance on fossil fuels, further lowering operational expenses and enhancing the economic attractiveness of PEM electrolysis. International Energy Agency (2019) claims that time has come to reduce cost of hydrogen production so that it can be widely used.

Aligning with EU and Finland’s ambitious decarbonisation targets, waste heat recovery from PEM electrolysis contributes to maximizing energy use and minimizing emissions. By reducing dependency on conventional heating sources, which often rely on fossil fuels, the recovered heat significantly lowers the carbon footprint of both hydrogen production facilities and district heating networks.

### 2.4.2 Financial Terms in the Context of the Study

Christensen (n.d.) highlight that model of cash flows included CAPEX, OPEX, and electrolyser replacement, country specific corporate taxes, depreciation and utility prices such as electricity and water. Their model considers a plant lifetime of 30 years, built over 2 years, with a hurdle rate of 7% and straight line depreciation at 5%.  Rosner et al. (2023) had used hurdle rate, capital structure, total plant construction costs (CAPEX), and fixed and variable operating, annual escalation rate, as important parameters in development of levelised cost of steel production.

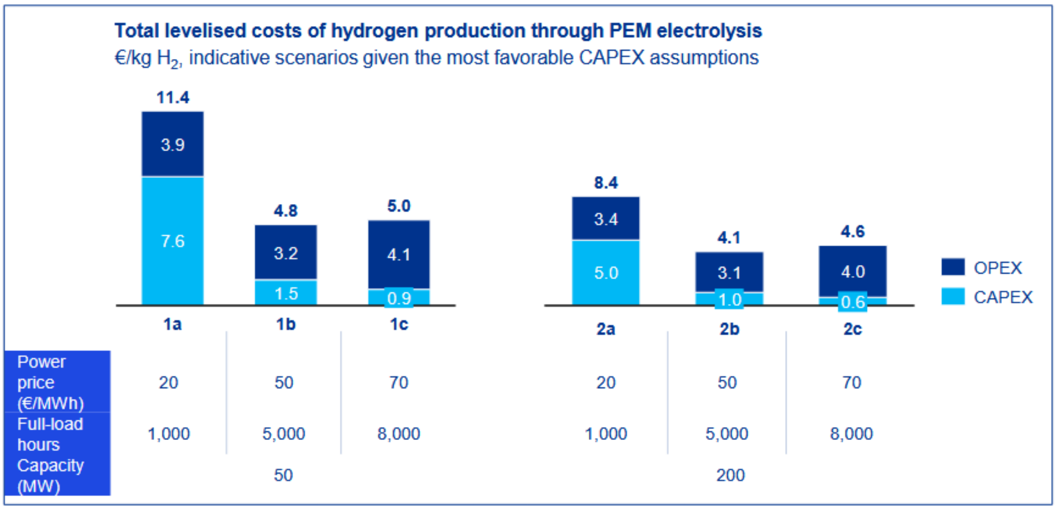
Operation of green steel production plant using green hydrogen generated from the PEM electrolysis process requires consideration of steel plant as well as $H_2$ production system. Hence, it will involve capital expenses related to PEM electrolysis for green hydrogen production, plant costs associated with H2-DRI production including cost for EAF and the waste heat recovery heat exchangers, pumps and other piping. There would also be operating and maintenance costs involved in both PEM electrolyser side for green H2 production and H2-DRI process for green steel production. Waste heat, is heat that is extracted using the heat exchangers and will be utilized in district heating network for the surrounding community. Furthermore, operating expenses include electricity used for operation of all equipment such as electrolysers, Steel mill, EAF, compressors and pumps required to pump H2 and waste heat to storage tanks, as well as water treatment costs associated with input to the PEM electrolysis plant.

To make the investment worthwhile, it is required that net present value, hurdle rate and return on investment is calculated. As per Iplik et al. (2022) , their study had implemented the following formulas in calculating LCOH, NPV. IRR is calculated by equating formula 4 to zero.

$$LCOH = \frac{\sum_{t=1}^{N} \frac{CAPEXt+Et}{(1+r)^{y}}}{\sum_{t=1}^{N} \frac{Mht}{(1+r)^{t}}} \quad \text{………….. ( 4 )}$$

$$NPV = \sum_{t=1}^{N} \frac{Cash\ Inflow - Cash\ Outflow}{(1+r)^{t}} \quad \text{………….. ( 5 )}$$

KPMG (n.d.) informs that to reduce the Levelized cost of hydrogen production, It is required to optimize the asset utilization, compared to maximizing. Their study of 10 green hydrogen projects resulted in their concluding that the maximum hours of operation should be limited to 5000-6000 hours for grid connected systems, purchase of electricity at short notice at spot prices as not feasible. This all results from the variability of supplies of the renewables at present. Figure 2 below illustrates the results of their findings.



Note: Assuming fixed OPEX to be 4% of CAPEX and power conversion to hydrogen to be 52 kWh/$H_2$. The electrolyzer lifetime (including stack) is equally set at 15 years. Though the PEM stacks will have to be replaced within 10 years, a larger share of the CAPEX has a much longer lifetime, thus balancing the overall lifetime at 15 years.

Source: ISPT; IRENA; EU Horizon 2020; IEA; Hydrogen Council; ICCT; research papers; KPMG analysis.

Figure 17. Total levelised costs of hydrogen production through PEM electrolysis- for grid connected business - (KPMG, n.d.)

## 2.5 Case Study Framework

The case study framework applies technical and economic principles to analyze the feasibility of waste heat recovery. The following key theories can be used in to analyze the feasibility of waste heat recovery from PEM electrolysis based on various research literature.

### 2.5.1 Chemical Analysis

Chemical reactions

At the Anode oxygen evolution reaction (ORE) takes place, in which water is oxidized to produce oxygen gas, electrons and protons.

$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ ………….. ( 6 )

At the cathode hydrogen evolution reaction takes where positively charged hydrogen ions combine with free electrons to produce hydrogen gas.

$4H^+ + 4e^- \rightarrow 2H_2$ ………….. ( 7 )

As per Carmo et al. (2013), the overall chemical reaction is endothermic requiring 237.2 KJ/mol of electricity and heat of 48.2 KJ/mol to split the water molecule

$H_2O_{(l)} \rightarrow 237.2\ KJ/mol\ (Elect.) + 48.6\ KJ/mol\ (Heat) + H_2 + 0.5\ O_2$ ………….. ( 8 )

Taking molecular weights of reactants into consideration

$H_2O_{(l)} \rightarrow$ 237.2 KJ/ mol (Elect.) + 48.6 KJ/mol (Heat) + $H_2$ + 0.5 $O_2$

(18 kg of Water) → (2 kg of Hydrogen) + (16 kg of Oxygen)

$$Chemical\ Efficiency = \frac{Theoretical\ Water\ Requirement}{Actual\ Water\ Requirement} \quad \text{………….. ( 9)}$$

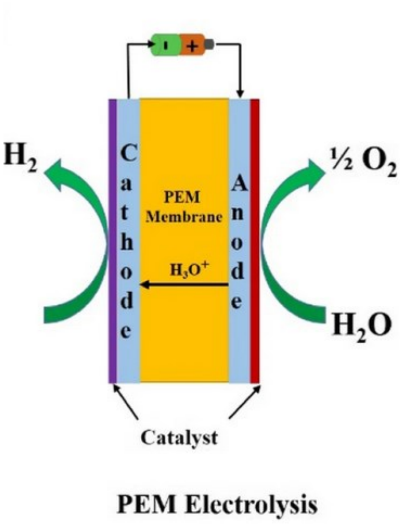


Figure 18. PEM Electrolyser products - (Wang et al., 2022)

A study by Panchawadkar (n.d.) suggests the system as shown in Figure 19 below for purification of oxygen released from the electrolysis.

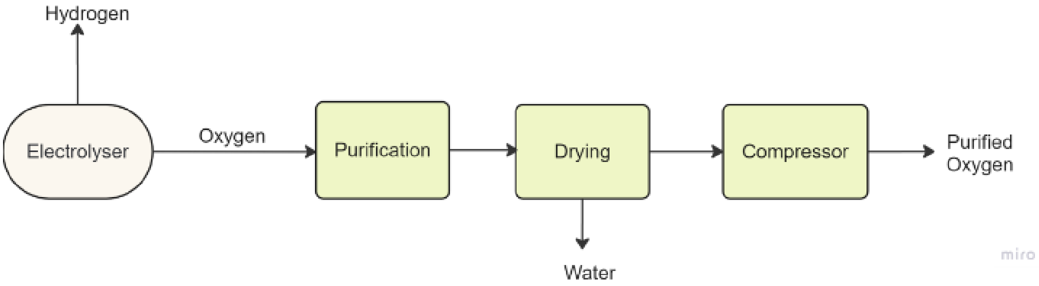


Figure 19. Oxygen purification from Electrolysis process - (Panchawadkar, n.d.)

Their study informs that purification step above is exothermic with the release of 244.9 KJ/mol.

$2H_2^+{}_{(g)} + O_{2\ (g)} \rightarrow 2H_2O + 244.9$ kJ/mol ………….. ( 10)

The specific energy demand for drying is reported at 5360 kJ/kg while the compression step consumes an electrical energy of 0.130 kWh/kg $O_2$ to compress the gas from 2 bar to 15 bar.

### 2.5.2 Thermodynamic Analysis

Basic thermodynamic analysis of the PEM electrolyser stack requires the knowledge of input and output thermal energies.

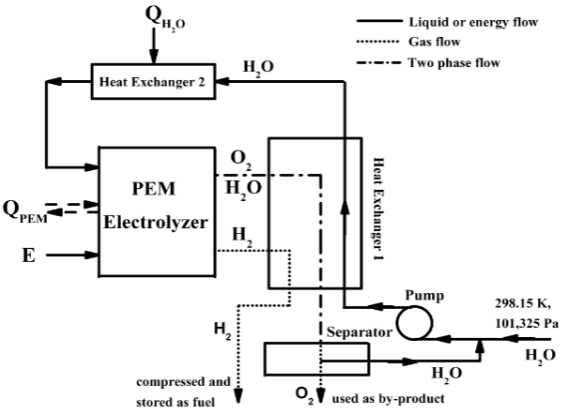


Figure 20. PEM electrolyser system for hydrogen production - (Zhang et al., 2012)

According to Zhang et al. (2012), electrolyser efficiency for the above system is calculated based on the formula below,

$$\eta_T = \frac{N_{H_2,out} LHV \eta_{H_2}}{E + Q_{PEM}(1-\frac{T_0}{T_x}) + Q_{H_2O}(1-\frac{T_0}{T_s})},$$

…………. ( 11 )

$N_{H2,\ out}$ –out flowrate of $H_2$

LHV - Lower heating value of $H_2$

E - Electric energy input

$Q_{PEM}$ - Thermal energy to the PEM electrolyze or released to environment

$T_O$, $T_X$ – Environment temperatures / External heat source temperature

$\eta_{H2} = 1 – (T_o/T_H)$

$T_H$ - Combustion temperature of $H_2$ at reference condition

$Q_{H2O}$ - Thermal energy input to the second heat exchanger for further heating up $H_2O$

More simplified formula taking into consideration of liberated energy from hydrogen combustion and the input electricity are given in (Harrison et al., n.d.).

$$Electrical\ efficiency\ = \frac{HHV\ or\ LLV\ of\ H2\ produced}{Electricity\ used} \qquad \text{............. ( 12 )}$$

Taking HHV of H2 as 39.4 kWh/kg, electricity used for H2 production can be obtained by

$$Electricity\ used\ = \frac{39.4\ kWh/kg}{Electrical\ efficiency} \qquad \text{............. ( 13 )}$$

Using a base electrical efficiency of 70.0%, the below diagram illustrates the generation of waste heat from the PEM process,

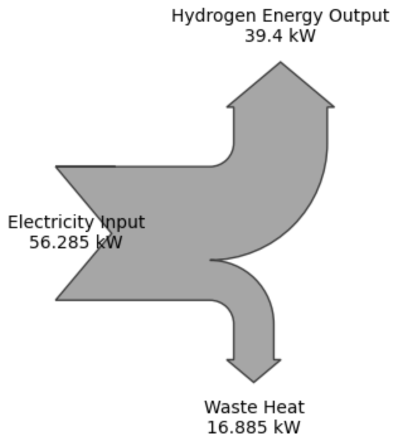


Figure 21. Theoretical Sankey Diagram for 1kg of Hydrogen Production via PEM Electrolysis

The theoretically available heat will be reduced due to losses to environment, conversion efficiencies of heat exchangers and transport losses.

### 2.5.3 Cost-Benefit Analysis

Cost-Benefit Analysis is used to compare the costs of implementing heat recovery systems with the financial and environmental benefits, such as reduced levelised cost of hydrogen production, reduced carbon emissions and additional revenue from heat sales. Consideration of green steel production process must be taken in to account as the core process requiring hydrogen production for the steel industry.

***Green Steel Production using H-DR process***

In order to meet the European Union target of reducing 80-95% of GHG by 2050 compared to 1990, the steel industry is making rapid changes to their value chain to develop emission free steel making process. Industry leading companies such as SSAB, LKAB and Vattenfall aim to develop a fossil free value chain where the iron produced using the DRI process is converted to steel in an electric arc furnace (Vogl et al., 2018). In their simplified model developed to increase the process understanding (Figure 22), with assumption that hematite reacts to iron and Wüstite, the following chemical reactions had been considered.

$Fe_2O_3 + 3H2 \rightarrow 2Fe + 3H_2O_{(g)} \quad \Delta H_R = 99.5\ kJ/mol$ ............. ( 14 )

$Fe_2O_3 + H2 \rightarrow 2FeO + H_2O_{(g)}$ ............. ( 15 )

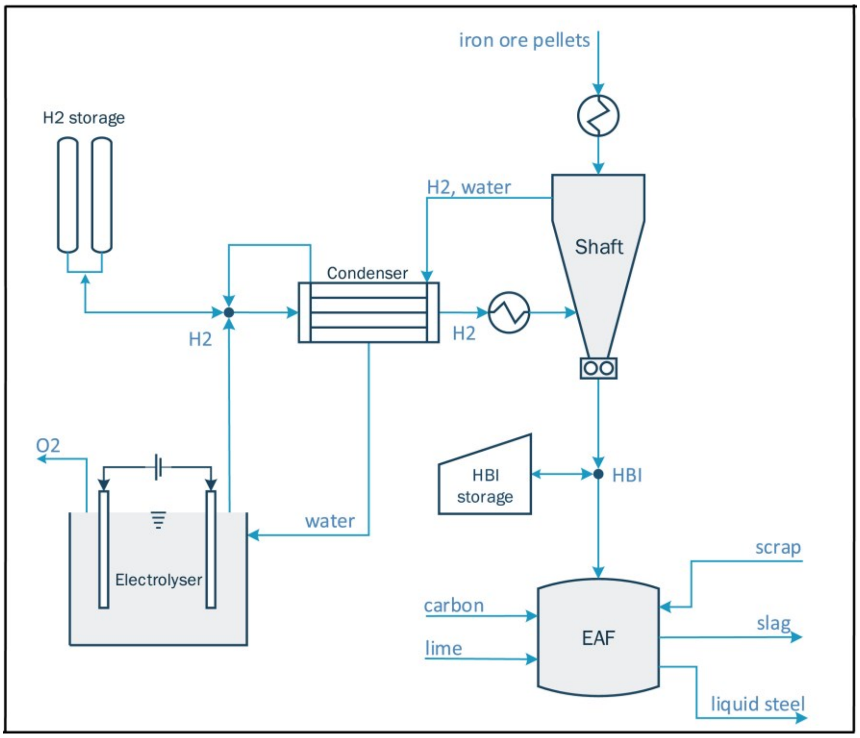


Figure 22. Proposed Hydrogen direct reduction process - (Vogl et al., 2018)

Furthermore, Vogl et al. (2018) had estimated the $CO_2$ emissions in EAF process using the following reaction.

$CaCO_3 \rightarrow CaO + CO_2$ ………….. ( 16 )

However as informed by Spreitzer & Schenk (2019), reduction of hematite does not occur directly to metallic iron, if the reduction temperate is less than 570 C, but follows a stepwise process where it is first reduced to magnetite and then continues to iron.

Hematite to Magnetite

$3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O$ ………….. ( 17 )

Magnetite to Wüstite

$Fe_3O_4 + H_2 \rightarrow 3FeO+H_2O$ ………….. ( 18 )

Wüstite to Iron

$FeO+H_2 \rightarrow Fe + H_2O$ ………….. ( 19 )

Rosner et al. (2023) had used Levelized steel production cost as a key parameter in determining the cost of steel production of H2-DRI based on the formula below.

$$LPSC = \frac{(\mathrm{CCF})(\mathrm{TOC})+\mathrm{OCfix}+(\mathrm{CF})(\mathrm{OCvar})}{(\mathrm{CF})(\mathrm{MTPY})} \quad \text{………….. ( 20 )}$$

Where, CCF, TOC, $OC_{fix}$, $OC_{Var}$, CF and MPTY are Capital charge factor, total cost of building the facility, fixed and variable operating costs, plant capacity utilization factor and the annual metric tons of expected steel production respectively.

### 2.5.4 Sensitivity Analysis

Sensitivity analysis must take into account the variation of parameters within the technical, financial and economic model that effect the levelised cost of hydrogen produced(LCOH), other economic and environmental benefits. Since, spot electricity prices in Europe are variable, predicting them is difficult and discounting rates vary based on the economic conditions which are even beyond the scope of the operating geographic location, as current regional economies are synergized to follow global economic trends.

In a case study conducted by Jonsson & Miljanovic (n.d.) , results showed that LCOH has the most impacted by variation in predicting CAPEX costs and discounting rate. Their results are indicated in the figure 23 below. In the same study, DH network temperatures were used in the sensitivity analysis stating that requirement to use a heat pump diminishes for DHN supply temperatures below 80C. The result is indicated in Figure 24.

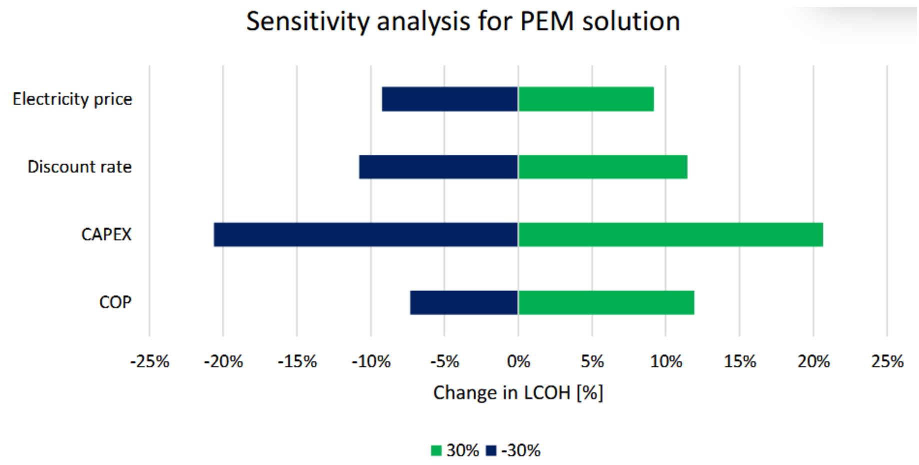


Figure 23. Parameters in Sensitivity analysis of PEM- Waste heat recovery - (Jonsson & Miljanovic, n.d.)

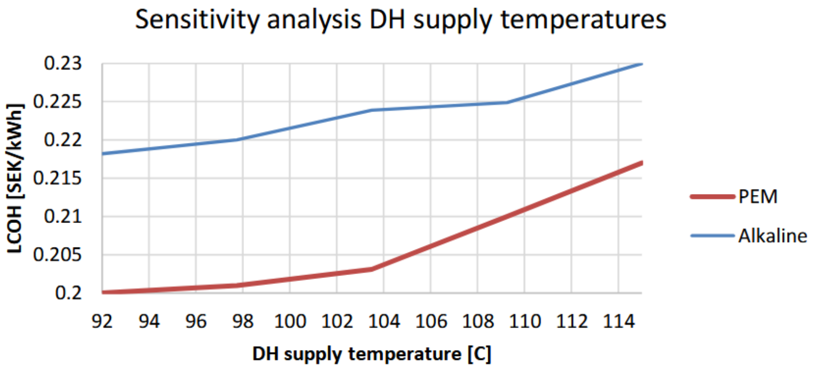


Figure 24 . DHN Supply temperature as a sensitivity analysis parameter - (Jonsson & Miljanovic, n.d.)

In another study conducted by Van Der Roest et al. (2023), considering two base cases where waste heat was used locally(in facility) as low grade or high grade energy using a pump, and a DHN network located in the local municipality showed that most important parameters of consideration should be electricity price, distance to local DHN and the $CO_2$ prices. Their summary of results for the sensitivity analyses using various scenarios are illustrated below.

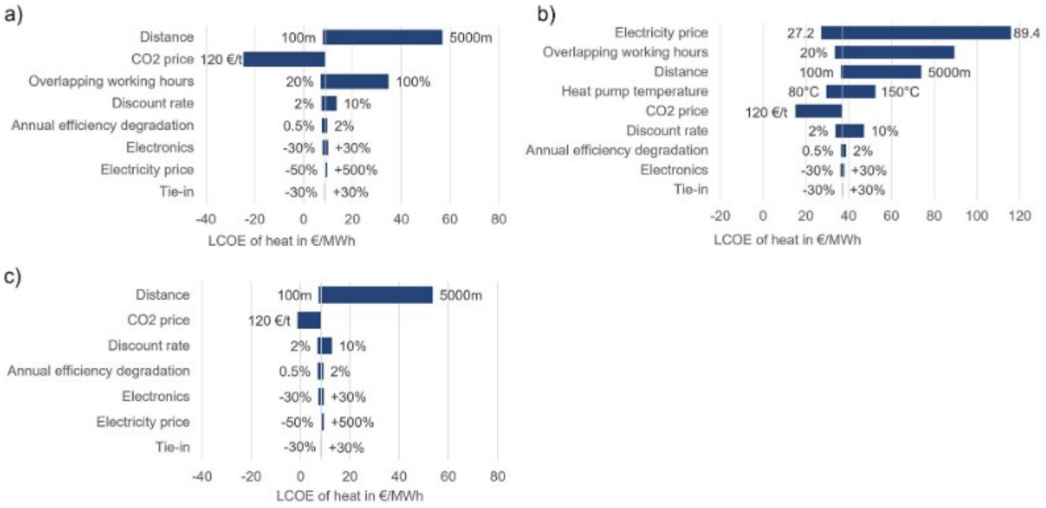


Figure 25. Parameter variation of sensitivity analysis IN 3 Cases - a)-Local-Low heat b) Local-High heat c) DHN- Low heat - (Van Der Roest et al., 2023)

Hence, parameters such as CAPEX, discounting rate, electricity prices, and distance to municipal DHN and COP for pumps are important considerations.

### 2.5.5 Economic Feasibility Analysis

Economics of green steel production are greatly affected by the final Levelised cost of steel production. Since, this study is mainly concentrated on recovering heat as a byproduct of green steel making process, the study takes in to consideration economic feasibility of the green steel making process and the impact of waste heat recovery on the final levelised cost of green steel production using PEM electrolysis. The suggested green steel making process Direct reduced Iron production from Electric Arc Furnace using $H_2$($H_2$-DRI-EAF) will be compared with the most prevalent steel making process in Finland, Blast Furnace – Basic Oxygen Furnace process(BF-BOF).

### 2.5.6 Integration in to DH networks

As an application of the recovered heat from the electrolyser plant, the same heat is planned to be used in the local DHN, where the supply LCOH (Levelized cost of heat) is an important parameter economically, while the reduction in carbon emissions associated with using waste heat content will be beneficial to attain futures sustainability goals.

### 2.5.7 Steel plant architecture from various literature

Devlin et al. (2023) suggest the following plant architecture for green $H_2$-DRI-EAF steel production system. This system integrates islanded renewable energy sources such as solar, wind or battery storage to drive the PEM process and the DRI shaft. Produced green $H_2$ is stored to ensure continuous steel production during low energy periods. $H_2$ produced is used in the DRI shaft to form sponge iron (DRI), which is fed in to the EAF process (using RE energy sources) to produce green steel. The entire process suggested uses green energy, thus reducing the carbon emissions sustainably.

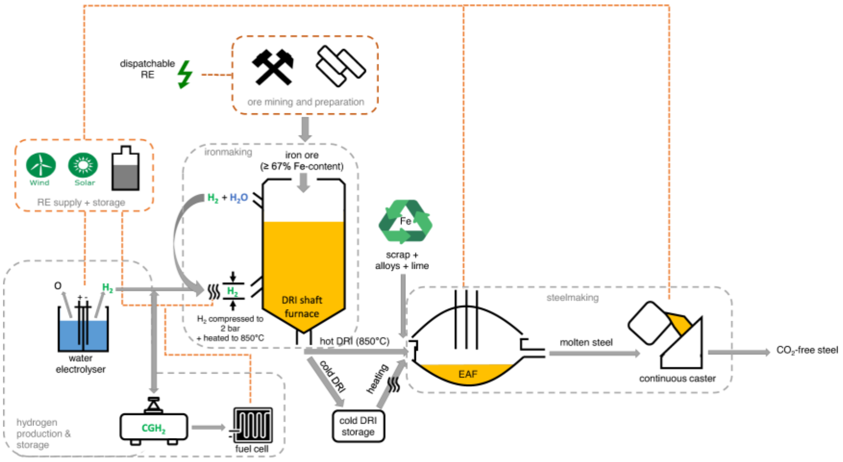


Figure 26. Green H2-DRI-EAF steel production system - (Devlin et al., 2023)

Jonsson & Miljanovic (n.d.) presents a schematic of the integration of a PEM electrolyser for hydrogen production with a waste heat recovery system. The diagram illustrates the collection of excess heat generated during electrolysis and its utilization in district heating networks or as an input for industrial processes. The setup also highlights how thermal energy management reduces overall energy demand and increases system efficiency, demonstrating the feasibility of integrating renewable hydrogen production with industrial heat recovery systems.

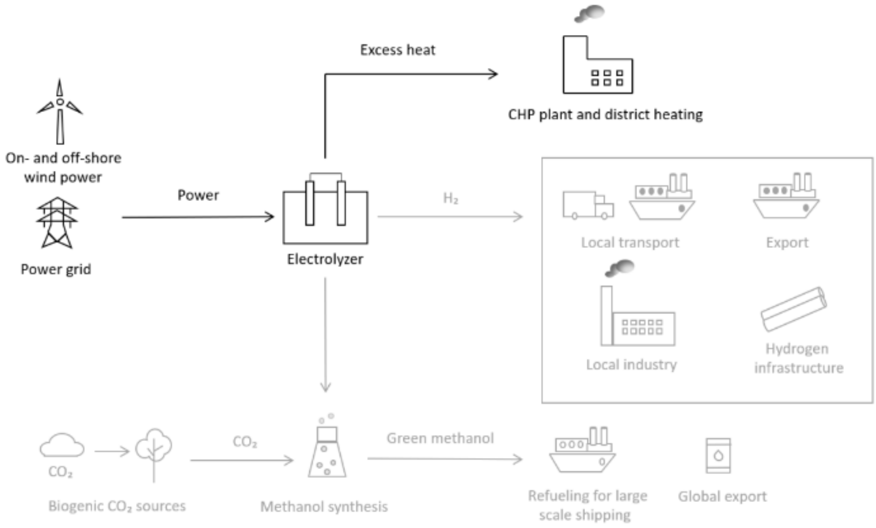


Figure 27. System schematic of the planned hydrogen hub in Luleå, Sweden - (Jonsson & Miljanovic, n.d.)

Rosner et al. (2023) illustrates the hydrogen-based direct reduction of iron (DRI) process. It highlights the integration of hydrogen as a reducing agent in steel production, replacing traditional fossil fuels. The schematic outlines the flow of hydrogen generated via PEM electrolysis powered by renewable electricity, its application in reducing iron ore to produce DRI, and the subsequent processing in an electric arc furnace to create steel. Figure 28 emphasizes energy efficiency through heat recovery systems and optimal utilization of waste heat in auxiliary processes, aligning with the goal of decarbonizing steel production.

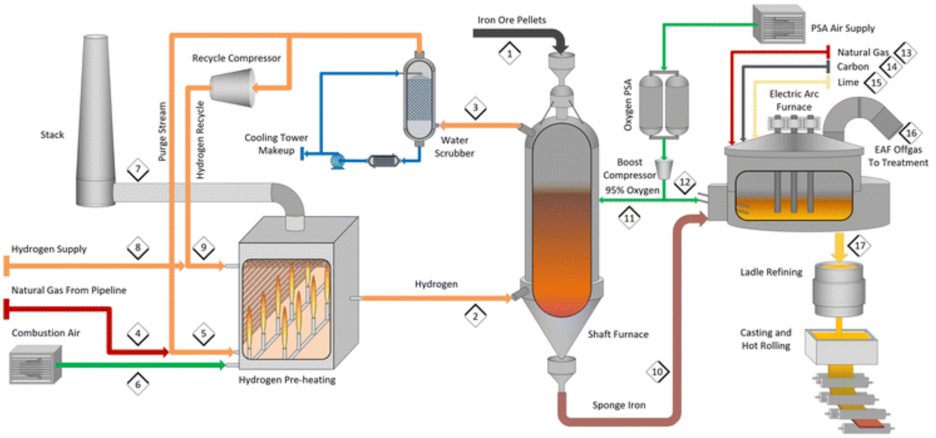


Figure 28. Simplified flowsheet of the integrated hydrogen-based DRI steel mill (H2-DRI-B) - (Rosner et al., 2023)

Van Der Roest et al. (2023) presents a schematic showing the utilization of waste heat generated by a PEM electrolyser in a localized heating system. In this case, the waste heat is directed into a district heating network to supply thermal energy to residential or industrial users. Figure 29 illustrates the flow of heat from the electrolysers cooling system through heat exchangers, where it is transferred to the heating system. The case emphasizes efficient energy use by capturing and reusing thermal by-products of hydrogen production, thereby reducing overall energy demand and improving system sustainability.

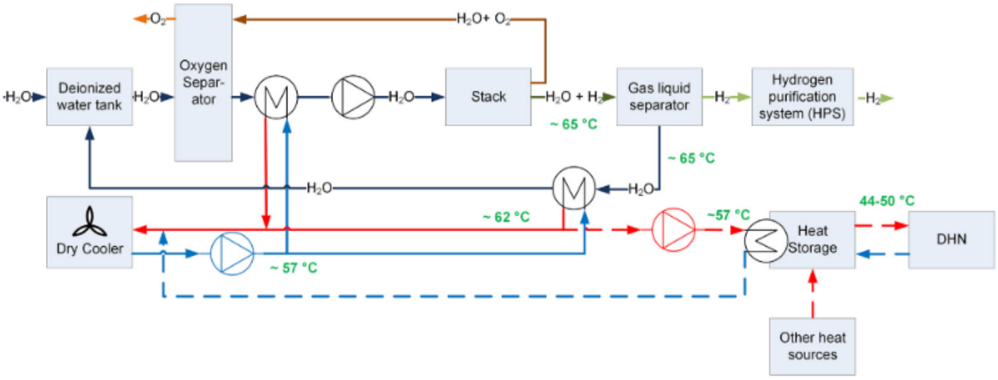


Figure 29. Use of Waste heat from PEM electrolysis LTDH network - (Van Der Roest et al., 2023)

Center on Global Energy Policy (2021) suggests a plant taking both pathways (Scrap and DRI) when implementing an electric arc furnace (EAF) for producing steel. In hydrogen-based direct reduction and EAF steelmaking, significant amounts of waste heat are generated. This waste heat can be captured and repurposed for preheating raw materials, generating steam for power production, or supplying heat to nearby industrial processes or district heating systems.

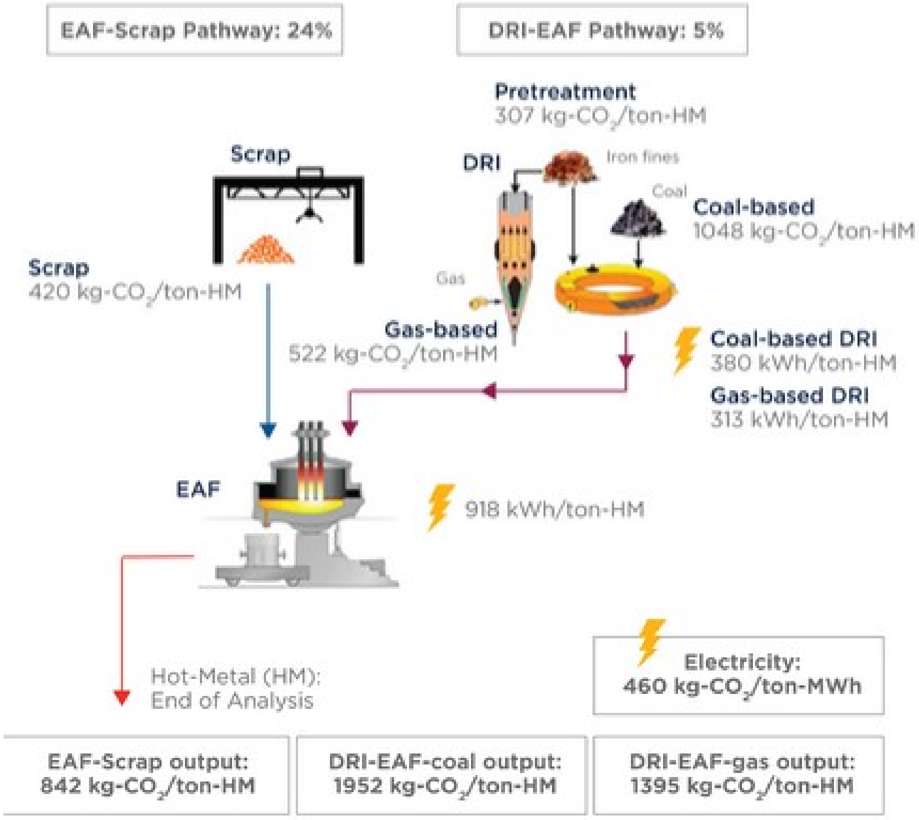


Figure 30. EAF Based steel plant using scrap and DRI - (Center on Global Energy Policy, 2021)

### 2.5.8 Steel production in Finland

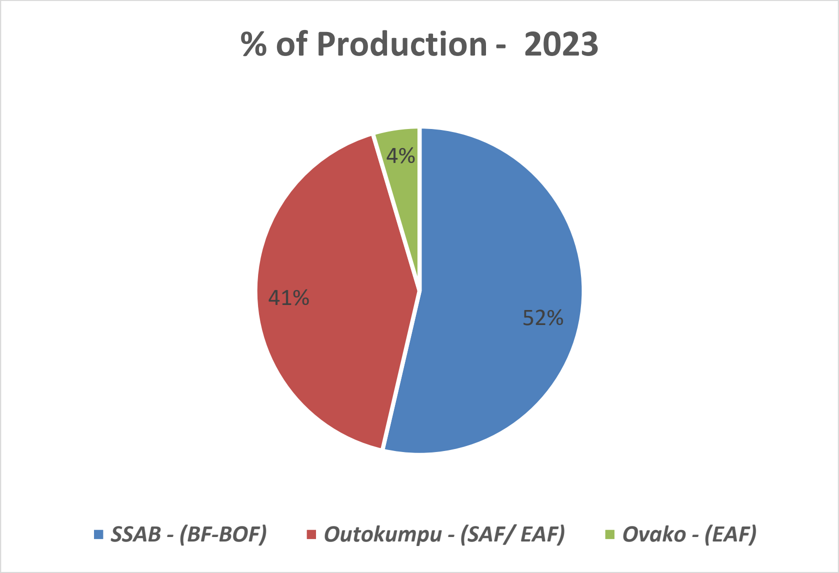


Figure 31. Percentage of Steel production in Finland (Company/Main Processes)- Motiva, (n.d.)

As reported by World Steel Association (2024) the steel production in 2023 in Finland who is ranked 38 in the world, were from Blast Furnace – Basic oxygen furnace (BF-BOF) process at 68% and Electric arc furnace (EAF) process at 32%. According to Motiva (n.d.), figure 31 highlights the percentage of production of main steel companies in Finland and their main process. It is seen that SSAB leads production volume with BF-BOF processes while, SAF/ EAF is used by the Outokumpu is concentrated on producing stainless steel. Hence, for our research study, we will benchmark the BF-BOF processes used by SSAB with the suggested steel production process using green hydrogen in 40MW PEM electrolysis.

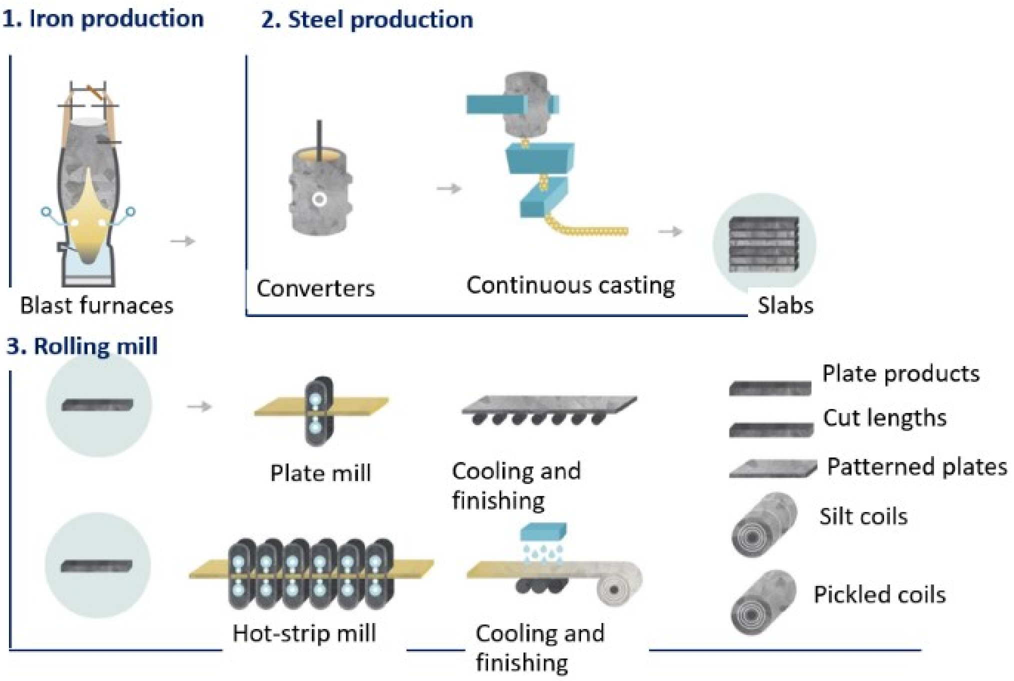


Figure 32. SSAB’s BF-BOF steel process in Raahe, Finland - Motiva. (n.d.).

Motiva (n.d.) reports that the Blast Furnace - Basic Oxygen Furnace (BF-BOF) process employed by SSAB converts enriched iron ore into steel through a series of steps. Initially, iron ore fines are agglomerated into sinter or pellets, with SSAB ceasing its sintering operations in 2011 and replacing it with a briquette plant to recycle iron-containing byproducts. Metallurgical coke, produced in-house by heating coal in the absence of oxygen, is used as both fuel and a reducing agent in the blast furnace to convert iron ore into pig iron. The pig iron, containing impurities and excess carbon, is decarbonized in a basic oxygen furnace (BOF) using high-temperature oxygen blowing, producing crude steel. This crude steel undergoes secondary refining in a ladle to achieve desired chemical properties before being cast into slabs via continuous casting. Subsequent hot and cold rolling processes reduce and uniform the slab thickness. Additionally, SSAB’s on-site power plant supplies excess heat to the city of Raahe, highlighting energy efficiency integration within its operations. World Steel Association (2024) reports that from their tabled data 71.1% production is based on BF-BOF process while 28.6% is based on EAF process. Their analysis reveals a carbon intensity of 2.33, 1.37 and 0.68 tons $CO_2$

per ton of crude steel cast, for the BF-BOF, DRI-EAF and Scrap-EAF processes respectively, based on calculations in 2022. Although not exact, is sufficient for the calculations of this research paper. Energy intensity was reported as 20.99 GJ/per ton of steel cast in general by the same source, as a weighted average of the 3 processes combined.

International Energy Agency (n.d.-b) indicates that BF-BOF route is used for 70% of world's steel making and the cost is around \$ 490/ ton of steel produced, whereas the cost of H2-DRI process is 25% more expensive, around \$ 650/ton. Devlin et al. (2023) reports that operational costs for BF-BOF ranged from \$621 to \$782 per ton in selected locations, a notable increase from \$428 to \$547 per ton in 2020. Value of \$ 700/ton will be used in this research as the cost associated with BF-BOF process.

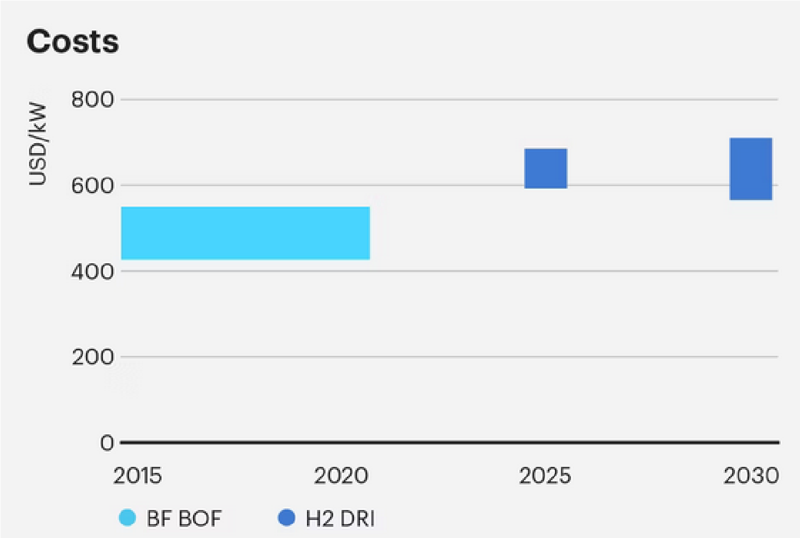


Figure 33. Cost of Production - BF-BOF vs. H2-DRI - (International Energy Agency, n.d.-b)

According to the report by the Center on Global Energy Policy at Columbia University, replacing natural gas with hydrogen in DRI production can significantly reduce $CO_2$ emissions. For instance, using 100% hydrogen can achieve a carbon abatement of approximately 437 kg $CO_2$ per ton of DRI. However, this reduction comes with increased fuel costs, rising from \$ 32.62 per ton of DRI (using natural gas) to \$162.20 per ton of DRI with 100% hydrogen. The corresponding carbon abatement cost is estimated at \$ 293.57 per ton of $CO_2$. As reported by International Energy Agency (n.d.-c), it is expected that $CO_2$ prices for electricity, industry and energy production will increase up to \$ 65, \$75 and \$ 90 /ton by year 2030, 2040 and 2050 respectively in the European Union.

# 3. KRISTINASTAD BUSINESS CASE

Studies shows that only one business idea become success out of fifty. So, business case is a crucial factor for evaluating the feasibility and financial viability of a project before allocating the resources. The structured approach is also important for decision making (Grifton, 1997). A well-prepared business case helps project sponsors in taking a decision financially but need to be consider quantitative cost benefit analysis and qualitative insights (Wang S., 2012).

A business case is a fundamental document that can be used for initiating a project by outlining the business problem or opportunity, analyzing cost and benefits, and recommending an optimal solution for approval. It is the first step of the project lifecycle and it will help to project align with the project objectives. The business case will provide a good insight to all stakeholders understanding the project with key aspects. Through a business case, management, operations, finance, investors especially and other interested parties can be informed very easily. On the other hand, it is essential for potential investors and debt holders to gain sponsor's concerns. Further it is important for lenders as well as shareholders when determining the direction of the business (Wang S., 2012).

The term "Business case" is mainly recognized in project management according to PMBOK, though different organizations may refer to it as a project feasibility study or concept study. A business case can also be referring to a structured document to support project, policy or investment decision because it provides analysis for cost, benefits, risk and alternatives relative to the business objectives. Actually, it is a decision-making tool and it defines the problem or opportunity, potential impact and offers recommendations based on cost benefits analysis. Ultimately, it will help to stakeholders to make judgment by projecting financial and business consequences (Wang S., 2012).

If we want to do a comprehensive business case evaluation, it is essential to consider strategic alignment, cost benefit analysis, and risk assessment for smooth decision-making process. However, in our research on waste heat utilization, we primarily focus on strategic alignment with hydrogen production cost for green steel, cost benefit analysis in waste heat delivery to the district heating network and assessing the economic feasibility and potential financial advantages of implementing waste heat recovery solutions.

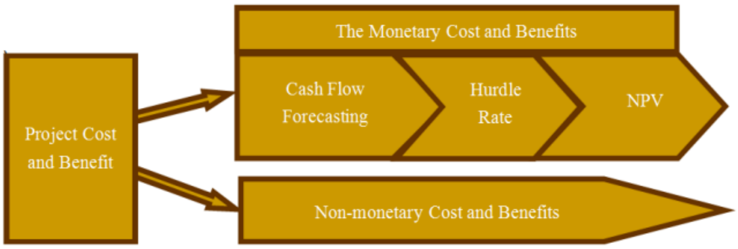


Figure 34. Cost and Benefit Analysis Process (Wang S., 2012)

Cost benefits analysis is a one of main components of project management and it will play a key role in the development of a business case. It helps to evaluate the feasibility and value of a project by systematically comparing expected costs and benefits. This process is structured when looking in to the illustrated analysis framework, to ensure the decision making. This method provides stakeholders with a clear understanding about project and its return benefits based on financial and strategic angle.

### 3.1 Kristinastad suggesteeed plant overview

Kristinestad steel plant by can be assumed to run continuously, similar to other steel plants around the world. Steel making is a continuous and very energy intensive process, hence, stopping and restarting would be costly, inefficient and may damage the equipment. Since, continuous operation ensures optimal energy use, consistent product quality and stable production, we will assume that Kristinestad plant operates 24/7 and 365 days a year.

As reported by Finnish Energy (n.d.-a), supply water temperature in Finnish DHN's vary between 65 and 115°C and in the return pipe usually between 40 and 60 °C.

According to Jonsson & Miljanovic (n.d.), since outlet water temperature from PEM electrolyser is at 79°C, there is a requirement to use heat pumps to feed the electrolyser water heat in to the district heating network.

The general plant architecture of the suggested plant is as illustrated below.

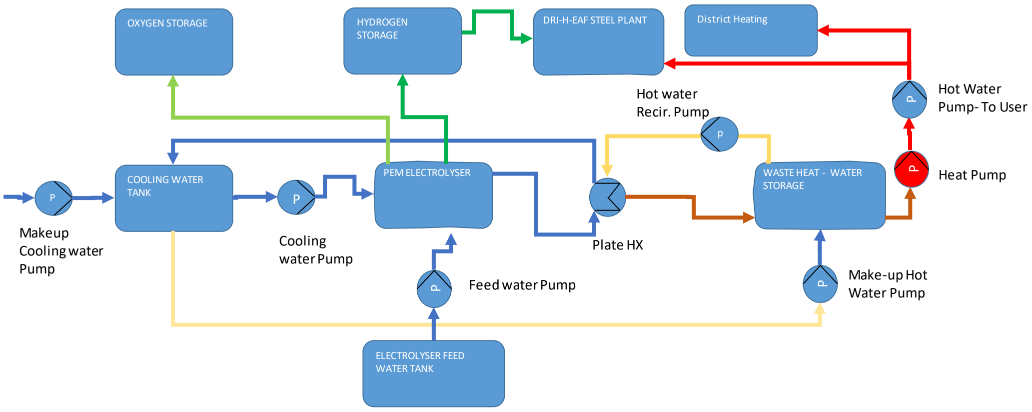
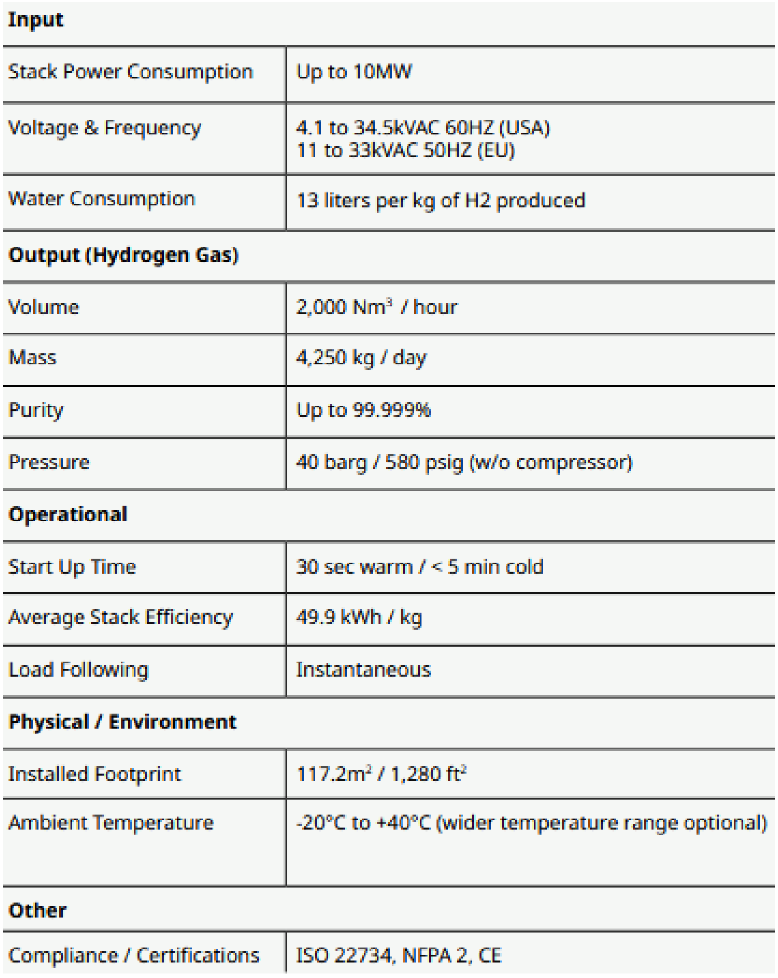


Figure 35. Suggested Simplified Plant Overview for 40 MW PEM Electrolyser plant in Kristinestad

## 3.2 Selection of the PEM Electrolyser

Cummins (n.d.) reports that Cummins electrolysers can easily be refurbished after 80,000 hours of operation and that they degrade by less than 1% per year assuming that 8500 hrs. of annual operation. Their HyLYZER® product range can deliver up to 20MW with a least system efficiency of 51 kWh/kg and deliver a hydrogen flow of 4000 Nm$^3$/h. Plug Power (n.d.-a) reports that their EX-4250D PEM electrolyser has a stack power up to 10 MW , consuming 13 liters/ kg of water of  with hydrogen output of 2000 Nm$^3$/h at a delivery pressure of 40 barg without compressor. Detailed specifications are illustrated in the figure 36 below. Plug Power (2022) report that their electrolyser stack has a life expectancy of 80,000 hrs. with an average stack efficiency of 49.9 kWh/kg and the product allows to combine modules up to gigawatts capacity.



| | |
|---|---|
| **Input** | |
| Stack Power Consumption | Up to 10MW |
| Voltage & Frequency | 4.1 to 34.5kVAC 60HZ (USA)<br>11 to 33kVAC 50HZ (EU) |
| Water Consumption | 13 liters per kg of H2 produced |
| **Output (Hydrogen Gas)** | |
| Volume | 2,000 $Nm^3$ / hour |
| Mass | 4,250 kg / day |
| Purity | Up to 99.999% |
| Pressure | 40 barg / 580 psig (w/o compressor) |
| **Operational** | |
| Start Up Time | 30 sec warm / < 5 min cold |
| Average Stack Efficiency | 49.9 kWh / kg |
| Load Following | Instantaneous |
| **Physical / Environment** | |
| Installed Footprint | 117.2$m^2$ / 1,280 $ft^2$ |
| Ambient Temperature | -20°C to +40°C (wider temperature range optional) |
| **Other** | |
| Compliance / Certifications | ISO 22734, NFPA 2, CE |

Figure 36. The Plug EX-4250D PEM electrolyser specifications - (Plug Power, n.d.-a)

Since the EX-4250D unit is scalable up to GW of capacity, theoretically the 4 similar units of 10MW capacity can be combined to produce 40MW capacity of electrolyser plant. As the installed footprint of single unit is 117.2 $m^2$, the entire installation will take approximately 468.8 $m^2$ for the electrolyser plant alone that produces green hydrogen from the DRI-$H_2$-EAF steel process.

Based on the Plug Power (n.d.-a) brochure above it is seen tha1 1kg of Hydrogen requires 13 kg of water compared to the theoretical requirement of 9 kg (Equation 7). Hence, chemical efficiency is 69.20%, which is comparable to PEM electrolyser efficiencies as reported in various literature.

### 3.3 Hydrogen production for DRI Process

The following table 3 illustrates the total hydrogen production per annum based on the unit data of Plug Power (n.d.-a) and continuous operation.

Table 3. Annual Hydrogen Production Capacity - 365 days of operation

| | | |
|---|---:|---|
| Unit Capacity(The Plug EX-4250D) | 10 | MW |
| No_Units | 4 | Nos. |
| Installed Capacity | 40 | MW |
| Hydrogen Gas Output - Purity | Up to 99.999% | |
| Hydrogen Gas Output - Pressure | 40 barg (w/o compressor) | |
| Hydrogen Gas Output - Volume/4 Units | 8,000 | Nm3 / hour |
| Hydrogen Gas Output - Mass/4 Units | 17,000 | kg / day |
| Annual Operation Hours (24*365) | 8,760 | hrs./annum |
| ***Total Hydrogen Gas Output - Mass*** | ***6,205,000*** | ***kg / annum*** |

### 3.4 Cooling water requirements

Eurowater (n.d.) reports that approximately 400L/MW.hr. of cooling water is required. Based on this data,

Cooling water for 40 MW electrolyser = 400 * 40 =16,000 L/ hr.

Cooling water / annum = 16,000 * 8,760 = 140,160,000 L / annum

### 3.5 Heat Production

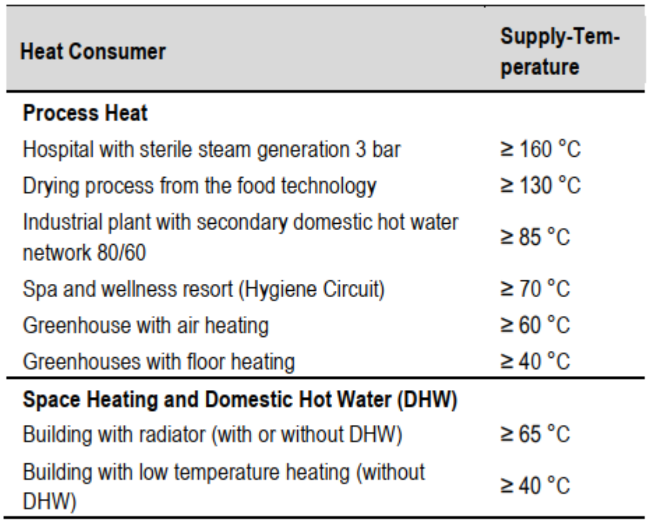
Heat produced by the PEM electrolysers are transferred from the cooling water to a heat exchanger that is used to maintain a heating buffer tank at the required temperature. Table 4 below illustrates the heat available for water heating.

Table 4. Annual Heat Availability for Applications

| | | |
|---|---:|---|
| Available Heat | 12.3 | MW |
| Annual Heat Availability | 107,815 | MWh |
| Heat Exchanger Effectiveness | 90% | |
| Annual Heat for water heating | 97,034 | MWh |

## 3.6 Applications of waste heat in Kristinastad

As reported by *Verenum* (n.d.) different consumers require different supply temperatures based on their application as shown in figure 37 below.



| Heat Consumer | Supply-Temperature |
|---|---|
| **Process Heat** | |
| Hospital with sterile steam generation 3 bar | ≥ 160 °C |
| Drying process from the food technology | ≥ 130 °C |
| Industrial plant with secondary domestic hot water network 80/60 | ≥ 85 °C |
| Spa and wellness resort (Hygiene Circuit) | ≥ 70 °C |
| Greenhouse with air heating | ≥ 60 °C |
| Greenhouses with floor heating | ≥ 40 °C |
| **Space Heating and Domestic Hot Water (DHW)** | |
| Building with radiator (with or without DHW) | ≥ 65 °C |
| Building with low temperature heating (without DHW) | ≥ 40 °C |

Figure 37. Supply temperature based on consumer - (Verenum, n.d.)

### 3.6.2.1 Swimming Pool Heating

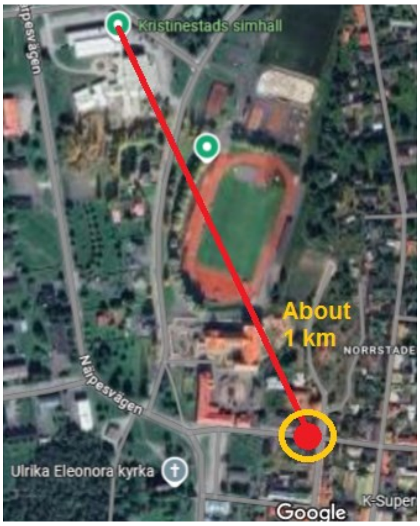


Figure 38 . Supply of Waste heat to Swimming Hall –Location - (Google Maps, n.d.)

Kristiinankaupungin Uimahalli (n.d.) indicate that swimming hall in Kristina Kaupunki consists of five pool areas (Table 5) requiring cooling of water to various temperatures.

Table 5. Kristina Kaupunki Swimming Hall Details - (Kristiinankaupungin Uimahalli, n.d.)

| ***Kristina Kaupunki - Swimming Hall*** | W(m.) | L(m.) | D(Mean m ) | Volume $m^3$ | T.req(°C) |
|---|---|---|---|---|---|
| Main Pool | 10 | 25 | 1.5 | 375 | 27 |
| Teaching Pool | 2.5 | 10 | 0.55 | 13.75 | 30 |
| Paddling Pool | 2 | 3.2 | 0.2 | 1.28 | 30 |
| Multipurpose Pool | 6 | 7 | 1.25 | 52.5 | 30 |
| Whirl Pool | 2.7 | 2.7 | 1 | 7.29 | 34 |

As indicated by Finnish Meteorological Institute (n.d.), the average daily temperatures vary throughout the year with a maximum of 17.3°C and minimum of -5.6°C.

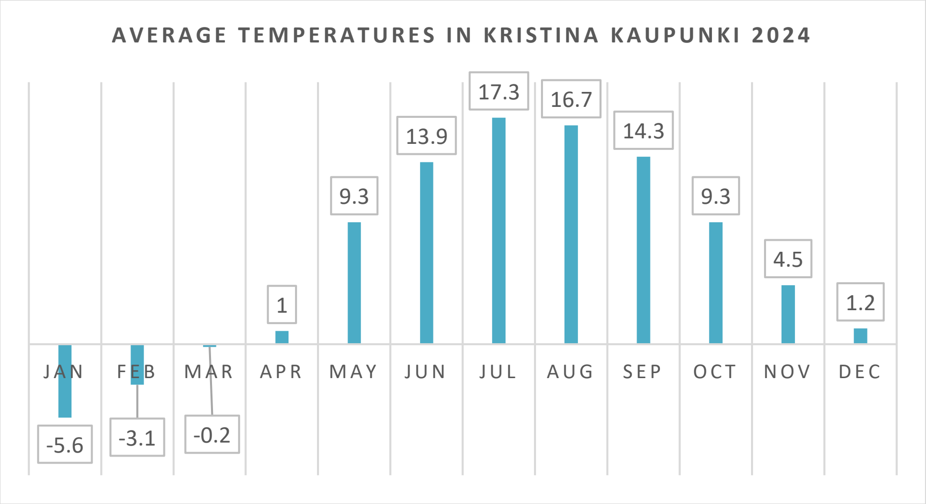


Figure 39. Average Temperatures Kristina Kaupunki - (Finnish Meteorological Institute, n.d.)

Based on above data heating requirements of swimming pool heating are illustrated below.

Table 6. Kristina Kaupunki Swimming Hall Pool Heating Requirements- MWh - (Own calculation)

| *Pool Heating MWh* | Main Pool | Teaching Pool | Paddling Pool | Multipurpose Pool | Whirl Pool | |
|---|---|---|---|---|---|---|
| *Jan* | 2,133 | 85 | 8 | 326 | 50 | |
| *Feb* | 1,969 | 79 | 7 | 303 | 47 | |
| *Mar* | 1,779 | 72 | 7 | 277 | 43 | |
| *Apr* | 1,701 | 70 | 6 | 266 | 42 | |
| *May* | 1,158 | 50 | 5 | 190 | 31 | |
| *Jun* | 857 | 39 | 4 | 147 | 26 | |
| *Jul* | 635 | 30 | 3 | 116 | 21 | |
| *Aug* | 674 | 32 | 3 | 122 | 22 | |
| *Sep* | 831 | 38 | 4 | 144 | 25 | |
| *Oct* | 1,158 | 50 | 5 | 190 | 31 | |
| *Nov* | 1,472 | 61 | 6 | 234 | 38 | |
| *Dec* | 1,688 | 69 | 6 | 264 | 42 | |
| *Total* | 16,055 | 675 | 63 | 2,577 | 419 | ***19,789*** |

Plugpower is planning to develop the electrolyser plant near the former coal power plant operated by Pohjolan Voima (Plug Power, n.d.-b). The below figure 39 illustrates that the distance between the suggested site and the swimming hall is below 1 km, hence, supply of heat to the swimming hall is feasible.

### 3.6.2.2 District Heating

There are two methods of supplying district heating to the Kristinastad district heating network. The heat can be supplied by a central pumping station , such as that located near the PEM electrolyser plant area or can be directly injected in to the existing supply piping network managed by another company.

*Verenum* (n.d.) indicates that there can be three network operating modes for district heating, with variable-constant operation mode being preferred for supply of room heat, process heat and hot water. The three operation modes are illustrated in figure 40 below. The same report highlights that modern district heating systems exclusively use the 2 pipe (one supply and one return) for connection between the heat source and the end consumer.

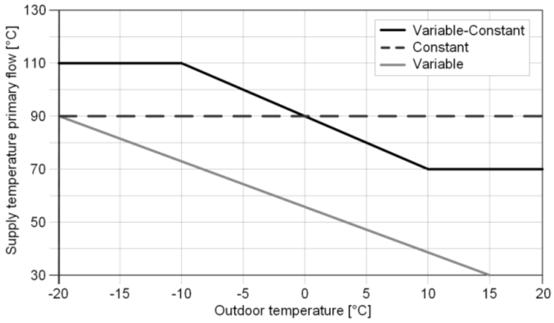


Figure 40 . District heating network operating modes - (Verenum, n.d.)

### 3.6.2.1 Centralized supply

Kristinestad is a small municipality located in Ostrobothnia. Hence, for this study, we will assume that the length of the piping network is 20 km and the supply temperature to the households to be at 115°C during the colder months of the winter. The return pipe temperature is assumed to be at 50 °C. The figure 41 below depicts the typical system components of the suggested system.

As the return water temperature from DHN was assumed to be 50 °C, it was assumed that buffer tank can be maintained at 55°C and the with the use of a heat pump, the temperature can be raised up to 115 °C, as required by the DHN. Main components of such a system are the buffer water tank and the heat pump. Approximated heat output and the annual heat pump power consumption are illustrated in Table 6.

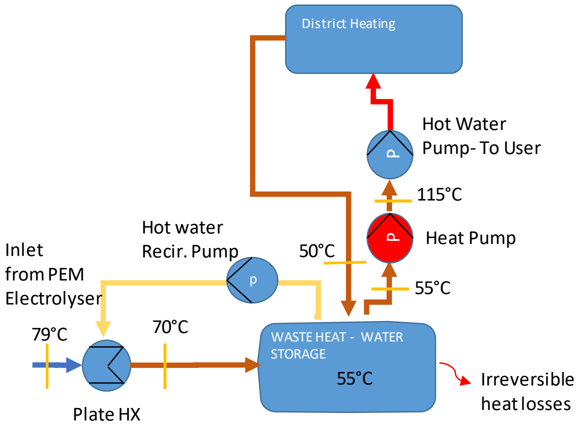


Figure 41 . District heating - Central Supply

Table 7. Annual Centralized Heat Supply to DHN & Heat pump power

| **Heat Exchanger** | | |
|---|---|---|
| Waste Heat from PEM | 12.3 | MW |
| HX Efficiency(Assumption) | 85% | |
| Heat Available to heat water | 10.46 | MW |
| *Heat Pump* | | |
| Outlet of Heat Pump T hot | 115 | °C |
| Thermal Storage Temperature T cold (assume) | 55 | °C |
| Carnot COP | 6.47 | |
| COP realistic (@50%) | **3.23** | |
| Heat output delivered for district heating | 33.8 | MW |
| Annual Heat Output to DHN using HP | **296.3** | GWh |
| Motor power required for heat pump | 3.24 | MW |
| Annual Heat Pump Power Requirement | 28.34 | GWh |

Assuming a plate heat exchanger as with temperature differences as shown, table 8 shows the surface area calculations. SWEP Heat Exchangers (n.d.) indicates that 5MW plate heat exchanger using steam/water interface costs around € 10,000. Hence, we will assume that the CAPEX cost of 12MW plate heat exchanger to be € 24,000.

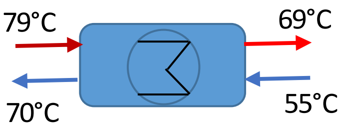


Table 8. Heat Exchanger Surface Area

| | | |
|---|---:|---|
| T,hi- Hot water from PEM | 79 | °C |
| T,ho - Hot Water Exit from HX | 69 | °C |
| T,ci- Cold Water Entry from TES | 55 | °C |
| T,co-Cold Water Exit from HX | 70 | °C |
| LMTD | 11.7 | °C |
| OHTC -HX (Assumption) | 1,200 | W/m$^2$.K |
| HX Surface Area (Q = U.A.LMTD) | 742 | m2 |

The buffer tank is required to balance supply and demand, improve efficiency, and stabilize temperature and pressure fluctuations. The required buffer tank size depends on factors such as network size, peak demand variations, and heat production flexibility. Since, heat demand data is not readily available in the literature, the buffer tank was assumed to store 12 hrs. of heat production, to mitigate any issues due to unexpected plant shutdowns.

Table 9. Buffer Tank for TES - Centralized supply

| **Buffer Tank** | | |
|---|---:|---|
| Annual Heat Supply | 296.3 | GWh |
| Average Hourly Heat Supply | 33.8 | MW |
| Buffer Tank Requirement | 12.0 | hrs. |
| Buffer tank volume before HP | 500.1 | m3 |
| Tank Height (Assume) | 10.0 | m |
| Tank Diameter | 8.0 | m |

### 3.6.2.2 Injection of heat to the Existing network

Injection of water in to the existing network requires matching of pressure and temperature of the existing network. This arrangement requires the heat pump and the buffer storage similarly to the centralized supply arrangement, however, capital cost is substantially reduced as laying of insulated pipeline underground for extensive lengths can be avoided.

# 4. METHODOLOGY

This research follows a techno economic analysis approach to evaluate the utilization of waste heat from PEM electrolysis with the case study of 40 MW hydrogen production plant at Kristinastad. The study mainly focuses on qualitative approach with literature review and case study analysis to compare findings with the previous researches on heat recovery and utilization from PEM electrolysis as well as economic feasibility. It will start by introducing various research approaches and methods related to the topic. This chapter will encompass a detailed description of the data collection techniques and an explanation of the data analysis process.

## 4.1 Research Approach

This research is based on literature review method and secondary data will be used as the primary method of data collection. We have adopted a structured approach by integrating existing literature and empirical data to analyse the techno economic feasibility of waste heat utilization from PEM electrolysis. The study begins with the theoretical background found in prior research and existing data analysis will be done and it will help to improve or adjust the existing ideas on waste heat recovery and utilization from PEM electrolysis. Researchers use different methods to carry out their research. It may be deductive, inductive or abductive methods. This research follows the deductive approach because it starts by reviving existing theories but inductive elements also can be seen within the research so by using both ways study ensures balance approach for theoretical as well as practical applications (Tennakoon, W., 2023).

## 4.2 Data Collection

Vidana Arachci et el. (2024) study about Finland hydrogen production, hydrogen production projects and their situation, economic and policy aspects as well as waste heat utilization. This research mainly focuses with the qualitative method. Van der Roest et al. (2023) shows that importance of heat recovery and utilization from PEM electrolysis by using separate key scenarios like end customer and district heating. End customer scenario is done with two cases with heat pump and without heat pump but finally show that district heating is the best way to waste heat integration from PEM electrolysis. Their methodology is case study approached. Similarly, Siecker et el. (2022) study about how to use waste heat from PEM electrolysis for different purposes and specially for domestic water heating. However, this study also shows that recovery and utilization of waste heat lead the increasing of efficiency and productivity of the hydrogen production process of PEM electrolysis. Tiktak (2019) study about two scenarios for waste heat recovery and utilization from PEM electrolysis. North Sea energy case study and Nieuwegein case study. Nieuwegein one is directly related to the district heating integration from waste heat. This research is totally based on model based approach. Lümmen et al. also study about waste heat recovery from condensing steam for hydrogen production via PEM electrolysis using a thermo-economic approach and its methodology is model base case study approach.

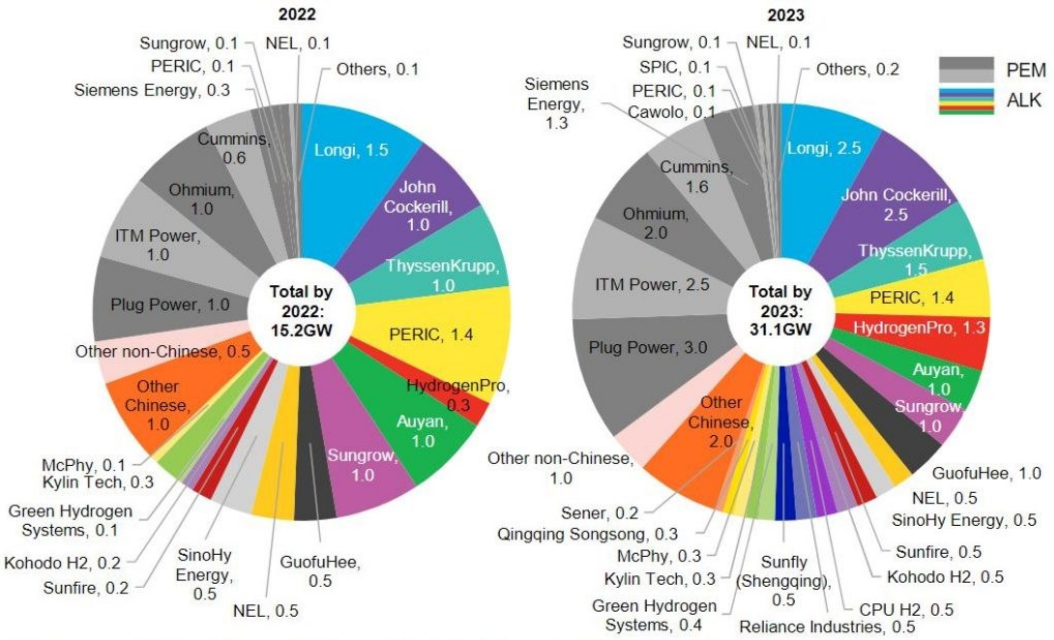
Our research primarily adopts a qualitative research approach**,** emphasizing an in-depth analysis of existing literature, theoretical frameworks, and case studies to evaluate the techno-economic feasibility of waste heat utilization from PEM electrolysis. The data will be collected by using existing literature and a one specific case study of 40 MW hydrogen production plant with PEM electrolysis at Kristinastad in Finland. This approach is directly focus with an aim and particular subject to study a real-world scenario. Always a single case study will provide an in-depth analysis and it is a very practical way to study a one research area.

# 5. FINANCIAL MODELING AND RESULTS

## 5.1 Key parameters and assumptions

As reported by Christensen (n.d.) PEM electrolyser CAPEX costs vary drastically from a low value of USD385/kW to 2068/kW. International Energy Agency reports that CAPEX cost for installed PEM electrolyser system are currently in the range of USD 1100-1800/kWe(*International Energy Agency, n.d.-a*). Solar PV Magazine reports that project costs in western markets are as much as four times high as compared to Chinese internal market and for PEM the cost is around USD 1400/kW( PV Magazine International, 2024). As reported by Deloitte (n.d.) CAPEX levels are expected to fall significantly by 2030, down to 400 – 600 kWh / kg H2 range, driven by on-going R&D initiatives and scale. Christensen (n.d.) had considered that cost of compressor CAPEX as USD 0.15/kg of $H_2$, its power consumption at USD 0.399/kg and that onsite storage cost to be approximate at USD 0.50-0.60/kg of $H_2$ storage. Furthermore, the study includes balance of plant costs including piping and electrical works at USD 50/kW.  In this study we have adopted a CAPEX cost of USD 700/kW based on assumption that PEM costs are expected to decline with advancing technology.

Christensen (n.d.) had adopted a fixed OPEX cost of $50/kW in their study, while Deloitte (n.d.) Indicate that most studies have maintained this value between 1-3% of CAPEXT cost and the range will be 2-4% of the CAPEX value based on the project scale by the year 2030.  Van Der Roest et al., (2023) had adopted 2% of CAPEX cost as OPEX cost in their model development, whereas KPMG (n.d.) indicate that fixed OPEX cost is attributed 2-4% of CAPEX cost, based on whether stack replacement is included. In the current study we have adopted a conservative value of 2.5% of CAPEX cost as the OPEX cost. KPMG (n.d.) further highlights full load hours, indirect CAPEX and OPEX as uncertainties in the investment figures and a case-by-case assessment of these complex and challenging aspects of the investment are required. Figure 42 illustrates the global electrolyser manufacturing capacity based on suppliers.



*Source: Company filings, industry sources, BloombergNEF. Note: The values refer to year-end capacities.*

Figure 42. Annual Electrolyser Manufacturing Capacity - (BloombergNEF, 2022)

The price range for large scale electricity customers vary between 4.5c/kWh to 9.5c/kWh(*Statistics Finland, n.d.*). It is estimated that renewable energy is expected to grow at a rate of 10.5% from year 2025-2029, annually (Statista, n.d.). We will take 5c/kWh as a conservative figure for this case analysis taking due note that renewable electricity prices are expected to decline as the technology of renewable energy sources such as solar and wind electricity matures.

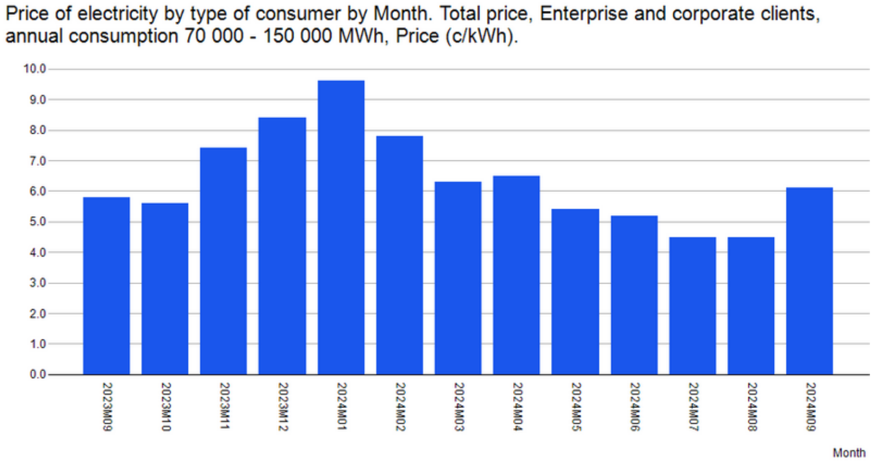


Figure 43. Price of Electricity Finland 09/23 -09/24 - (Statistics Finland, n.d.)

Matošec (2022) report that three types of water are required for the operation of a green hydrogen plant, namely, ultra-pure water used as feedstock for the electrolyser, cooling water and pure water. He further states PEM electrolysers and alkaline electrolysers relying on advanced electrodes need the conductivity of ultra-pure water to be below 0.1 µS/cm to reduce the costs associated with cleaning and corrosion. As informed by Matošec (2022), the amount of feed water required for PEM electrolysis plant increases almost by 2.5 fold and energy consumption increases nearly 3.5 fold when desalination is concerned in comparison with groundwater use. However, compared to the energy use for electrolysis, this is negligible, hence we have not considered the energy use for water treatment in this study. Based on KRS-veden hinnat nousevat 1.1.2024 (n.d.)**,** water cost including waste water is priced at € 3.72/m$^{3,}$, if domestic water is used.

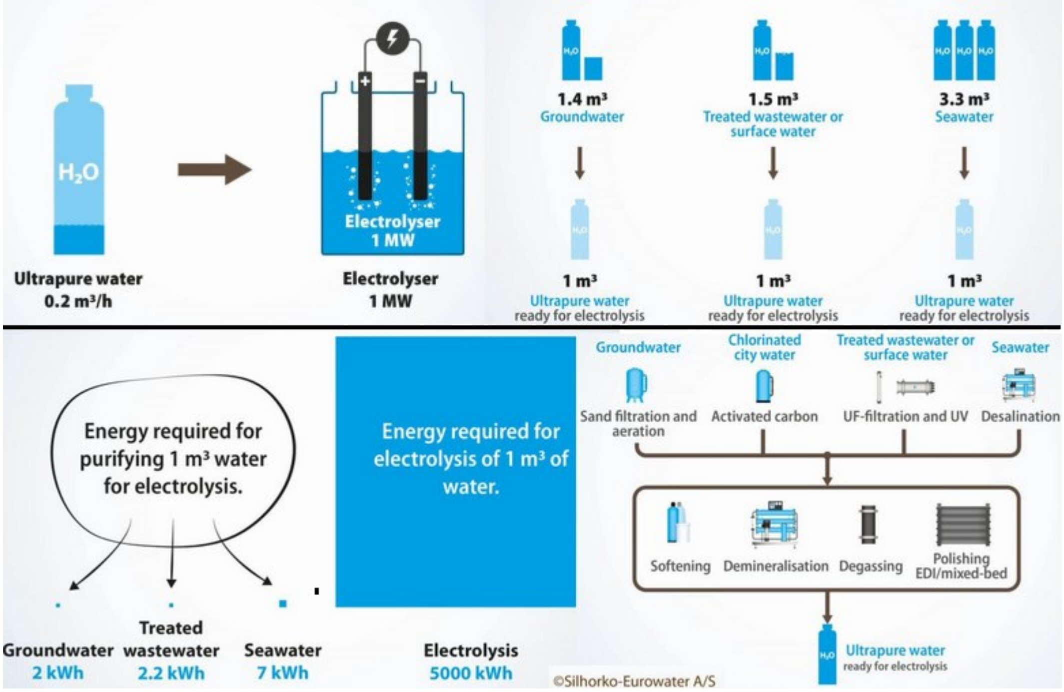


Figure 44. Water Purification for Electrolysis - (Matošec, 2022)

Hydrogen storage is a critical component in the hydrogen supply chain, directly influencing the overall cost-effectiveness of hydrogen as an energy carrier. CAPEX and OPEX associated with hydrogen storage vary depending on the chosen storage method, such as compressed gas storage, cryogenic liquid storage, or underground storage in geological formations.

Tank storage above ground is suitable when storing hydrogen up to a couple of days. Storing hydrogen as a compressed gas typically involves high-pressure tanks made from advanced materials to withstand high pressures up to 1000 bar. The cost for such storage solutions is approximately $ 500 -1000/ kg. Hydrogen can also be stored as a cryogenic liquid at temperatures around -253°C. This method requires specialized insulated tanks to maintain such low temperatures (Mekonnin et al., 2025). The other method of storage is using underground storage where Hydrogen could be stored for seasonal requirements expanding up several months. Since DRI-H2-EAF processes require Hydrogen at much lower pressures (below 50 bar), steel tanks may be used for storage. We will assume that CAPEX cost for such a tank is around \$400/kg of H2 stored and that 6 hours of buffer storage is sufficient to take daily variations.

Statistics related to District heating from Finnish Energy (2025) indicate the Pohjanmaa region in Finland is having 940 GWh of district heating requirement per annum with a total installed pipe capacity of 404 km. Hence, the excess heat produced by PEM electrolyser can be used in the Kristinestad district heating network.

Literature sources are very rare that exclusively specify the CAPEX cost of heat exchangers used in PEM electrolysis. However, SWEP Heat Exchangers (n.d.) reports that the CAPEX requirements for plate heat exchangers for steam/water heat exchange applications as € 1000 for 5MW Capacity. Since superheated steam requires more stringent design of heat exchangers to operate at higher temperatures with superheated steam, we have assumed that heat exchangers used for PEM electrolysis heat recovery can be sought at a similar conservative price of € 2000/MW. Furthermore, Pieper et al. (2018) report that CAPEX requirements for heat pump used in DHN as 0.8- 1.1 million €/MWh. Saranpää (2024) informs based on few investments made by companies in Finland that 1 million €/ MWh was used in their study. Danish Energy Agency (2024) indicate that compression type heat pumps up to 10MW for capturing excess waste heat from industrial applications have a CAPEX cost around 0.71 €/MWh. Hence, for our study we will use CAPEX Values as 0.71 M€ / MWh for the heat pump. As a buffer storage tank would be required to maintain continuous supply of hot water to DHN, we have used a 500m$^3$ capacity tank as the buffer in this study. However, literature review does not reveal any data related to buffer tank CAPEX costs, hence the CAPEX cost of the buffer tank for thermal energy storage was left out of the calculations.

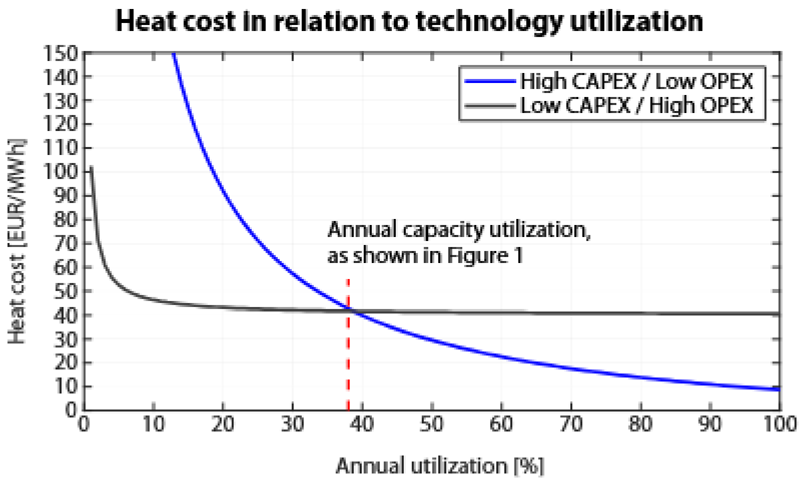


**Figure 2.** Heat generation cost in respect to unit annual utilization. The black line represents low CAPEX / high OPEX heat plant, and the blue line represents high CAPEX / low OPEX.

Figure 45. Heat cot in relation to technology utilization- (Gudmundsson & Thorsen, n.d.)

Finland, as a leader in carbon pricing policies show that 67% of the carbon emissions are priced above € 60/ton of $CO_2e$, while Net Effective Carbon Rates are € 94.37 per ton of $CO_2e$ on average in Finland in 2023, when measured in real 2023 euros (*OECD, n.d.*). Similar to Van Der Roest et al. (2023), we have used € 60/ton of $CO_2e$ as the cost of carbon emissions in this study.

Van Der Roest et al. (2023) had used a CAPEX value of € 230/m of piping in the district heating network in his study based on 2019 prices. Based on Polytherm (n.d.) the CAPEX price of Euro 586.70/m is used for 150-150 mm piping. Assuming approximate linear variation of prices we have assumed that 300-300 mm piing would consume € 1,000/m length of piping.

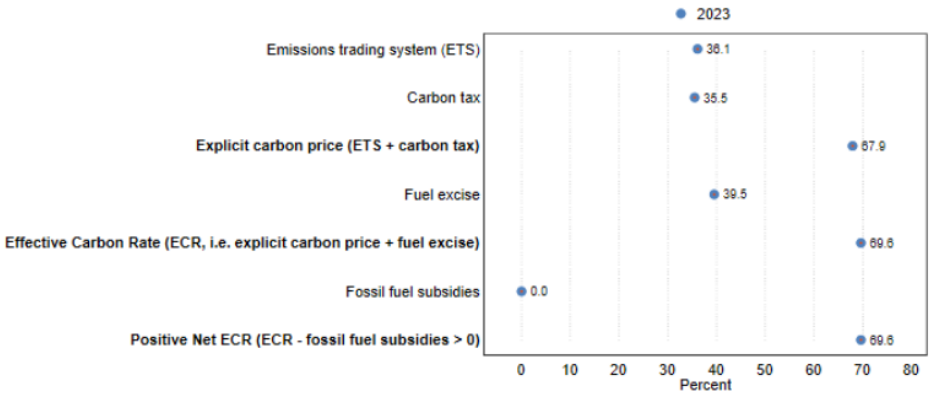


Figure 46. Carbon pricing in Finland - (OECD, n.d.)

Finnish Energy (2025) indicate that majority of district heating supply is provided by biomass based sources with only 24% from fossil fuel based sources. Thus in this study we assume that biomass is used for district heat production at present and the average price to consumer as 96.26 €/MWh.

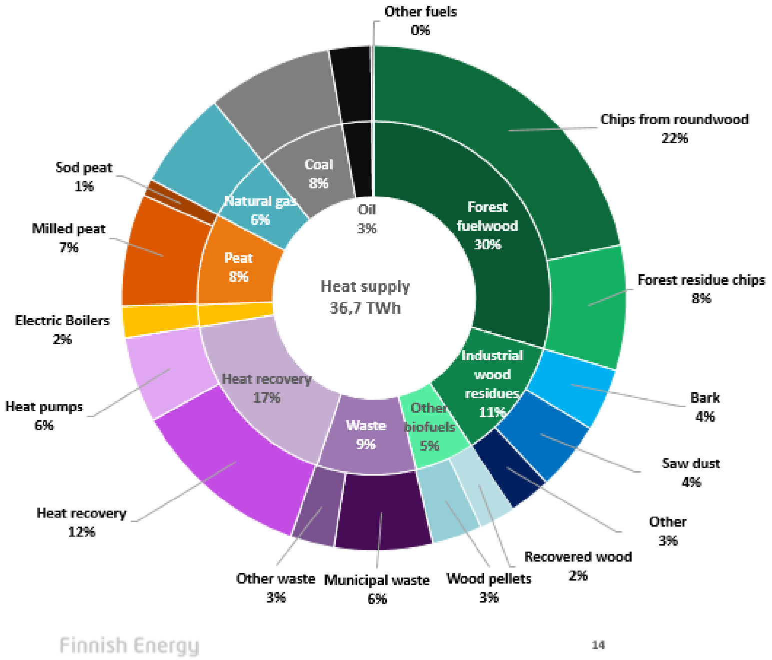


Figure 47. Energy sources for district heat supply in 2023 by fuels -Finnish Energy (2025)

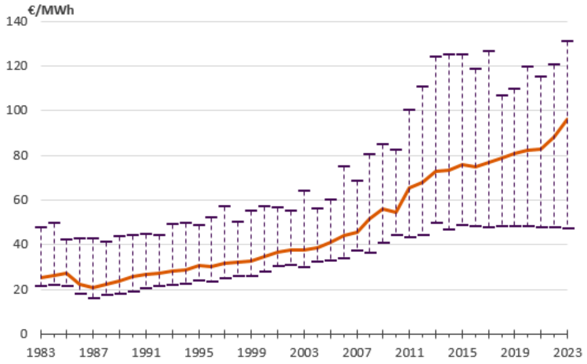


Figure 48. Price of district heat (incl. VAT) Average, minimum and maximum values - Finnish Energy (2025)

## 5.2 Formulation of equations

Following simple equations have been used to to determine the levelised cost of hydrogen for PEM electrolysis and levelised cost of heat production for waste heat recovery from the same process.

$$Levelized\ Cost\ of\ Hydrogen\ (LCOH) = \frac{(Annualized\ CAPEX+OPEX)_{PEM}}{Total\ Hydrogen\ Output\ per\ Annum}$$

………….. (21)

$$Levelized\ Cost\ of\ Heat\ (LCOh) = \frac{(Annualized\ CAPEX + OPEX)_{DHN}}{Total\ Heat\ Output\ to\ DHN\ per\ Annum}$$

………….. (22)

$$\sum_{Year\ 0}^{n}(Heat\ Sales - CAPEX - OPEX) = 0$$ ……….. (23)

The above formula for LCOH has taken in to account that PEM production requires equipment purchase in the form of PEM Plant, Balance of plant that includes cost of Compressor, hydrogen storage for 6 hours and the cost of electrical and piping connections, whereas hydrogen output takes in to account the published data from PlugPower. Simple payback period is calculated by accounting for heat sales ,CAPEX and OPEX requirements.

### 5.3 Financial Modelling

The research study has taken into several key assumptions in its financial modelling. Based on literature review, we had made key assumptions on the cost of CAPEX and OPEX for both PEM and district heating, discounting rate, project lifetime and cost of utilities (water, electricity) etc. as discussed in previous sections. Table 10 below illustrates the cost assumptions.

Table 10. Cost Assumptions Summary

| **Cost Assumptions** | | |
|---|---|---|
| PEM ELECTROLYSIS | | **Unit** |
| CAPEX | 700 | USD/KW |
| OPEX | | |
| Fixed | 2.5 | % of CAPEX |
| Variable | | |
| Water | 3.72 | €/ m3 |
| Electricity | 5 | c€/ kWh |
| Balance of Plant | | |
| Electrical, Piping Connections | 50 | USD/KW |
| Compressor | 0.15 | USD/kg |
| H2 Storage Tank | 400 | USD/kg |
| DISTRICT HEATING | | |
| CAPEX | | |
| Heat Exchanger | 2,000 | €/MW |
| Heat Pump | 710,000 | €/MW |
| Water Pump(Assume) | 200,000 | € |
| Piping network | | |
| Double Preinsulated Pipe DN 300-300 | 1,000 | /m |
| Pipe Accessories | 25% | of Total Pipe Cost |
| Installation | 50% | of Total Pipe+Acc Cost |
| OPEX | | |
| Fixed | | |
| Heat Exchanger | CAPEX Cost/ Service Life | |
| Heat Pump | 2126.7 | €/ MW |
| Water Pump | CAPEX Cost/ Service Life | |
| Variable | | |
| Heat Pump | 1.8 | €/MWh |
| Project Details | | |
| Expected Plant Life | 30 | Years |
| Expected Discount Rate | 6% | |

| | | |
|---|---|---|
| **Kristinestad Plant** | | |
| PEM Plant Capacity | 40 | MW |

### 5.3.1 Levelized Cost of Hydrogen

| | | |
|---|---|---|
| PEM ELECTROLYSIS | | |
| **CAPEX** | | |
| PEM Electrolyser | 28,000,000 | USD |
| Balance of Plant | | |
| Electrical, Piping Connections | 2,000,000 | USD |
| Compressor | 930,750 | USD |
| H2 Storage Tank -Gas (6 hrs.) | 1,700,000 | USD |
| **Total CAPEX** | 32,630,750 | USD |
| | **31,325,520** | **€** |
| Capital Recovery Factor | 0.073 | |
| Annualized CAPEX | **2,275,765** | **€** |
| **OPEX** | | |
| Fixed | 700,000 | USD/Annum |
| | 672,000 | €/Annum |
| Variable | | |
| Water | 300,074 | €/Annum |
| Electricity | 17,520,000 | €/Annum |
| **Total OPEX** | **18,492,074** | **€/Annum** |
| **Total Cost/ annum** | **20,767,839** | **€/Annum** |
| | | |
| Levelized Cost of Hydrogen Production -LCOH | **3.35** | €/kg |

The above calculation had taken into account a currency conversion factor of 0.96 to convert from USD to EURO as at 19/2/2025.

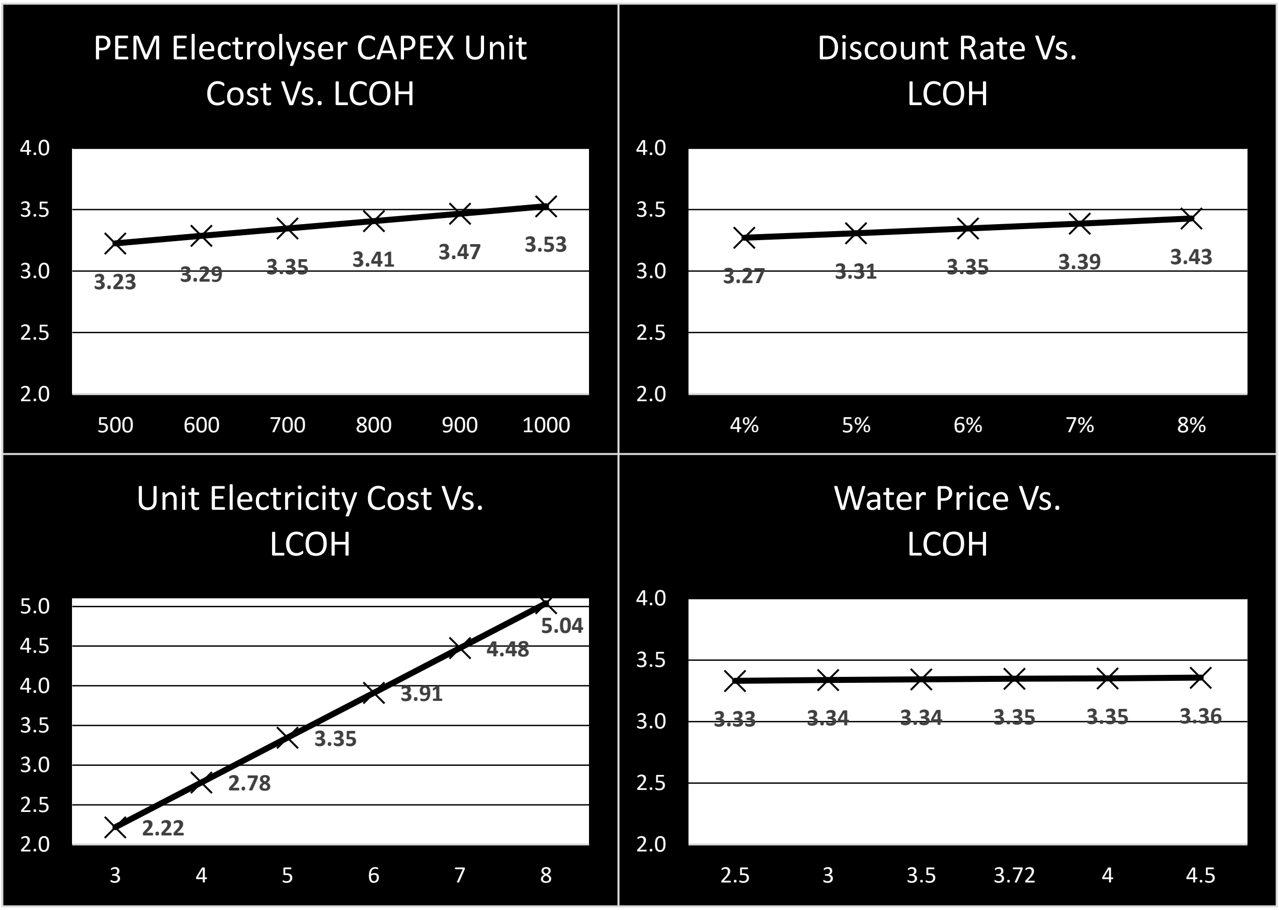
### 5.3.2 Levelized Cost of Heat

| **District Heating** | | |
|---|---|---|
| **Length of network** | 100 | km |
| **CAPEX** | | |
| Heat Exchanger | 26,175 | € |
| Heat Pump | 7,427,692 | € |
| Water Pump(60000x3) Assume | 180,000 | € |
| Piping | 187,500,000 | € |
| **Total CAPEX (With Piping)** | **195,133,868** | € |
| ***Annualized Total CAPEX (With Piping)*** | **14,176,263** | € |
| **Total CAPEX (Without Piping)** | **7,633,868** | € |
| ***Annualized Total CAPEX (Without Piping)*** | **554,592** | € |
| **OPEX** | | |
| Heat Exchanger(15 yrs. service life) | 1,745.02 | € |
| Heat Pump | 533,363 | € |
| Water Pump(15 yrs. service life) | 12,000 | € |
| **Total OPEX** | **547,108** | € |
| **Total Cost/ annum (With Piping)** | **14,723,371** | **€/Annum** |
| **Total Cost/ annum (Without Piping)** | **1,101,700** | **€/Annum** |
| Levelized Cost of Heat Production -LCOh(With Piping) | **49.69** | €/MWh |
| Levelized Cost of Heat Production -LCOh(Without Piping) | **3.72** | €/MWh |

### 5.3.3 Sensitivity of Hydrogen Price to Variables

The graphs below indicate that LCOH is more sensitive to variation in unit electricity price than any other variable considered.

| | | | | | | |
|---|---|---|---|---|---|---|
| *Unit Capex Cost* | 500 | 600 | 700 | 800 | 900 | 1000 |
| *LCOH* | 3.226 | 3.287 | 3.347 | 3.407 | 3.468 | 3.528 |
| *Discount Rate* | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | |
| *LCOH* | 3.272 | 3.309 | 3.347 | 3.387 | 3.429 | |
| *Electricity Rate* | 3 | 4 | 5 | 6 | 7 | 8 |
| *LCOH* | 2.218 | 2.782 | 3.347 | 3.912 | 4.476 | 5.041 |
| *Water Price* | 2.5 | 3 | 3.5 | 3.72 | 4 | 4.5 |
| *LCOH* | 3.331 | 3.338 | 3.344 | 3.347 | 3.351 | 3.357 |


PEM Electrolyser CAPEX Unit Cost Vs. LCOH

Discount Rate Vs. LCOH

Unit Electricity Cost Vs. LCOH

Water Price Vs. LCOH

Figure 49 . Variables vs. LCOH

This indicates the importance of setting up electricity supply agreements that are cost effective for the operation period. As renewable energy supplies such as wind and solar become more cost effective in the future, hydrogen production using

PEM electrolysis become comparable with traditional hydrogen making processes such as Steam Methane Reforming(SMR).

Variation of LCOH with cost of water is minimal, hence can be considered as the least important parameter when municipal water is considered for the lifetime of the project. However, water can be made cheaper by using novel technologies such as desalination when economies of scale are considered.

### 5.3.4 Variation of Levelized cost of Heat Production with Variables

The table 12 below illustrates the variation of levelised cost of heat production with most notable parameters such as Length of piping network, COP of heat pumps and CAPEX costs of DHN equipment as reported in various literature.

Table 11. LCOh with Variables (in Euros)

| DHN CAPEX Cost | -15.0% | -7.5% | 14.2M€. | 7.5% | 15.0% | |
|---|---|---|---|---|---|---|
| LCOh(With Piping) | 45.86 | 49.45 | 53.04 | 56.62 | 60.21 | |
| Length of Network, km | 60 | 80 | 100 | 120 | 140 | |
| LCOh(With Piping) | 34.65 | 43.84 | 53.04 | 62.23 | 71.42 | |
| COP-HP | 2.5 | 3 | 3.5 | 3.72 | 4 | 4.5 |
| LCOh(With Piping) | 67.08 | 56.76 | 49.39 | 46.77 | 43.86 | 39.56 |
| LCOh(Without Piping) | 7.63 | 7.21 | 6.92 | 6.81 | 6.70 | 6.53 |

As indicated in the table 12 above, LCOh increases with CAPEX price of the DHN network equipment including piping. However, the notable increase in LCOh is with the Length of network, where 140km network is having LCOh of €. 71.42/kWh of thermal. The figure 49 below illustrate the trends with variables and also show that LCOh is significantly lower, as much as €. 7/ kWh of thermal, when direct injection in to the existing DHN piping network is considered.

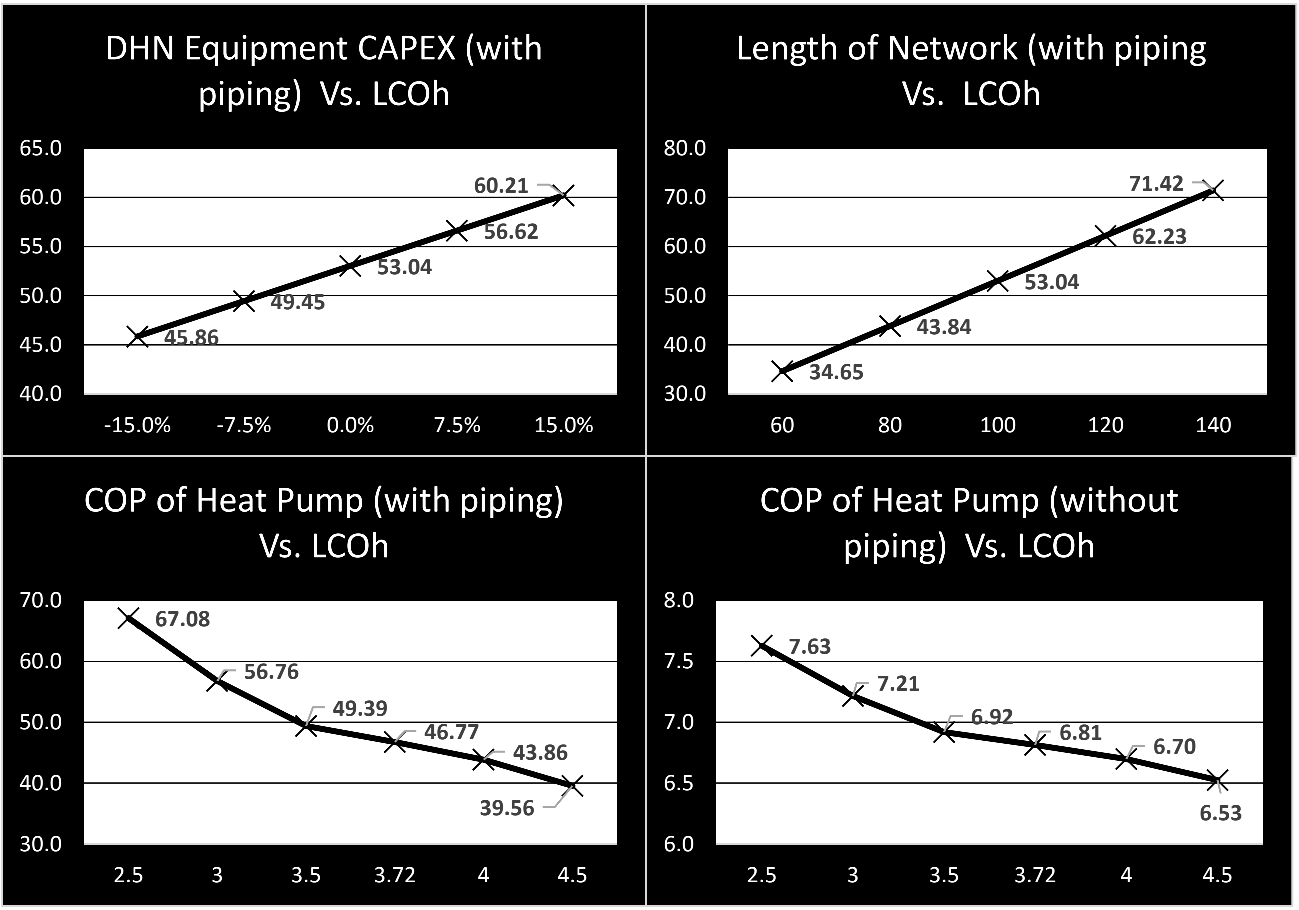


Figure 50 . LCOh with Variables

### 5.3.5 Financial Benefits of waste heat from PEM Process

This study considers the carbon abatement of H2-DRI-EAF Process with that of the existing BF-BOF process predominantly used in SSAB, Finland. The formula related to carbon abatement from using a clear process is as follows.

$$Annual\ Carbon\ Abatement = (\Delta\ carbon\ emmisions\ between\ BF - BOF\ and\ DRI - EAF\ processes)\ X\ Steel\ production\ per\ annum$$

…………. ( 24)

To calculate the theoretical steel production quantity using the H2-DRI-EAF process we can use formula 14, where 3 moles of hydrogen process 2 moles of iron or 6.048 grams of Hydrogen produces 111.7 grams of iron. Using data obtained from the theoretical framework section, the below table 13 illustrates the carbon abatement by utilizing H2-DRI-EAF process.

Table 12. Carbon savings in H2-DRI-EAF process

| | | |
|---|---:|---|
| Theoretically 1 Kg hydrogen produce | 18.47 | Kg steel |
| Process losses(Assumption) | 5% | |
| Practical Steel production/ kg hydrogen | 17.55 | Kg steel |
| Annual Steel production with 40MW PEM Plant | 108,869.6 | Tons steel |
| Carbon Intensity of BF-BOF Process | 2.33 | Tons /ton Crude steel |
| Carbon Intensity of DRI-EAF Process | 1.37 | Tons /ton Crude steel |
| Carbon Abatement in steel production/ Annum | 104,514.85 | Tons of $CO_2$ |
| Carbon Abatement Savings/ Annum | ***6,270,891*** | **€** |

However waste heat from PEM electrolysis process and as well as Biomass based heat sources, which most of Finland currently use for district heating are considered as carbon neutral methods for district heat production. However, as reported by Finnish Energy (2025), there is a possibility of replacing use of Light Fuel Oil, Heavy Fuel Oil, Hard coal and anthracite, Milled peat and Sod peat used for DH production in Pohjanmaa region by the waste heat recovery process of PEM electrolysis.

Table 13. Fuel energy consumed in DH production and CHP production, Pohjanmaa region

| Pohjanmaa | GWh |
|---|---|
| Light fuel oil | 4 |
| Heavy fuel oil | 2.6 |
| Hard coal and anthracite | 19.7 |
| Milled peat | 71.1 |
| Sod peat | 1.2 |
| Chips from roundwood | 312.6 |
| Forest residue chips | 131.1 |
| Hog fuel from stumps | 19 |
| Bark | 132.6 |
| Saw dust | 47.6 |
| Other industrial wood residue | 16.7 |
| Recovered wood | 12.3 |
| Biogas | 0.9 |
| Recovered fuels | 6.8 |
| Municipal waste /mixed waste | 449.2 |
| Electricity consumed by electric boilers | 171.6 |
| Steam | 12.6 |

As per UK Government. (2024), the following emission factors can be used to calculate the possible abatement by transferring DH generation by non-renewable energy sources to waste heat.

Table 14. Emission factor for Non-Renewable Fuels - (UK Government, 2024)

| Emission Factors/ kWh | $KgCO_2$ |
|---|---|
| Light fuel oil | 0.267 |
| Heavy fuel oil | 0.267 |
| Hard coal and anthracite | 0.3 |
| Milled peat | 1.1 |
| Sod peat | 1.1 |

Possible Carbon Abatement by waste heat use =

$$\sum(Fuel\ Consumption\ X\ Emmision\ Factor)$$

…………. ( 25 )

Using the formula above, we obtain the following results related to carbon abatement from using waste heat recovery process in PEM electrolysis.

Table 15. Carbon Abatement from Waste heat recovery

| | | |
|---|---:|---|
| Possible Carbon Abatement/Annum | 87,202 | Tons $CO_2e$ |
| Carbon Abatement Savings | ***5,232,132*** | ***€*** |

Furthermore, we have assumed that 25% profit margin is required from LCOh when selling heat to potential users such as Kristinastad or industrial users.

Table 16. Heat Supply Sales

| | | |
|---|---:|---|
| Annual heat supply to DHN/Others | 296.31 | GWh |
| LCOh | 49.69 | €/MWh |
| Profit Margin | 25% | |
| Sale Price | 62.11 | €/MWh |
| Annual heat sales | **18,404,214** | **€** |

Total Benefit / Annum = Carbon Abatement Savings + Heat sales

= **€ 23,636,346**

Taking CAPEX and OPEX related to heat distribution in a district heating network, it is seen that the simple payback period is 9 yrs. for a new piping heat distribution network, whereas injection in to the existing network yields payback within the first year itself.

Table 17. Simple Payback for District Heating - New Piping (in Euros)

| ***Total Expenditure*** | | ***Benefit*** | ***Cumulative*** |
|---|---|---|---|
| ***Yr1*** | (195,680,975) | 23,636,346 | (172,044,630) |
| ***Yr2*** | (547,108) | 23,636,346 | (148,955,392) |
| ***Yr3*** | (547,108) | 23,636,346 | (125,866,154) |
| ***Yr4*** | (547,108) | 23,636,346 | (102,776,917) |
| ***Yr5*** | (547,108) | 23,636,346 | (79,687,679) |
| ***Yr6*** | (547,108) | 23,636,346 | (56,598,441) |
| ***Yr7*** | (547,108) | 23,636,346 | (33,509,203) |
| ***Yr8*** | (547,108) | 23,636,346 | (10,419,965) |
| ***Yr9*** | (547,108) | 23,636,346 | ***12,669,272*** |

Table 18. Simple Payback for District Heating - Injection to Existing network (in Euros)

| ***Total Expenditure*** | | ***Benefit*** | ***Cumulative*** |
|---|---|---|---|
| ***Yr1*** | (8,180,975) | 23,636,346 | ***15,455,370*** |

# 6. DISCUSSION AND CONCLUSIONS

## 6.1 Waste Heat Generation and Utilization Technologies

*How much waste heat is generated by a 40 MW PEM electrolysis plant, and what are the most viable technologies for capturing and utilizing this heat in Finland's district heating systems or other industrial applications?*

The first research question explored the amount of waste heat generated by a 40 MW PEM electrolysis plant and the viable technologies for capturing and utilizing this heat within Finland’s district heating networks or industrial applications. According to the thermodynamic and chemical analyses presented, a significant fraction, approximately 20–30% of input energy, is released as waste heat, predominantly in the form of low-grade heat at temperatures between 50–80°C. This aligns well with the requirements of 4th Generation District Heating (4GDH) systems, which operate within a similar temperature range.

Technologically, the study identifies plate heat exchangers and shell-and-tube heat exchangers as suitable solutions for initial heat recovery. Heat pumps, particularly those operating with $CO_2$ as the refrigerant, can be deployed to elevate the temperature when necessary, especially for applications requiring higher-grade heat. Water based Thermal Energy Storage (TES) and Aquifer Thermal Energy Storage (ATES) offer flexibility in managing heat demand fluctuations. Based on the heat recovery considerations of Van der Roest et al. (2023) (direct local use, use with heat pump, and integration into DHN), the integration with 4GDH was found to be most efficient, and a study by Tiktak (2019) indicated yielding up to 91.5% total system efficiency in modeled scenarios such as the North Sea and Nieuwegein case studies.

These findings, supported by literature and technical modeling, demonstrate that PEM electrolysis can serve as a dual-purpose system, producing green hydrogen and simultaneously supplying usable waste heat to existing infrastructures. Given

Finland's mature and extensive district heating networks, this dual benefit provides a further opportunity for increasing energy efficiency and reducing overall emissions. Moreover, practical applications such as swimming pool heating and localized heating in Kristinestad further substantiate the adaptability and effectiveness of waste heat capture technologies in real world environments.

## 6.2 Technical and Economic Requirements for Implementation

*What are the technical and economic requirements for implementing waste heat recovery systems in a 40 MW PEM electrolysis plant, including the capital and operational costs, potential revenue streams, and payback period?*

The second research question focused on the technical and economic requirements for implementing waste heat recovery systems in a 40 MW PEM electrolysis plant, exploring capital and operational expenditures, revenue streams, and financial metrics such as payback period. From a technical standpoint, integration of the waste heat system necessitates the installation of high-efficiency heat exchangers, pumping systems, thermal storage tanks, and, optionally, heat pumps to ensure compatibility with district heating temperatures.

On the economic front, capital investment is a critical barrier. The study identifies that while initial capital costs (CAPEX) are high due to the need for specialized components and infrastructure modifications, operational costs (OPEX) can be minimized by optimizing system efficiency. Revenue streams stem primarily from the sale of heat to local district heating operators and industrial consumers. For instance, heating supply to Kristianstad’s swimming hall and other municipal buildings offers immediate financial returns and environmental benefits.

Simple payback period calculations indicate that the injection of waste heat into existing district heating networks yields more favorable economics compared to new piping installations. According to Table 19, the payback for network injection was substantially shorter, below a year, compared to new network deployment, which can take almost a decade. Furthermore, the Levelized Cost of Heat (LCOh) was more sensitive to heat pump integration and electricity costs than other factors, highlighting the importance of strategic component selection and local energy pricing in determining project viability.

### 6.3 Financial Modelling and Sensitivity Analysis

*What are the key parameters for developing a financial model to assess the feasibility of waste heat utilization, and how do factors such as CAPEX cost, electricity prices, heat pump performance, discounting rate and length of district heating network ect. affect the economic viability?*

Addressing the third research question, the financial model developed in this study identifies the most influential variables affecting the feasibility of waste heat utilization. These include electricity prices, capital costs, heat pump performance (COP), discounting rate, and the proximity to district heating networks. Sensitivity analysis revealed that electricity price variability and CAPEX were the two most influential factors affecting Levelized Cost of Hydrogen (LCOH), while COP and Length of Network affected Levelized Cost of Heat (LCOh) most.

In this study, the Levelized Cost of Hydrogen (LCOH) was estimated at approximately 3.35 € /kg, which is comparable with values reported in other studies such as Saranpää (2024), who observed LCOH ranges around 4-6 € /kg as reported by H2Valleys (n.d.).The slight cost reduction in our model is attributed to favorable electricity pricing assumptions and CAPEX, and efficient system design with minimal conversion losses.

For the Levelized Cost of Heat (LCOh), our results show a clear economic advantage when using existing infrastructure, 49.69 € /MWh with new piping installation versus only 3.72 € /MWh when injecting waste heat into an existing district heating network. These findings align well with Van der Roest et al. (2023), who reported LCOE heat values of 3.5 € /MWh (Case 2) for integration into the district heating network. However, our value of 49.69 €/MWh is on the high side when using a heat pump, as we have considered higher values for piping networks. This comparison underscores that the most cost-effective configurations are those minimizing infrastructure expansion and maximizing direct injection to the existing network, especially when carbon pricing is considered. This study concludes that waste heat recovery can be economically feasible, especially when integrated with existing DH infrastructure and minimal additional pumping or conversion requirements.

### 6.4 Practical Contribution

This study provides a comprehensive prefeasibility framework for utilizing waste heat from PEM electrolysis in large-scale hydrogen production facilities. It explores the underexplored area of waste heat recovery in green hydrogen production, especially at the multi-megawatt scale. The Kristinestad case serves as a replicable model for other industrial hydrogen facilities aiming to leverage energy synergies and reduce lifecycle emissions.  It offers practical technical guidelines for integrating waste heat into 4th Generation District Heating (4GDH) networks, highlighting suitable technologies like plate heat exchangers, heat pumps and storage requirements such as TES systems. The developed financial model also delivers actionable results for assessing economic viability under varying market conditions, helping future energy planners, project developers and policymakers make informed decisions for hydrogen and district heating integration projects.

In conclusion, the study confirms the strong technical and economic feasibility of waste heat recovery in a 40 MW PEM electrolysis plant in Kristinestad, Finland. From a technical perspective, the waste heat produced is highly suitable for integration into modern 4GDH systems without significant modifications to system architecture. Economically, the combination of waste heat sales, $CO_2$ savings, and improved overall efficiency supports a compelling case for investment.

The financial model developed offers a robust tool for project stakeholders to evaluate feasibility under varying economic conditions. It confirms that factors such as electricity price, heat pump performance, and infrastructure proximity must be carefully considered. The model's findings align with broader sustainability goals, suggesting that the integration of waste heat recovery not only improves hydrogen economics but also supports national and EU decarbonisation targets.

### 6.5 Limitation and future study

While this research offers strong modeling insights, it is based on prefeasibility assumptions rather than existing field data. Real world variables such as fluctuating energy market dynamics, actual seasonal heat demands and unexpected heat losses, performance deterioration and maintenance complexities were simplified. Future studies can focus on pilot scale demonstrations in Finnish context, dynamic operation under real time electricity pricing, exploration of advanced heat recovery materials for PEM stack, and how regulatory frameworks can be reevaluated to improve the technical and economic feasibility.

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