# Integrating Waste Heat from Hydrogen Production into District Heating

Fawzi Kayali

LUNDS UNIVERSITET

Department of Energy Sciences

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Department of Energy Sciences, Lund University
Box 118
SE-221 00 LUND
Sweden


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# Abstract

The aim of this research is to explore the feasibility of the integration of waste heat from electrolyzers within a Combined Heat and Power (CHP) plant and district heating (DH) network and suggest a practical setup for integration. With the escalating emphasis on the development of green hydrogen through electrolysis powered by renewable energy, a substantial amount of waste heat is generated, typically left unused. This study explores the potential of harnessing this waste heat and integrating it into DH networks, thereby enhancing the system's overall efficiency and sustainability. Using advanced simulation software, the research demonstrates that an existing 37 MW CHP plant can feasibly accommodate up to 21 MW of waste heat injection into a DH network with negligible impact on the electrical power output. The incorporation of waste heat significantly increases the heat absorbed by the DH water, thereby improving the quality of heat supplied to connected buildings. The findings from this research contribute to a deeper understanding of waste heat recovery in green hydrogen production and its potential benefits in the context of sustainable heating systems.

Keywords:
Hydrogen, Electrolysis, Waste Heat Recovery, Combined Heat and Power Plant, District Heating, Simulation, Sustainable Heating Systems

# Acknowledgements

I would like to express my deepest appreciation to my supervisor, Professor Magnus Genrup, whose expertise, understanding, and patience added considerably to my graduate experience. His unwavering guidance, insightful critiques, and the encouragement I received from him have been invaluable and motivating throughout this research journey.

# Contents

# 1. Introduction

This chapter will give a brief introduction on the subject and current development in the world of hydrogen and waste heat recovery. It will explain and underline the relevance of the research direction and present a clear objective.

## 1.1 Hydrogen’s Role in the Future of Sustainable Energy

The growing recognition of the climate crisis has set the stage for a global transition towards sustainable and low-carbon energy systems. As of 2019, energy consumption accounts for about 76% of global greenhouse gas emissions, primarily through burning fossil fuels for electricity, heat, and transportation [1]. Urgent and significant measures are required to mitigate these impacts, necessitating a shift towards more sustainable sources of energy. This is expressed in international commitments such as the Paris Agreement, which aims to limit global warming to well below 2℃ above pre-industrial levels [2]. In this context, hydrogen is emerging as a crucial player in the global energy transition.

Hydrogen, as a versatile, clean-burning, and carbon-free energy carrier, holds tremendous potential in decarbonizing various sectors, ranging from energy storage to transport, and heavy industry [3]. Hydrogen is considered the energy carrier of the future due to several reasons. Hydrogen has a high energy content per unit mass, making it an attractive alternative to fossil fuels for powering transportation and other energy-intensive applications. Moreover, when used in fuel cells, hydrogen produces only water and heat, making it a zero-emission energy carrier. This makes it a promising solution for reducing greenhouse gas emissions and addressing climate change. A study from the International Energy Agency (IEA) suggests that hydrogen could contribute up to 6% of the world's cumulative emissions reductions by 2050, offering a solution to many urgent energy challenges [3].

The hydrogen industry is expanding rapidly, it is currently valued at USD 155.35 billion in 2022, and growing at a compound annual growth rate of 9.3% from 2023 to 2030 [4]. However, there are still challenges to be addressed in terms of scaling up green production, reducing costs, and ensuring safety. Most of the hydrogen production today relies on fossil fuels, resulting in significant carbon emissions. To address this, there is increasing focus on green hydrogen production, which involves producing hydrogen from renewable sources such as wind and solar through electrolysis. Green hydrogen is expected to become a key contributor to achieving global climate goals, with the IEA projecting that the production of renewable hydrogen could increase from 0.4 million tons in 2019 to 207 million tons by 2050 [3]. The growth of green hydrogen production is being driven by falling renewable energy costs, supportive policies, and increasing demand for decarbonization in key sectors.

Electrolyzers, the devices that produce hydrogen via electrolysis, generate excess heat as a byproduct of the process. Much of this thermal energy is currently wasted, representing a significant opportunity for energy recovery and utilization. One potential solution is to integrate this waste heat into district heating (DH) networks, which distribute heat for residential and commercial heating from a centralized location. DH is especially prevalent in northern European countries like Sweden, where over 50% of all homes and buildings are connected to DH networks [6]. Utilizing the excess heat from electrolysis in these networks could improve overall energy efficiency, provide additional heat capacity, and further reduce greenhouse gas emissions.

This research explores the feasibility and impact of integrating waste heat from hydrogen production into a DH network, thus contributing to the broader efforts of creating sustainable, efficient, and resilient energy systems.

## 1.2 Electrolysis and Waste Heat

Electrolysis is a promising method for producing hydrogen from renewable sources, but it suffers from several inefficiencies, with waste heat being a major factor. During the process of electrolysis, electrical energy is used to split water into hydrogen and oxygen, generating a considerable amount of waste heat in the process. In fact, waste heat accounts for over 20% of the total energy consumption of an electrolysis system [7][11][21]. This waste heat needs to be cooled away to maintain the optimal temperature for the electrolysis reaction, which typically involves the use of water as a cooling medium. However, this cooling process is energy-intensive and reduces the overall efficiency of the system. Integrating the waste heat from electrolysis into a DH network can significantly increase the efficiency of the system, as the waste heat can be utilized for space heating and hot water supply. A recent study by W.J. Tiktak showed that “an electrolyser is very well suited to be connected to a DH network” [7]. This highlights the potential benefits of waste heat recovery from electrolysis and the importance of exploring such integration for improving the sustainability of hydrogen production.

## 1.3 Research Objective

The objective of this research paper is to develop and suggest a method to integrate waste heat from an electrolyzer into an already existing DH network in a combined heat and power (CHP) plant in an efficient manner. The following research questions will be investigated and answered:

Is it technically feasible to cool an electrolyzer stack with a DH network?

What is the best way to integrate the electrolyzer into the DH network?

What are the effects of integrating an electrolyzer on the overall performance of the network/plant?

## 1.4 Limitations

Despite the thorough approach and meticulous measures taken in this research, it is important to note that this study is not without its limitations.

1. **Model Simplification:** The modelling of the system involved certain assumptions. For example, while waste heat from the electrolyzer was modelled as a heat injection component with a manually input value in MW, this simplification may not completely account for the real-world dynamic behavior of the electrolyzer, its waste heat output, and the heat exchange process. Operational conditions of an electrolyzer and heat exchanger can vary depending on multiple factors, leading to potential fluctuations in waste heat, which could impact the results.

2. **Model Validation:** While the model has been designed carefully to reflect real-world conditions, it is important to note that it hasn't been validated against operational data from an actual CHP plant integrated with an electrolyzer. Such a validation would have ensured a more accurate representation of actual performance.

3. **Scale of the System:** The results and conclusions drawn in this study are specific to the scale of the CHP plant and the DH network considered in the model. Scaling up to a larger CHP plant or DH network could introduce additional complexities and factors that have not been considered in this research. The simulation results may not scale linearly with size due to these complexities.

4. **Socio-Economic Factors:** While the technical feasibility of integrating waste heat from an electrolyzer into a DH system has been investigated in this study, the economic feasibility and social implications of such an integration have not been analyzed. The adoption of this method in a real-world setting could be influenced by economic and social factors, such as cost-effectiveness, consumer acceptance, and regulatory environment.

5. **Environmental Impact:** While this study suggests a positive environmental impact due to better utilization of waste heat, a comprehensive Life Cycle Assessment (LCA) considering the environmental impact of all stages of the process was not conducted. Thus, the complete environmental footprint of the system is not accounted for in this research.

While these limitations should be taken into consideration while interpreting the findings, this study nevertheless provides valuable insights into the potential benefits and technical feasibility of integrating waste heat from electrolysis into DH systems. Future research can address these limitations by conducting a more comprehensive study, incorporating real-world operating data and broader socio-economic factors.

# 2. Literature Review

This section will cover relevant literature on the most current hydrogen electrolysis technologies and their waste heat characteristics. It will also review current DH systems and their integration with heat sources.

## 2.1 Overview of Electrolysis Technologies

Electrolysis is a process that uses electrical energy to split water into hydrogen and oxygen. There are currently several commercially available electrolysis technologies for producing hydrogen from water, each with its own unique features and advantages. According to the IEA, alkaline electrolyzers are currently the most widely used type of electrolyzer for hydrogen production, accounting for approximately 60% of the total installed electrolyzer capacity worldwide in 2020, while proton exchange membrane (PEM) electrolyzers account for about 40% of the total installed capacity [8]. Alkaline electrolyzers are known for their robustness, long lifespan, and lower cost compared to PEM electrolyzers. On the other hand, PEM electrolyzers are favored for their high efficiency, fast response time, and suitability for small-scale applications. Additionally, solid oxide electrolyzers offer high efficiency and flexibility in terms of feedstock but are still in the early stages of commercialization. Furthermore, emerging technologies such as photoelectrochemical water splitting and membraneless electrolysis offer the potential for even higher efficiency and lower costs, but they are still in the early stages of research and development, and their commercial viability and scalability are yet to be demonstrated [23][25]. Table 2.1 summarizes some of the differences between the main electrolysis technologies.

Table 2.1: Comparison of different electrolysis technologies [23][24][25]

| **Electrolyzers** | **AEC** | **PEMEC** | **SOEC** |
|---|---|---|---|
| Electrolyte | Solution of NaOH or KOH | Hydrated polymeric membranes | Ceramic |
| Charge ion conductor | $OH^-$ | $H^+$, $H_3O^+$ | $O^{2-}$ |
| Electrodes | Ni, C | C | Ceramic/ cermet |
| Catalyst | Ni, Fe, Pt | Pt | Ni, perovskites (LSM, LSCF) |
| Interconnector | Metal | Carbon-metal | Stainless steel, ceramic |
| Operating temperatures (C) | 40-90 | 20-150 | 700-900 |
| Development status | Mature | Commercialized | R&D |
| **Specific Comparison** | | | |
| Operating temperature (C) | 80 | 80 | 800 |
| Efficiency (%) | 50-78 | 50-83 | 89 |
| Cell pressure (bar) | <30 | <70 | 1 |
| Hydrogen production rate (mol $H_2/m^2h$) | 50 | 175 | 211 |
| Hydrogen production per energy consumed (mol $H_2$/kWh) | 27 | 40 | 110 |

According to the IEA, the deployment of electrolysis technologies is steadily increasing in recent years. With over 1GW of capacity installed worldwide by the end of 2022 [8]. Manufacturers are already ramping up production of electrolysers to meet increasing demand in the coming years, with approximately two-thirds of the global manufacturing capacity going for alkaline electrolyser production.

Since the alkaline electrolyser is the technology currently dominating the market, it will be selected as the electrolyser to integrate with the DH network. Moreover, the operating temperature of the alkaline electrolyser is also ideal for integration with a DH network which will be further discussed throughout this research.

## 2.2 Alkaline Water Electrolysis

Alkaline water electrolysis is a fully mature, reliable, commercially available technology with a long history in the industry. The working principle is simple. Alkaline electrolysis cells consist of two electrodes (an anode and a cathode) separated by a porous membrane or diaphragm. The electrodes are typically made of steel plates treated with nickel or other metals, and the membrane or diaphragm is usually made of asbestos or polymers. The electrolyte is typically a solution of potassium or sodium hydroxide, which is highly conductive and provides the ions necessary for the electrolysis reaction [23].

During the electrolysis process, an electrical current is passed through the solution from the anode to the cathode. At the anode, water molecules are split into oxygen gas ($O_2$) and positively charged hydrogen ions ($H^+$). Meanwhile, at the cathode, the hydrogen ions are reduced to hydrogen gas ($H_2$) by gaining electrons from the electrical current. The hydrogen gas and oxygen gas are then separated and collected for further use [23].

The overall chemical reactions that take place in an alkaline electrolysis cell can be represented as follows:

**Cathode:** $2H_2O + 2e^- \rightarrow 2OH^- + H_2$
**Anode:** $2OH^- \rightarrow 1/2\ O_2 + H^+ + 2e^-$
**Overall:** $H_2O \rightarrow H_2 + 1/2\ O_2$

Alkaline electrolysis cells are typically operated at high temperatures and pressures to improve efficiency, with temperatures ranging from 40 to 90 °C and pressures ranging from 1 to 30 bar. The high temperature helps to reduce the energy required to split the water molecules, while the high pressure helps to increase the solubility of the gas products and improve the efficiency of the gas separation process [23][24].

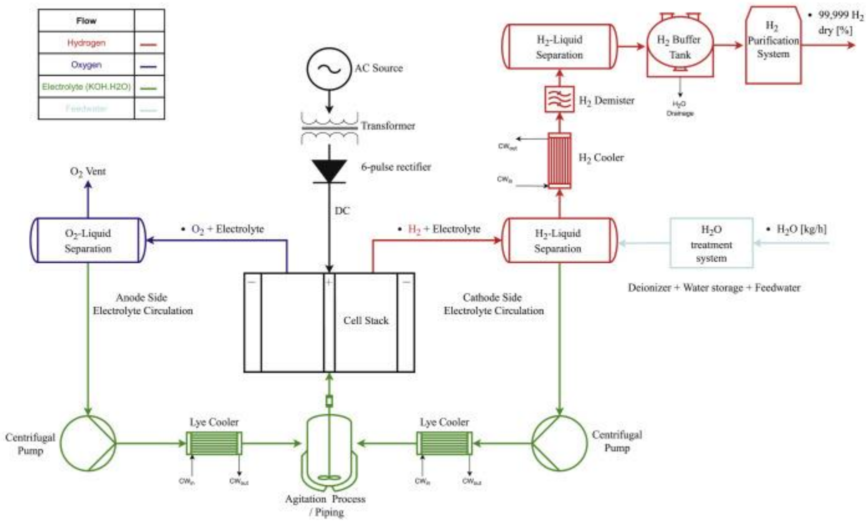


Figure 2.1: Alkaline water electrolyzer plant process diagram [11]

Figure 2.1 shows a schematic diagram that represents most commercialized MW-scale alkaline electrolysis plants. The setup is power by an AC electrical current source which is transformed and passed through a rectifier to provide DC current to the electrolyzer stack. The electrolyzer stack contains a KOH electrolyte with a concentration of 20-30%, which performs the water splitting reaction and produces oxygen and hydrogen at the anode and cathode respectively. Then, the mixture of gas molecules and electrolyte solution is divided into two streams before being separated at the separation tanks [11].

The electrolyte is pumped out of the separator and recirculated back into the electrolyzer stack. The pumps play an important role in maintaining the mass flow of the electrolyte in the closed loop and driving the fluid through the heat exchangers. The temperature control of the electrolysis process is done through controlling the temperature of the electrolyte using shell-and tube heat exchangers and PID control of the mass flow valve of the cooling water which will be further discussed in the following section [11].

The electrolyte is also passed through an agitation tank before returning to the electrolyzer stack and closing the loop. This tank represents a piping system that mixes the cathode and anode electrolyte flows with controlled valves. This is necessary due to the asymmetry of the gas production at each electrode [11].

## 2.3 Thermal Performance of Alkaline Electrolyzers

The operational performance of an alkaline electrolyzer can be visualized and described by its characteristic I-V curve. This curve shows how much cell voltage is required to produce current through the electrolyzer at different operating points. According to Faraday's law, the current density determines the rate of hydrogen production. So, a higher cell voltage at the same current density will produce the same amount of hydrogen while consuming more energy [9]. Therefore, ideally the electrolyzer should be operated in conditions that minimize the cell voltage while maintaining the current to increase the efficiency of the electrolysis process.

There are several factors that influence the I-V curve of an alkaline electrolyzer like exchange current density and electrolyte thickness [9] but the most relevant to this research is temperature. Figure 2.2 shows the effect of temperature on the I-V curve. It is evident that higher temperatures allow the electrolyzer to achieve the same current density with less voltage.

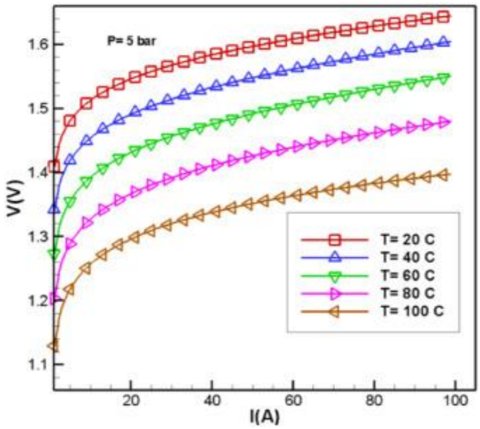

Figure 2.2: Effect of operating temperature on I-V characteristic curve of an alkaline electrolyzer [10]

The temperature of the electrolyzer is also dependent on the current as shown in Figure 2.3. Higher current means the temperature of the electrolyzer rises faster and to a higher temperature. An equilibrium temperature is reached around 2-3h after the electrolyzer starts working. When producing hydrogen from green energy sources, the amount of available energy input is intermittent and unstable. This means that alkaline electrolyzers used in green hydrogen production systems are inherently vulnerable to fluctuations during operation. These fluctuations can be simulated with a sinusoidal current as shown in Figure 2.4. When the current is unstable, the temperature never reaches a steady equilibrium.

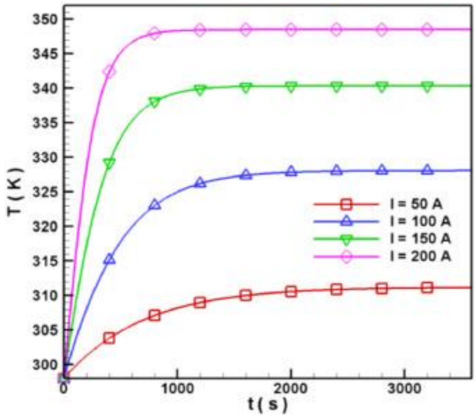


Figure 2.3: Temperature variation versus time at different electrical currents [10]

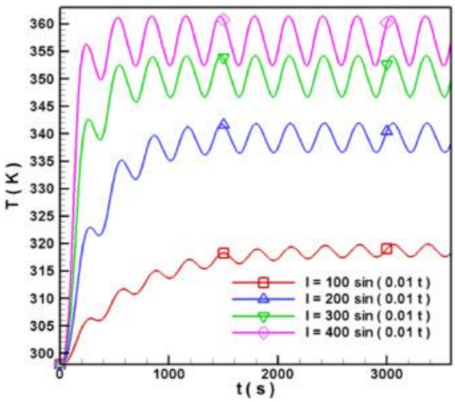


Figure 2.4: Temperature variation versus time at different sinusoid electrical current [10]

Figure 2.5 shows the amount of heat produced by the electrolyzer to heat the stack and the amount of heat disposed or wasted over time. Initially, the produced heat transfer rate is high in order to increase the temperature of the stack to the equilibrium point. As the temperature increases, the generated heat decreases and the disposed heat increases. The electrolyzer reaches a steady-state equilibrium when the produced and disposed heat transfer rates are equal.

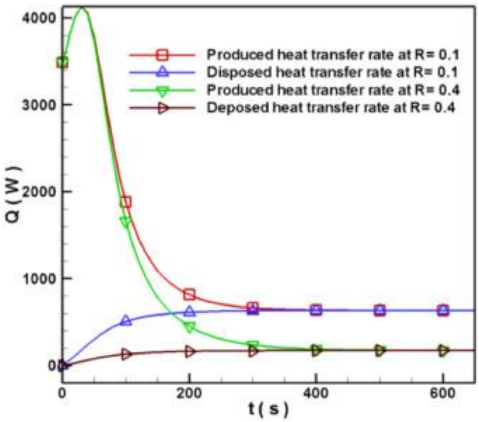


Figure 2.5: Produced and disposed heat rate versus time at different thermal resistance of the cells and constant current [10]

This shows that operating an electrolyzer supplied by clean energy like solar or wind comes with inherent fluctuations and instabilities during operation. That means that an electrolyzer cannot be directly integrated into a DH network because it will cause the DH network to inherit the same fluctuations. This could lead to DH networks with fluctuating heat outputs that depend on the heat being input by the electrolyzer. Therefore, the waste heat must be incorporated in a manner that takes this behavior into account and ensures that DH temperatures are immune to the instabilities of the electrolyzer operation.

## 2.4 Electrolyser Heat Management and Recovery

Heat management is an important consideration in alkaline electrolysis, as the process generates significant amounts of heat that can affect the efficiency and lifespan of the electrolysis cell. The heat is generated during the electrochemical reactions and can cause the temperature of the electrolyte to increase, which can lead to electrolyte degradation and decreased cell performance. On the other hand, if the operating temperature is too low, the efficiency of the electrolyzer is jeopardized. Therefore, heat management is necessary to maintain the optimal operating temperature range and prevent thermal runaway [11].

In industrial alkaline electrolyzer setups, the temperature of the process is controlled by cooling the temperature of the electrolyte. This is typically done through shell-and-tube heat exchangers and using cooling water to absorb the heat out of the electrolyte. PID controllers are used to control the mass flow of the cooling water inlet by keeping the temperature of the electrolyte at 70°C [11].

In order to accurately understand the thermal behavior of a electrolyzer, it is useful to know how much excess heat is cooled away in the process. This is directly related to the feasibility of extracting this heat to use for other processes like DH. There must be sufficient available waste heat to justify the costs associated with recovering it. Figure 2.6 shows a Sankey diagram of the energy distribution of a 3MW alkaline electrolysis plant operated at steady-state conditions.

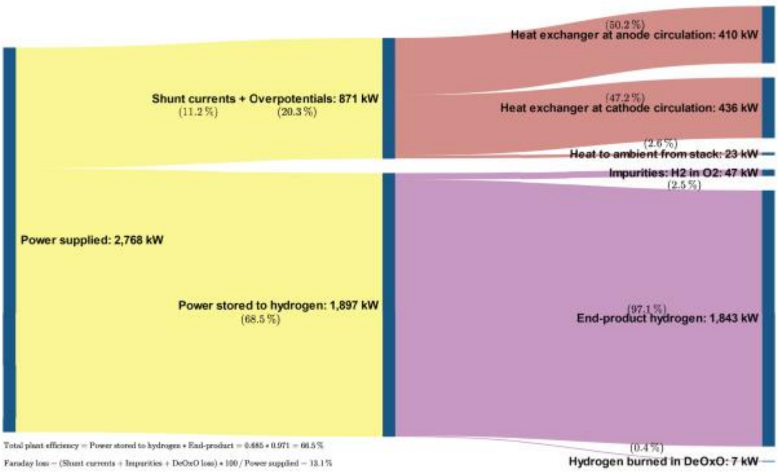


Figure 2.6: Supplied power consumption/distribution in the stack and system level of a 3MW alkaline electrolysis plant [11]

Around 30% of the total input energy is wasted in the process. This is mainly due to overpotential losses. This excess heat must be cooled away providing about 0.85 MW of heat energy at the electrolyte heat exchangers. Theoretically, this heat can be easily integrated into a DH system by using the DH water as cooling water for electrolyte cooling.

Ultimately, the feasibility of heat recovery from alkaline electrolysis cells depends on several factors, such as the size of the electrolysis plant, the operating conditions, and the availability of high-quality waste heat. The larger the scale of the plant, the more heat is available for recovery. The availability of high-quality waste heat is directly related to the operating conditions. For example, the rate of temperature increase of the electrolyzer stack during start-up is heavily dependent on the current supply. So, an electrolyzer operating at full-load will reach high-quality temperatures much faster compared to part-load operation as shown in Figure 2.7. In addition, the use of excess heat for DH may require additional investments in infrastructure, such as heat exchangers and pipelines.

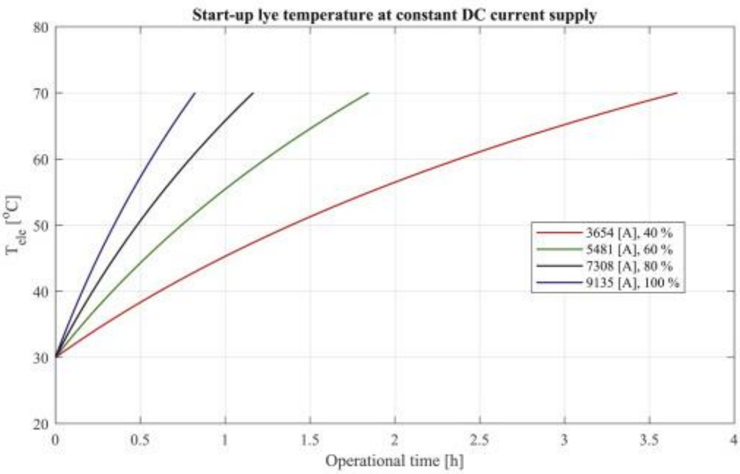


Figure 2.7: Simulated start-up electrolyte temperature at various constant DC current supplies [11]

Temperature control is an extremely important aspect of electrolyzer operation, especially at high-loads because that's when the trade-off between energy efficiency and safety becomes prominent. Higher temperatures increase the stack efficiency because the reaction kinetics are favored, however, the electrolyte is at risk of degradation. When attempting to control temperatures with PID controllers, the temperature cannot always be maintained at the set point. This is due to the large thermal inertia and time delay of the system. An increase in load causes an overshoot in the stack temperature and the cooling effects of the water only start taking effect about 0.4 hours after the load increase. This can put the electrolyzer at risk of degradation if the temperature overshoots beyond the optimal range frequently. This can be avoided by lowering the set point of the controller but that means the electrolyzer will operate at lower efficiencies during steady-state operation, which is also not ideal [12].

Temperature control of an electrolyzer can be classified into two types: before-stack and after-stack temperature control. The difference is the location of the measured and controlled temperature. The type of control used has a noticeable difference on performance. Before-stack control results in low average temperature of the stack which leads to lower operating efficiency. On the other hand, the after-stack control leaves the system vulnerable to overshoot and potential degradation. In the interest of energy efficiency, the after-stack control is preferred. The overshoot phenomenon can be mitigated using more advanced and novel controllers that use load information to regulate the flow of cooling water in advance [12].

## 2.5 District Heating

DH is a technology that plays a crucial role in decarbonizing energy infrastructure by improving the energy efficiency of heating systems and facilitating the integration of renewable energy sources.

Fundamentally, DH is the idea of using fuel or heat resources that would otherwise be wasted in order to meet heat demands of households [13]. DH systems use a network of pipes to distribute heat from a central source, such as a power plant or a waste heat recovery system, to multiple buildings or households. This allows for the centralization of heating production and the use of more efficient heating technologies, such as CHP and heat pumps. By using more efficient heating technologies and reducing energy losses associated with individual heating systems, DH systems can significantly reduce greenhouse gas emissions and improve the overall energy efficiency of heating systems [15].

It is estimated that DH systems contribute to reducing global $CO_2$ emissions by about 1 billion tons annually. But this only accounts for 3% of all $CO_2$ emissions from fuel combustion. Extending the reach and availability of DH can play a significant role in achieving climate goals and mitigating emissions [13].

In Sweden, DH market share has been steadily increasing as fuel oil boilers got phased out as seen in Figures 2.8 and 2.9. In addition, the original energy sources that are used for supplying heat have been evolving over the past decades in order to use more environmentally friendly sources, shown in Figure 2.10. The combination of efficient centralized heat distribution and clean energy sources allowed Sweden to effectively decrease the emissions resulting from their DH systems, visualized in Figure 2.11 [14].

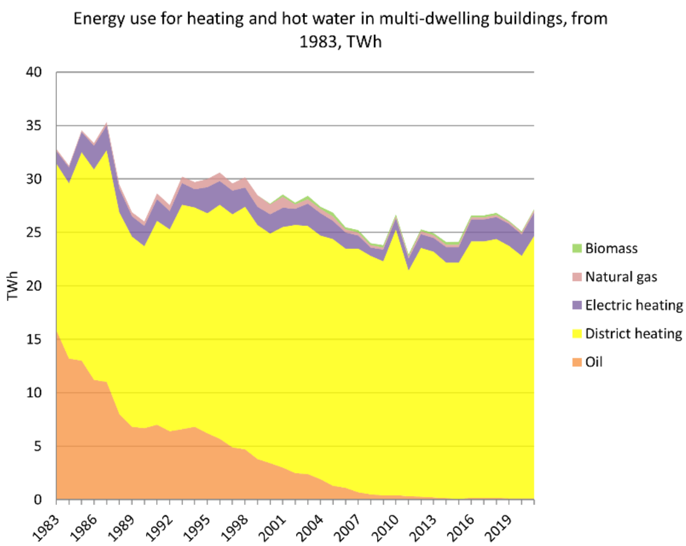


Figure 2.8: Market shares for heat supply to multi-dwelling residential buildings in Sweden between 1983 and 2021 [28]

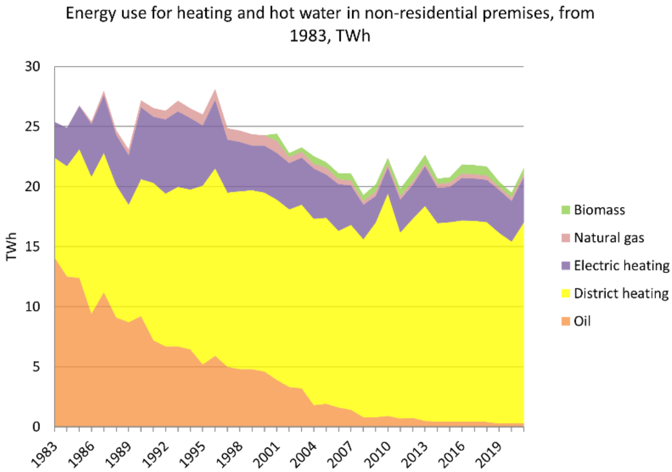


Figure 2.9: Market shares for heat supply to non-residential buildings in Sweden between 1983 and 2021 [28]

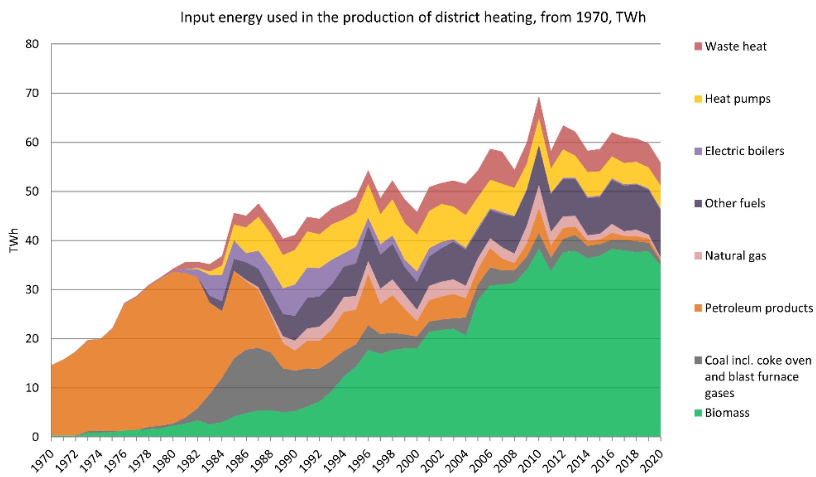


Figure 2.10: Input energy sources used for heat supplied into Swedish DH systems 1970–2020 [28]

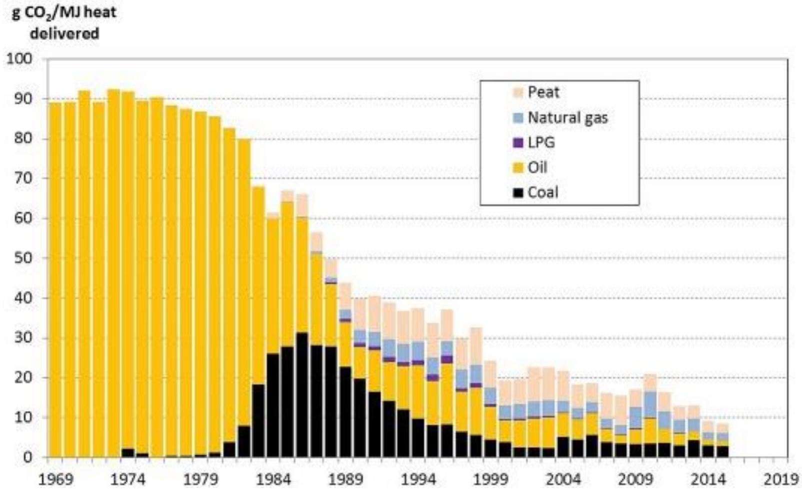

Figure 2.11: Specific carbon dioxide emissions from Swedish DH systems 1969–2015 [14].

The data proves that DH can play an important role in decarbonization and that DH systems should be more widely adopted globally. However, newly installed DH systems should not be designed for the present energy system but rather for the future energy system. Renewable energy sources of the future, such as solar and wind, are variable and can be challenging to integrate into the electricity grid. This can help to balance the electricity grid and increase the utilization of renewable energy sources [15].

The first DH systems were introduced in the 1880s and used steam instead of water. Also known as first generation DH, these systems are considered outdated today because they require high steam temperatures, generating substantial losses. The second generation of DH used pressurized hot water and was characterized by supply temperatures exceeding 100°C. The third generation, which is also the most common today, also uses pressurized water as the heat carrier but is characterized by supply temperatures below 100°C. As DH technology evolves, the operating supply temperatures are decreasing [15]. This enables the integration of even more low-quality waste heat sources into the system, increasing its overall efficiency. Figure 2.7 illustrates the evolution of DH and the trend of decreasing supply temperatures.

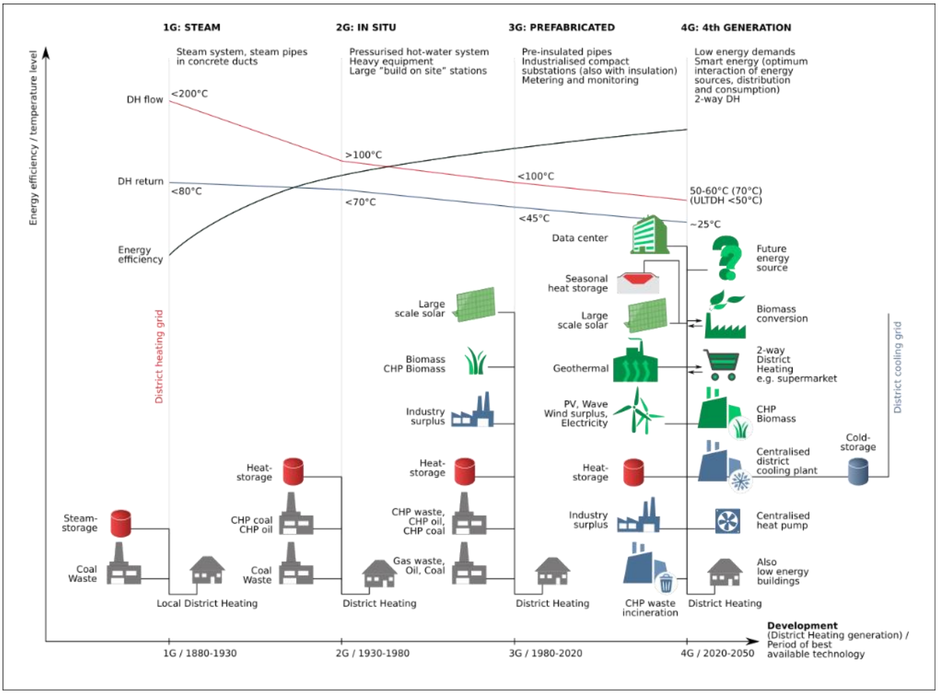


Figure 2.12: Illustration of the concept of 4th Generation DH in comparison to the previous three generations [16]

Recent studies have been exploring the idea of 4$^{th}$ generation DH systems. This new development in DH aims to lower supply temperatures and heat distribution losses further in order to allow the integration of low-temperature heat. These grids of the future will be characterized by a supply temperature of 50°C and return temperature of 20°C [15].

## 2.6 Integration of Waste Heat Sources into DH

Integrating waste heat sources into DH networks is a powerful tool for improving energy efficiency and reducing greenhouse gas emissions. Waste heat is generated as a byproduct of various industrial processes, such as power generation, manufacturing, and chemical processing. By capturing this waste heat and integrating it into DH networks, it can be used to provide space heating and hot water to buildings, reducing the need for conventional heating systems and improving overall energy efficiency. As of today, there is increasingly growing interest and preliminary research in the area of using waste heat from hydrogen production for DH, but large-scale, commercially proven applications are not yet implemented. However, there are several large-scale commercial projects that successfully integrate other waste heat sources into DH networks.

For instance, the Tallaght DH Scheme (TDHS) in Ireland is a project that began construction in May of 2021. The TDHS is an innovative DH network that can be fully supplied by waste heat during normal demand from a nearby Amazon data center. The network is projected to provide up to 50,000 homes with low-carbon heat [17]. In Austria, the government commissioned a project that absorbs waste heat from a data center and supplies it to a nearby hospital by using heat pumps. It is estimated to reduce $CO_2$ emissions by 4,000 tons annually [18].

The integration of waste heat sources into DH networks can be achieved through various technologies, including heat pumps and heat exchangers. Heat pumps can upgrade waste heat to a higher temperature and provide space heating [19]. Heat exchangers can transfer waste heat from one fluid to another, allowing for the recovery of heat energy and its distribution to buildings. In order to determine and justify which waste heat recovery system is most suitable, it is necessary to investigate the amount and grade of recoverable heat [20]. Further research reveals that a plate heat exchanger is most suitable for recovering heat from an alkaline electrolyzer because it is the cheapest and smallest in size compared to other alternatives [21].

# 3. Background

This section will cover some relevant theoretical background regarding practical steam cycles, the standard for CHP plants and DH in Sweden, and how heat from an electrolyzer can be effectively integrated.

## 3.1 Standard Swedish CHP Plant Setup

The Swedish energy system has been recognized for its efficient utilization of resources, particularly in the realm of DH and power production. The typical Swedish CHP plant is designed to efficiently convert fuel into electricity and heat via a combined cycle.

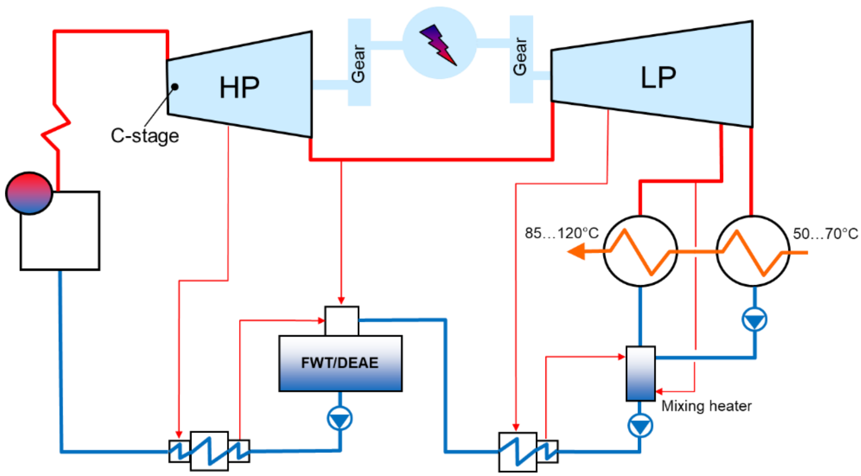


Figure 3.1: Standard Swedish CHP Setup with DH [22]

This diagram illustrates the standard Swedish CHP plant setup, showing a typical steam cycle. At the heart of the system is a boiler that generates high-pressure steam. This steam is first passed through a high-pressure (HP) turbine, where a portion of its energy is converted into mechanical energy for electricity production. Multiple steam extractions from the HP turbine are directed to a feedwater tank or deaerator to preheat the feedwater, improving the overall efficiency of the system.

The steam exiting the HP turbine is then fed into a low-pressure (LP) turbine for further energy extraction. The LP turbine is also the source of steam for two DH condensers, which transfer heat from the steam to the DH water. The presence of two DH condensers allows for a more efficient heat recovery and greater control over the DH water temperature.

In this setup, heat exchangers are employed to transfer heat between different fluid streams without mixing the fluids, thereby optimizing the heat transfer process and reducing energy wastage. This model exemplifies the Swedish approach to CHP, which emphasizes high efficiency and effective heat recovery for DH applications.

## 3.2 Use of Two DH Condensers

As discussed in the previous section, the presence of two DH condensers allows for a more efficient heat recovery. This can be explained by figure 3.2 which presents a comparative analysis of single versus dual district DH condenser systems. The analysis is visualized in two different charts: a Temperature vs. Heat graph and an Enthalpy vs. Entropy graph.

In both graphs, the single DH condenser system exhibits a higher degree of heat loss compared to the dual DH condenser setup. The efficiency of the system, denoted by alpha ($\alpha$) in the figure, is also shown to be lower in the single condenser setup. This is further supported by the decrease in electrical power output that accompanies the single condenser scenario, highlighting the overall performance advantage of the dual condenser setup.

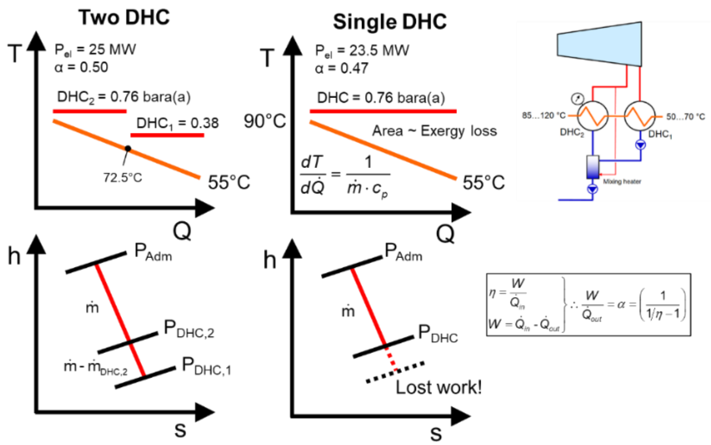


Figure 3.2: Comparison between Single and Dual DH Condenser Systems [22]

It's crucial to note that in the dual DH condenser system, each condenser extracts steam from the turbine at a different pressure (0.76 bar and 0.38 bar, respectively). This differential pressure extraction enables a more efficient heat recovery process, allowing each condenser to operate in a more optimized manner, and thereby contributing to the improved performance metrics seen in the dual condenser setup.

This figure shows the numerous advantages of employing a dual DH condenser system in a CHP plant, including enhanced heat recovery, higher system efficiency, increased electrical power output, improved steam cycle, and efficient operation at low DH temperatures.

## 3.3 Integration of Electrolyzer into DH Network

There are several challenges that must be addressed for this concept to be commercially viable. These include the technical integration of the two systems, the mismatch between the availability of waste heat and the demand for DH, the inherent instabilities of green hydrogen production, and the relatively low grade of the waste heat.

Due to the nature of the electrolyzer, it provides relatively low-quality waste heat. This issue can be mitigated by integrating the heat into a medium temperature heat network. This allows for heat recovery without the need for heat pumps to upgrade the heat quality, which is more economical. Moreover, in order to avoid any extra losses, it is necessary to use an electrolyzer that is located onshore [21].

Some recently published research investigates the potential of recovering excess heat from PEM electrolyzers using electrochemical and thermal modeling. The results show that up to 90% of the wasted heat can be recovered, showing promising potential. The results also show that the electrolyzer efficiency increases from 80% to 92% when utilizing the waste heat [7].

In order to address the other issues, a branching method is proposed, whereby the main DH line is split into two streams. One stream passes through the electrolyzer, absorbing the waste heat, before rejoining the main stream. The flow rate of the branched stream is controlled to maintain a constant after-stack temperature, regardless of the amount of heat injected by the electrolyzer. This approach ensures that the temperature of the DH water remains consistent, while maximizing the utilization of waste heat from the electrolyzer [22].

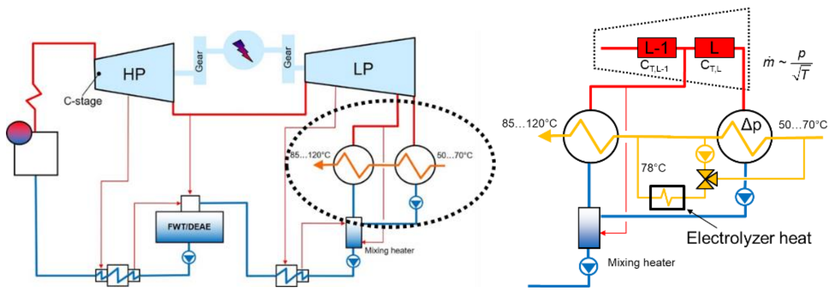


Figure 3.3: Integration of Electrolyzer Heat into DH Network [22]

Figure 3.3 illustrates a strategic method for the integration of waste heat from an electrolyzer into a DH system. This setup introduces several changes to the operation of the system that ultimately enhance its performance.

One primary change is the reduction in flow to the second DH condenser (DHC2), caused by the higher inlet temperature due to the waste heat integration. This condition results in a higher pressure in DHC2 and consequently, an increased stage loading for stage "L".

Another significant feature of this setup is the incorporation of a three-way valve that allows for an optimal electrolyzer operating temperature. This valve ensures the appropriate mixing of flows to maintain the electrolyzer temperature within its optimal range, thereby maximizing its efficiency.

Interestingly, the integration of waste heat from the electrolyzer also results in a higher mass flow and stage heat drop for stage "L", leading to an increase in output. This demonstrates the potential of waste heat recovery from an electrolyzer to enhance the output of a DH system [22].

Theoretically, there are several advantages of integrating waste heat from an electrolyzer into a DH system, including efficient temperature regulation, improved system performance, and increased output.

# 4. Methodology

This section will discuss the method and simulation tools used to answer the research questions. The method includes designing a model of an already existing CHP plant with DH on EBSILON, a thermodynamic cycle process simulation tool, and then integrating the waste heat from the electrolyser into the DH system.

## 4.1 Rationale for Methodology

The methodology employed in this study was chosen after careful consideration of the research objectives, the available data, and the existing literature in the field. The primary aim of this research was to develop a method for integrating waste heat from hydrogen production into a DH network. To achieve this goal, it was essential to have a clear understanding of the latest research and developments in alkaline electrolyzer heat management, DH, and waste heat integration.

Given the complex nature of the problem and the need for a comprehensive understanding of the interactions between different components of a CHP plant and DH network, a simulation-based approach was deemed most suitable for this study. The use of EBSILON Professional software allowed for the accurate modeling of the plant's components and provided the necessary flexibility to design the CHP plant in both design and off-design modes. This enabled the evaluation of the performance and efficiency of the integrated system under varying operating conditions, as well as the potential impacts of waste heat integration on the overall performance of the plant.

The simulation methodology was chosen because it allows for the detailed investigation of the system's behavior and facilitates the identification of potential issues and areas for improvement. It also enables the evaluation of the effectiveness of the proposed integration method by simulating the effects of varying amounts of waste heat inputs on the system's performance. Furthermore, the simulation-based approach offers a cost-effective and time-efficient means to test and optimize the proposed integration method before implementing it in a real-world setting.

In summary, the chosen methodology effectively addresses the research objectives and provides a solid foundation for understanding the system's behavior and potential benefits of waste heat integration in a DH network. This approach ensures that the study's findings and recommendations are grounded in a rigorous and systematic investigation of the problem at hand.

## 4.2 Simulation and Analysis

### EBSILON Professional Software

EBSILON Professional is a comprehensive software tool designed for modeling, simulating, and analyzing thermodynamic cycles and energy conversion systems. It is an industry standard tool able to reliably calculate the potential performance behavior and efficiency of a plant in a range of operating conditions.

### CHP Plant and DH Integration

In the first step of the analysis, a CHP plant with DH was designed using EBSILON Professional's design mode. In this mode, the software calculates the steady-state performance of the system components based on predefined design parameters, such as mass flow rates, temperatures, and pressures.

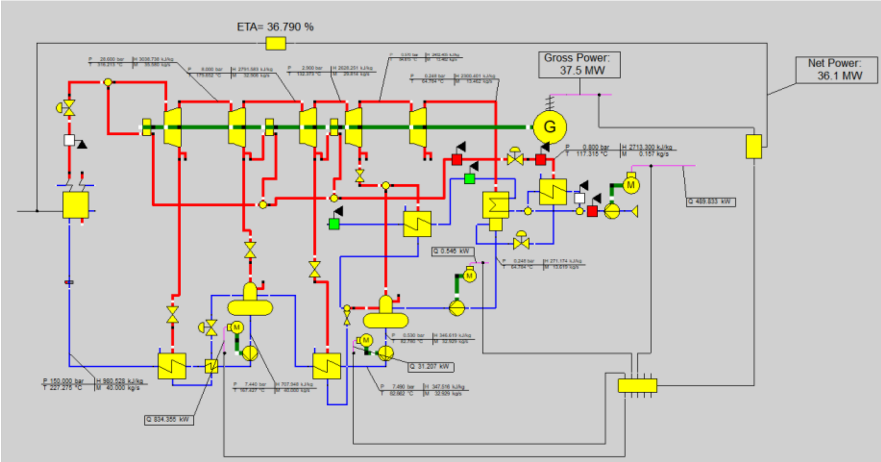


Figure 4.1: EBSILON Model of initial CHP Plant with DH

Figure 4.1 shows the initial model of the CHP plant with DH that is built on the software. It consists of a water/steam cycle with a multistage turbine expansion that powers a generator. This specific setup is chosen because it resembles an already existing plant in Sweden, it is identical to the setup illustrated in Figure 3.1. The research is demonstrated on an already existing commercial setup because that provides the most value to the industry, solutions that can be applied on already existing infrastructure.

## Turbine Calculations: Stodola Ellipse Law

EBSILON Professional software uses several theoretical equations to calculate the performance of system components. One such equation is the Stodola Ellipse Law, which is applied for part-load calculations of steam turbines in off-design mode.

For an uncontrolled multistage expansion, the pressure-flow rate ratio relation can be approximated for each expansion point:

$$PHI = \frac{M_i}{\sqrt{P_i/V_i}} = constant$$

(with i = Expansion point)

PHI is set according to the Stodola Ellipse:

$$PHI = \sqrt{1 - (\frac{Pout_j}{P1N_j})^2}$$

(with j = Extraction group)

With Pi = PINj = P1 and POUTj = P2, the result is:

$$M_1^2 = \frac{P_1^2 - P_2^2}{P_1 \cdot V_1}$$

Comparing the design and off-design cases, we obtain:

$$(\frac{M_1}{M_{1N}})^2 = \frac{P_1^2 - P_2^2}{P_{1N}^2 - P_{2N}^2} \cdot \frac{P_{1N} \cdot V_{1N}}{P_1 \cdot V_1}$$

where:

M = mass flow
P = pressure
V = specific volume
Index 1: inlet
Index 2: output
Index N: nominal value from design calculation

Converted:

$$M_1 = C_t \cdot \frac{\sqrt{P_1^2 - P_2^2}}{P_1 \cdot V_1}$$

$$C_t = M_{1N} \cdot \frac{\sqrt{P_{1N} \cdot V_{1N}}}{\sqrt{P_{1N}^2 - P_{2N}^2}}$$

The coefficient, $C_t$, of the turbine is determined during the design calculation. Sometimes it is also referred to as the "swallowing capacity" of a turbine.

Converted, the result is:

$$P_1 = \sqrt{P_2^2 + P_1 \cdot V_1 \cdot (\frac{M_1}{C_t})^2}$$

This equation is solved iteratively.

The Stodola Ellipse Law allows for the calculation of the turbine's performance at varying load conditions and helps assess the efficiency and flexibility of the system when integrating waste heat from the electrolyzer [26].

It is important to note that turbines are governed by their swallowing capacity, sometimes referred to as swollen capacity, which represents the maximum amount of mass flow that a turbine can accommodate at a given pressure and temperature without suffering from operational issues such as choking or excessive pressure losses. The swallowing capacity is primarily determined by the turbine's geometry and the properties of the working fluid. “As the steam mass flow rate increases, the steam cycle pressure must increase to allow the steam turbine to swallow more steam” [27]. Turbine performance is affected by changes in the mass flow rate, and the ability to accommodate these changes is crucial for maintaining optimal performance and efficiency under varying operating conditions.

## Heat Exchanger Calculations: Design Mode vs. Off-Design Mode

In design mode, EBSILON Professional calculates the heat exchanger's geometry and performance based on predefined design parameters, such as flow rates, inlet and outlet temperatures, and pressure drops for both the hot and cold fluids. The software uses the effectiveness-NTU (Number of Transfer Units) method, along with other correlations, to determine the required heat transfer surface area, number of plates or tubes, and the overall heat transfer coefficient.

In off-design mode, the geometry of the heat exchanger, including surface area and plate or tube configuration, is fixed based on the values determined in design mode. The software then calculates the heat exchanger's performance under varying operating conditions, such as changes in flow rates, inlet temperatures, and pressure drops.

## Integration of Waste Heat from Alkaline Electrolyzers

Next, the model was switched to off-design mode to integrate the waste heat from the alkaline electrolyzer into the DH line by modeling it as a heat injection component. Off-design mode allows for the analysis of the system's behavior under varying operating conditions and enables the optimization of component performance.

In off-design mode, EBSILON Professional calculates the performance of the system based on actual operating conditions, such as inlet and outlet temperatures and pressures, as well as the characteristics of the working fluid, while the geometries and specifications of the components are fixed. These calculations are essential for evaluating the efficiency and performance of the integrated system, as they account for changes in the system's operating conditions when the waste heat from the electrolyzer is utilized.

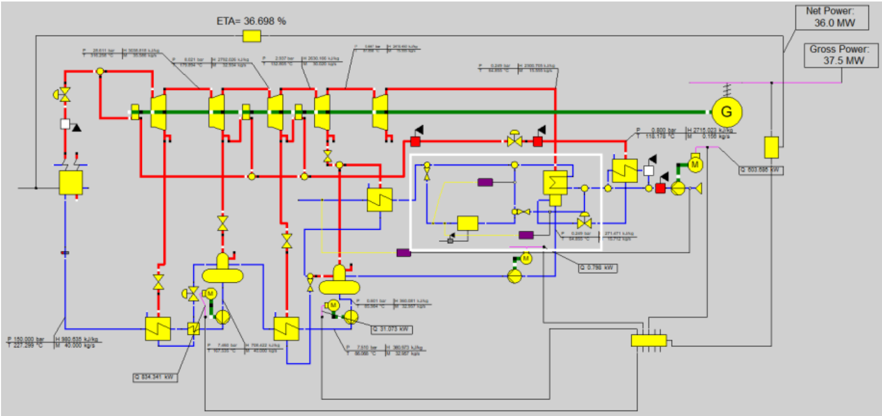


Figure 4.2: EBSILON Model of CHP plant with 20 MW heat waste source integrated into DH system.

The heat source is integrated in this configuration for several reasons. It allows the system to be fully functional even when no heat is being injected from the electrolyzer. The mass flow of the water streams that are used to absorb the waste heat from the electrolyser are controlled to ensure that the after-stack temperature at the outlet of the electrolyzer is kept at 82 °C.

## Heat Exchanger and System Optimization

The waste heat from the alkaline electrolyzer was modeled into the DH system through a heat injection component. This heat injection component represents what would be a heat exchanger in reality. The heat exchanger allows the district water to be heated while simultaneously cooling the electrolyzer to maintain its optimal operating temperature. By using a heat injection component, we can simplify the research to focus on the issue of integration since designing the heat exchanger is outside the scope of this research.

## Analyzing the Effect of Waste Heat Integration on Plant Performance

An essential aspect of the analysis was to assess the impact of integrating the waste heat from the electrolyzer on the overall performance of the CHP plant and DH system. The evaluation included the changes in efficiency, thermal output, and electrical output of the system when waste heat is recovered and utilized. This analysis allowed for the identification of potential benefits and challenges associated with the integration of waste heat recovery into the existing system.

## System Behavior with Varying Heat Input Values

The system's behavior was analyzed at different values of waste heat input from the alkaline electrolyzer. By varying the heat input values, the study aimed to determine the system's response to changes in the electrolyzer's operating conditions and evaluate the system's adaptability and resilience to fluctuations in waste heat availability. This examination provided valuable insights into the optimal operating conditions for both the electrolyzer and the integrated CHP plant and DH system.

# 5. Results

This section will present and explain the results of this research. As discussed in the previous section, the results will show the effect of waste heat integration on plant performance as well as how the system behaves at different heat injection values.

## 5.1 Initial CHP Plant Performance

In order to be able to quantify the results of this research, the performance of the initial CHP plant and DH system should be analyzed, this initial state will be referred to as datum 1. By stating the performance of the initial system, the benefits or drawbacks of the heat integration can be easily identified through comparison. Table 4.1 lists the most important metrics of datum 1.

Table 5.1: Properties of the initial CHP plant and DH system, Datum 1

| **Variable** | **Value** | **Unit** |
|---|---|---|
| Efficiency | 36.79 | % |
| Gross Power | 37.5 | MW |
| Net Power | 36.1 | MW |
| DH Mass Flow | 416.95 | kg/s |
| Heat Absorbed by DH Water | 61342 | kW |
| DH Supply Temperature | 82 | ℃ |
| DH Return Temperature | 47 | ℃ |

The efficiency presented in tables 5.1 and 5.2 represents the efficiency of the CHP plant, which is the ratio of electrical net power output to heat power input to the steam generator.

## 5.2 Effect of Heat Integration on Plant Performance

The simulation data shows that the initial CHP plant, datum 1, operated at a slightly higher electrical power output compared to the scenario with the waste heat source integrated into the DH network. However, the amount of heat absorbed by the DH system increases compared to datum 1. As the amount of heat injection increases, the power output of the CHP plant and heat absorbed by the DH system increase consequently.

Table 5.2: Properties of the CHP plant and DH system with waste heat integrated but set to 0 MW input heat, Datum 2

| **Variable** | **Value** | **Unit** |
|---|---|---|
| Efficiency | 36.54 | % |
| Gross Power | 37.2 | MW |
| Net Power | 35.9 | MW |
| DH Mass Flow | 385.63 | kg/s |
| Heat Absorbed by DH Water | 61594 | kW |
| DH Supply Temperature | 85 | °C |
| DH Return Temperature | 47 | °C |

Table 5.3: Waste Heat Injection Simulation Data

| Heat injection (MW) | Gross Power (kW) | Net Power (kW) | ΔQ(kW) |
|---|---|---|---|
| 0 | 37177 | 35857 | 61594 |
| 1 | 37194 | 35867 | 62583 |
| 3 | 37228 | 35887 | 64562 |
| 6 | 37277 | 35914 | 67533 |
| 9 | 37325 | 35939 | 70506 |
| 12 | 37371 | 35962 | 73481 |
| 15 | 37415 | 35983 | 76456 |
| 18 | 37458 | 36003 | 79433 |
| 21 | 37499 | 36021 | 82412 |

The scenario with the heat injection integrated but the input heat set to 0 MW will be referred to as datum 2, its properties listed in table 5.2. The simulation data is presented in table 5.3 and plotted for visual representation in figures 5.1 and 5.2.

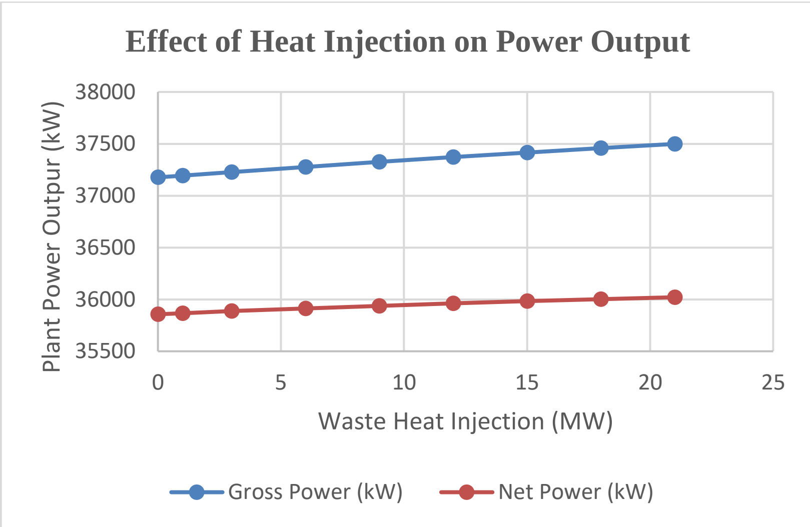


Figure 5.1: CHP plant power output plotted against amount of waste heat injected into DH system

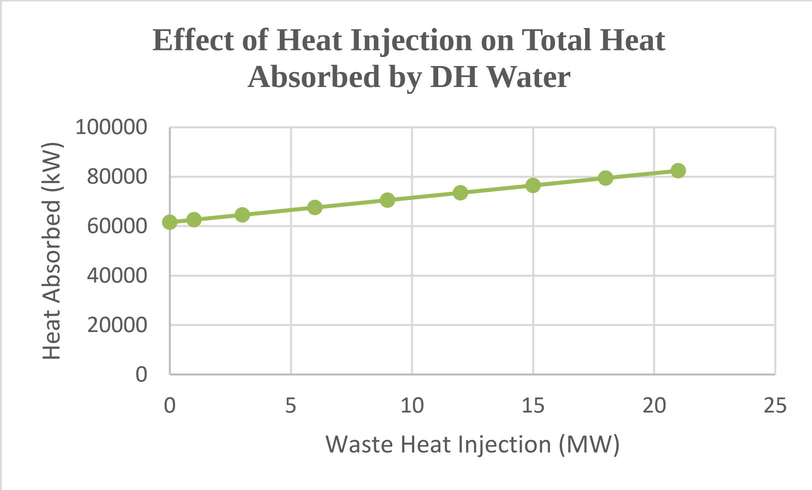


Figure 5.2: Amount of heat absorbed by DH water plotted against amount of heat injected into DH system

The results show that an already existing 37MW CHP plant and DH network can easily accommodate up to 21 MW of heat injection without running into any issues besides negligible loss in electrical power output. The DH water gains a significant amount of heat as well as 3 degrees of temperature on the supply side of the DH system, increasing the quality of heat supplied to buildings connected to the DH network.

If the heat injected exceeds the value of 21 MW, the software displays an error message concerning the DH pump: “Actual point > last point of characteristic.” This error message suggests that the current operation point of the DH pump exceeds the maximum point defined by the pump's performance curve or characteristic in the software simulation.

In the context of pumps, the "characteristic" refers to the pump performance curve, a graph that illustrates the relationship between the pressure (head) that the pump can generate and the volume of fluid it moves (flow rate). It is typically created by the pump manufacturer and describes the pump's optimal operating conditions.

It is important to note that the DH supply temperature is increased from 82°C to 85°C when the waste heat is integrated. This causes the net power to drop by about 200kW in the datum 2 scenario. Simultaneously, the heat absorbed by the DH water increases by 200 kW. So, the energy is not lost, it is just transferred to the DH system. If the supply temperature is kept the same when the waste heat is integrated (82℃), the drop in electrical power output is not observed. However, the system can only accommodate up to 15 MW of heat before the pump exceeds its maximum operating point.

# 6. Discussion

The simulation results provide compelling insights into the potential of integrating waste heat from an alkaline electrolyzer into a DH network. The results demonstrate the feasibility of this integration and reveal several key performance dynamics of the CHP plant under this new operational scenario.

The simulation results reveal a slight decrease in electrical power output from the CHP plant when the waste heat source is integrated into the DH system. That is, the electrical output of datum 2 is less than datum 1 by about 200 kW. However, this reduction is counterbalanced by a significant increase in heat absorbed by the DH system, enhancing the overall efficiency of the CHP and DH system. The DH supply temperature of datum 2 is 85 °C compared to 82 °C in datum 1, which causes DHC2 to extract steam at a higher pressure in the datum 2 scenario, accounting for the decrease in electrical output. This finding underscores the inherent trade-off between electrical power output and heat utilization in CHP systems, which aligns with established principles in energy engineering literature.

By integrating waste heat into the district heating system, the supply temperature of the DH water is increased from 82°C to 85°C, which allows for a greater amount of heat to be utilized in the DH system. This is an effective strategy to recycle the waste heat which otherwise would have been wasted, contributing to the overall energy efficiency of the system.

However, the consequence of this integration is a reduction in electrical power output. Essentially, the same amount of energy is present, but its distribution between electrical power and heat has been altered. This reduction in electrical power output is not a loss in the typical sense, but rather a redistribution of energy from one form to another.

When the supply temperature is kept constant at 82°C, the electrical power output doesn't decrease, but the system's capacity to integrate waste heat decreases to 15 MW. This constraint is likely due to the limitations of the DH pump, which can only handle a certain flow rate and pressure, both of which would increase with the addition of more waste heat.

This highlights the importance of carefully designing and operating CHP systems to achieve the desired balance of electrical power and heat production. System parameters such as the DH supply temperature and the integration of waste heat need to be carefully managed to avoid exceeding the operational capabilities of the system components, such as the DH pump.

It might be possible to mitigate these constraints and improve the system's capacity to integrate waste heat by upgrading the DH pump or making other system modifications. However, any such changes would need to be evaluated for their technical feasibility, cost-effectiveness, and potential impacts on other aspects of system performance. Further research and testing would be required to explore these possibilities and develop optimal strategies for the integration of waste heat into district heating systems.

A novel aspect of this research is the method of integrating waste heat into the DH system, designed to manage fluctuations in the heat supply from the electrolyzer. The system's design introduces a branching stream from the main DH line where waste heat is incorporated. This branched stream is then controlled to maintain a constant after-stack temperature of 82 degrees before rejoining the main DH stream. This design feature allows the system to accommodate variable waste heat input while ensuring a stable output temperature, enhancing the resilience and reliability of the DH network.

The simulation results further show that the CHP plant and DH network can accommodate substantial amounts of waste heat from the electrolyzer – up to 21 MW in this case. This finding indicates a high degree of flexibility and adaptability in the CHP system, an attribute that is increasingly important in modern energy systems as we seek to integrate more variable and diverse energy sources.

When the software displays the message "Actual point > last point of characteristic," it means the simulation is trying to operate the pump beyond its specified range. In this case, injecting more than 21 MW of heat into the DH system causes a flow rate that exceeds the pump's capabilities according to its performance curve.

This suggests that to handle heat injections beyond 21 MW, the system requires a larger pump, additional pumps, or a modification to the system so the existing pump can handle the increased load. However, the specific solution would depend on the details of the DH system and the nature of the constraint, whether it's related to flow rate, pressure, or another parameter. In a real-world scenario, operating a pump beyond its defined characteristics can lead to increased wear and tear, decreased efficiency, or even damage to the pump or associated systems. Hence, it's important to respect these limits in both simulations and practical applications.

Moreover, the added heat to the DH system improves the quality of heat supplied to buildings connected to the network, leading to potential benefits such as enhanced customer satisfaction, reduced demand for additional heating, and potentially significant cost savings for end-users. This is reflected by the significant increase in $\Delta Q$ value, as well as the increase in temperature at the hot side of the DH stream by 3℃.

The system's energy efficiency is a crucial performance indicator, which seems to be barely affected by the integration of the waste heat from the electrolyzer. The simulation shows a minimal drop from 36.79% to 36.54% in efficiency, as shown in tables 5.1 and 5.2, which can be considered negligible considering the additional benefits provided by the waste heat integration.

Regarding the environmental impact, it's plausible to deduce a positive effect on greenhouse gas emissions reduction. The improved quality of the DH water, resulting from the integration of waste heat, allows for more efficient heating of residences connected to the network. This improved efficiency effectively offsets the emissions that would've otherwise been generated by other heating sources, contributing to a more sustainable and eco-friendly energy system.

In the simulation, the electrolyzer is modeled as a heat injection component to simplify the analysis, but it's important to consider the implications of these elements in real-world applications. Future research could explore the performance of the system in a real-world scenario under varying operational and environmental conditions, including fluctuations in load demand, variations in input power quality, and maintenance cycles.

Finally, the results of this study are based on a specific CHP plant and DH network configuration. The findings may not be directly applicable to other configurations or scales of operation. Further research should, therefore, consider a broader range of scenarios and include sensitivity analyses to assess the robustness of the findings under different conditions.

In conclusion, the simulation results offer strong support for the feasibility of integrating waste heat from an alkaline electrolyzer into a DH network. This study, based on specific assumptions and conditions, provides a valuable foundation for future work aiming to fully realize the potential benefits and overcome the challenges of this integration.

# 7. Conclusion

This research study embarked on an investigation into a relatively untapped area of sustainable energy systems – the integration of waste heat from electrolysis into DH networks within the operational environment of a CHP plant. The relevance for the study was derived from the current global energy transformation, particularly the substantial surge in green hydrogen production, and its associated challenges and opportunities.

The results yielded from the detailed modeling and simulation analysis have shown that waste heat from electrolyzers can be efficiently incorporated into DH networks. Specifically, an existing 37 MW CHP plant was demonstrated to have the potential to accommodate up to 21 MW of waste heat injection without significant perturbations to the electrical power output. Importantly, the study found that the quality of heat supplied to buildings connected to the DH network was improved due to an increase in heat absorbed by the DH system.

Even though the electrolyzer is simplified in the simulation model and the heat exchanger that will transfer the heat from the electrolyzer to the DH water is unaccounted for, these factors were deemed non-critical to the main objectives of the research, further backed by the proposed operational control methodology for the integrated system. A clear understanding of the efficiencies and potential impact on greenhouse gas emissions is also crucial and was assessed in the context of this study.

The scalability of the findings to larger CHP plants and DH networks is an interesting avenue for future research. Further research could also be conducted on the economic viability, potential barriers to implementation, and the more detailed dynamics of heat exchange.

In conclusion, this thesis has made significant strides in understanding the potential of waste heat recovery from green hydrogen production. It opens up new possibilities in the field of sustainable heating systems and contributes to the broader quest for sustainable energy solutions. As the world continues to advance in its energy transformation, research such as this continues to play a pivotal role in uncovering innovative solutions and driving us closer to a sustainable future.

# 8. Recommendations for Future Research

This research has brought to light many interesting facets of integrating waste heat from electrolysis into DH networks. Yet, this subject is vast and delicate, and much more can be explored. A list of directions that future research could take is recommended:

1. **Thermal Storage Integration:** Future studies might consider how thermal storage could be integrated into the DH network. By storing excess heat generated during periods of low demand, it might be possible to improve the efficiency of the system even further.

2. **Hybrid Systems:** Investigating hybrid systems, where waste heat recovery is combined with other renewable energy technologies like solar and wind power, could also yield interesting results. How do these technologies work in tandem? What are the potential benefits and drawbacks?

3. **Economic Analysis:** While this study focused on the technical feasibility of integrating waste heat from electrolysis into DH networks, the economic feasibility is just as critical. Future research should undertake a detailed cost-benefit analysis, considering both capital costs and operational costs.

4. **Environmental Impact Assessment:** A more comprehensive environmental impact assessment would be beneficial. This could include quantifying the reduction in $CO_2$ emissions achieved by integrating waste heat into the DH network and comparing this with other strategies for reducing $CO_2$ emissions in the heating sector.

5. **Regulatory and Policy Analysis:** Investigating the regulatory and policy landscape around integrating waste heat into DH networks could also be valuable. What are the existing regulations, and how do they impact the adoption of this technology? Are there any policy changes that could encourage wider adoption?

6. **Real-world Experimentation:** The simulations carried out in this research show promising results; however, there is a significant difference between simulations and real-world conditions. Therefore, a key recommendation would be to conduct pilot studies where the proposed setup is implemented and tested in real DH networks. This would help validate the simulation results, address unforeseen challenges, and generate practical knowledge about system installation, operation, maintenance, and troubleshooting. A successful pilot test could pave the way for scaling up the implementation across other district heating networks and would be a significant step towards realizing the potential of waste heat recovery from electrolysis on a broader scale. This will not only contribute to enhancing the performance and sustainability of DH networks but could also stimulate industry interest and uptake of this novel integration strategy.

The integration of waste heat from electrolysis into DH networks is a rich and promising field for further study. It is hoped that this research will spur more in-depth investigations into these and other topics, ultimately leading to more sustainable and efficient heating solutions.

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